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Contactless vital signs monitoring based on optical fiber Mach-Zehnder interferometer aided with passive homodyne demodulation methods

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Abstract: Two Mach-Zehnder Interferometer (MZI) based passive homodyne demodulation methods (PGC and 3×3coupler) are conducted for heart rate (HR) and respiration rate (RR) detection. © 2020 The Author(s)

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1. Introduction

Vital signs such as heartbeat and respiration rates are essential symbols of health of our human being. In order to better diagnose and treat respiratory diseases, heart diseases and other severe diseases, as well as to have a better monitoring of vital signs for patients and the elderly, a real-time detection of this crucial signal is particularly important. However, traditional methods of measuring respiration and heartbeat are cumbersome, such as Photoplethysmography (PPG) [1, 2], which requires a device to be clipped to a finger, as well as Electrocardiography (ECG) [3], which requires several cables to be attached on human body. These approaches affect the patients' experience and even worse, incur skin irritation and cross infection, especially when they are needed to be monitored over prolonged period of time[4].

In this case, fiber-optic sensor has drawn people's attention for its excellent stability, high sensitivity, high speed, low loss and cost-effective [5]. An MZI-based sensor had been proposed to measure respiratory and heartbeat information [6]. However, this method may lead to unsatisfactory signals detection or even fading problem when it is affected by environmental issues [7]. Several feasible methods have been improved to solve this problem such as active homodyne by using adjustable wavelength laser or piezoelectric transition (PZT) and passive homodyne including phase generated carrier (PGC) or 3×3 coupler [8-10].

The demodulation scheme proposed in this paper is used to solve this problem and make it more stable. Here we demonstrate the results by using PGC and 3×3 coupler demodulation methods, respectively. For PGC approach, a high-frequency sinusoidal carrier signal (typically 3 to 10 times higher than the desired signal) is added to the phase term of the output signal of interferometer to weaken the influence of detection sensitivity caused by random phase shift [7]. After that, the required signal is restored from the carrier through signal processing. As for 3×3 coupler method, an MZI structure is cascaded with a 3×3 coupler to form the sensing component. The three output of 3×3 coupler will then be used to restore the signal of interest.

The traditional MZI-based method is facing the fading problem, that is, the output intensity would be affected by external thermal drift while the worst condition is signal fading. However, these two passive homodyne methods we adopted here are able to get rid of the thermal-induced phase shift and restore a satisfactory signal.

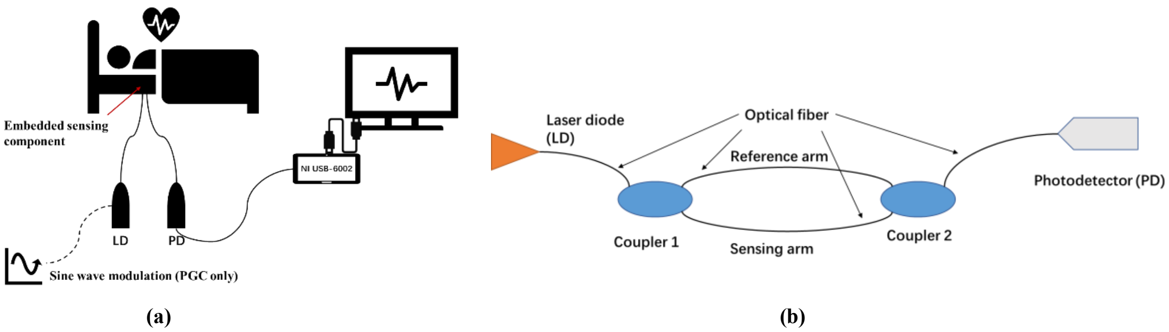

Fig. 1. (a) Contactless vital signs monitoring system, (b) Structure diagram of Mach-Zehnder interferometer.

2. Methods

The whole set of system for passive homodyne demodulation is shown in Fig. 1. Light emitted from laser diode (LD) propagates into the sensing optical fiber and then the outputs are connected to photodetectors (PD)s. Finally, by using a data acquisition (DAQ) card we can display and store the signal in upper computer. For these two methods, there are still some slight differences that will be further introduced, respectively. Optical fibers we use here are all 1550 nm single mode fibers (SMFs) with a 0.9 mm tubing. A healthy man is lying in bed and his heartbeat and respiration information are obtained by the sensing structure which is located at the chest position under the mattress.

2.1 PGC

An adjustable wavelength vertical-cavity surface-emitting laser (VCSEL) with a 0.6 nm wavelength shift by changing the tuning voltage through a function generator which is used for phase modulation purpose. The MZI-based sensing component which has a fixed tiny physical length difference between two arms is embedded under the mattress. This difference produces a 0.8 nm interference period for the MZI structure. A PD is connected at one of the output ends of MZI and a 16 bits DAQ card (NI USB-6002, National Instrument, Austin, TX) with 10 kHz sampling rate is adopted for data collection which helps to directly store and process the signals in upper computer.

2.2 3×3 coupler

The LD we used in this method is the same with PGC method. For the sensing part, we select one 1×2 coupler with 1:1 splitting ratio to form MZI, as well as a 3×3 coupler with 1:1:1 splitting ratio which are cascaded with each other. Then the three PDs are connected to the ends of 3×3 coupler. Light emitted from LD propagates into one input through MZI and then its two output ends are connected to two inputs of the 3×3 coupler. For data collection, we still select DAQ card NI-USB6002 with 1 kHz sampling rate and use LabVIEW to store it in upper-computer.

3. Results and discussion

Here for both methods we select differential-cross multiplication (DCM) method for signal demodulation and processing [11]. Fig. 2. (a), (c) shows the desired results for both methods. As can be seen that both the heartbeat signal and respiration signal are well restored, and the fading problem no longer exists at all peaks and bottoms. After filtering, we can extract heartbeat signal separately, as shown in Fig. 2. (b), (d). Every single heartbeat would have its clear feature, which is easy for the HR detection. For 3×3 coupler method, a relevantly clear I-J-K complex is recovered. To better compute the RR and HR, we process wavelet transform (WT) to recognize every heartbeat [12]. Fig. 3 shows the processed results for PGC method, which is of high accuracy and stability while 3*3 coupler method will also be processed in the same way. In this 60-seconds time during, RR of the user is approximately 8 beats-per-minute (bpm) while HR is 63 bpm. As for PGC method, the accuracy is up to 99.57% and for 3×3 coupler, the accuracy can reach 100% (in a 3-minutes time during).

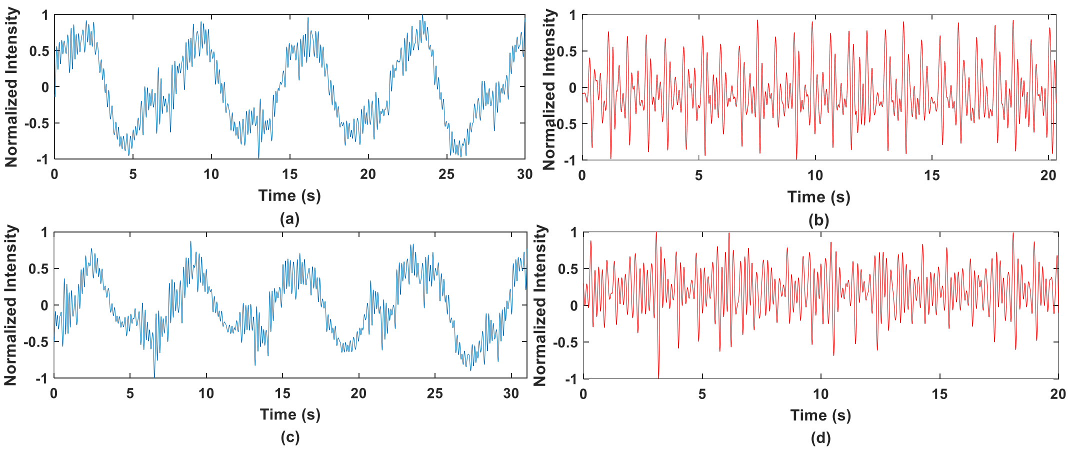

Fig. 2. (a) Demodulated signal for 3×3 coupler method, (b) Heartbeat signal for 3×3 coupler method., (c) Demodulated signal for PGC method, (d) Heartbeat signal for PGC method.

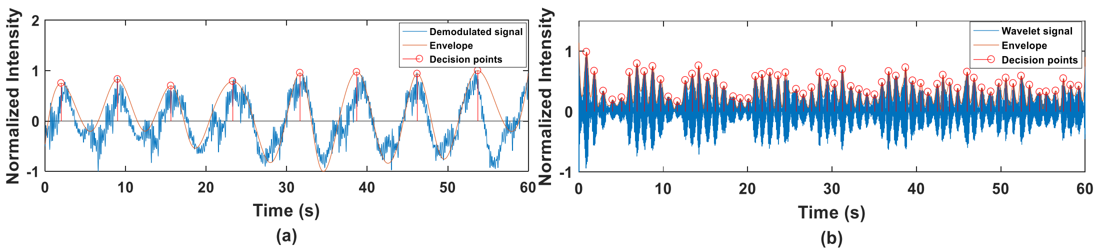

Fig. 3. (a) Respiration rate detection for PGC method, (b) Heart rate detection for PGC method.

4. Conclusion

In summary, two MZI-based passive homodyne demodulation methods (PGC and 3×3coupler) show a satisfactory result for HR and RR detection. Thermal-induced phase shift would not worsen the signal of interest anymore. The features of heartbeat signal are restored to a great extent which is good enough to be detected. The whole system shows a bright future for its cost-effectiveness and high stability for household and hospital.

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