Research Article

Experimental Study on the Concept of Hollow-Core Photonic Bandgap Fiber Stethoscope

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An experiment is proposed to show the feasibility of using hollow-core photonic bandgap fibers (HC-PBF) in the fiber-optic interferometric stethoscopes to generally improve the sensitivity and overcome the problems associated with the electronic stethoscopes. In the experiment, the HC-1550 is used as a measuring arm of an unbalanced Mach-Zehnder interferometer (MZI) and the conventional single-mode optical fiber (SMF) is used as an isolated reference arm. Detection and demodulation of the relative phase shift is performed passively using phase-generated carrier homodyne technique (PGC). The proposed results indicate the significance of using HC-PBFs in the future stethoscopes.

1. Introduction

Stethoscopes are important devices for the early diagnosis of heart dysfunction. The current electronic stethoscopes have some advantages over traditional stethoscopes such as the ability to amplify output sound which is important especially in noisy environment or emergency areas, enhancing the frequency range, reducing the ambient noise, and recording, replaying, and visual displaying of the output data. On the other hand, the fundamental problem of the traditional electronic stethoscopes is its susceptibility to electronic interference by other devices causes distortion of the device output signal which affects the correct diagnosis. A solution to avoid this disadvantage is to use fiber-optic stethoscope. Many of its features make it a very promising alternative to the conventional piezoelectric ceramic sensors. These features include light weight, high sensitivity, large dynamic range, inability to conduct electric current, immunity to electromagnetic interference, robustness and more resistant to harsh environments, easy integration into a wide variety of structures, and multifunctional sensing capabilities such as strain, pressure, corrosion, temperature, and acoustic signals [1–4]. Fiber-optic sensors can measure change in light intensity, phase, wavelength, and polarization. Interferometric fiber-optic sensors are very sensitive and can detect submicron changes of optical fiber length. For this

purpose we adopt the interferometric fiber-optic sensors where a fiber-optic sensor utilizes phase changes of the propagating light to monitor patient's cardiac activity. The concept of the interferometric fiber-optic sensor system for human psychophysical activity detection was introduced in [5]. In [6], a multimethod approach for respiration and heartbeat detection from an optical interferometric signal was introduced. The measurement setup used optical fiber Michelson interferometer and sophisticated signal processing to extract the useful data, where the used optical fiber was spirally twisted and built in a bed mattress. In [7], authors proposed design and implementation of a noninvasive fiber-optic sensor and its associated adaptive signal processing system for fetal heart rate monitoring. The probe utilized sensing elements operating on the basis of the Mach-Zehnder Interferometer. In [8], breathing sensor based on a photonic crystal fiber (large-mode-area (LMA-10), NKT Photonics) interferometer that operates in reflection mode was introduced. The used optical fibers in the previous related work were either the conventional SMF or the solid-core photonic crystal fibers (SC-PCF) that have structures reduce its sensitivity to the acoustomechanical signals generated by the patient. Although the previous references introduced novel approaches and signal processing techniques for monitoring human vital activities, the research in this topic needs further investigation to improve the performance of these systems.

In this study, we have benefited from our simulation and experimental results proposed in [9, 10], respectively. The results showed the superiority of HC-PBF over SMF in terms of sensitivity and noise reduction. In [9], COMSOL multiphysics was used to study and compare the response to acoustic pressure of the HC-PBF represented by HC-1550, a SC-PCF represented by LMA-5, and a conventional SMF represented by SMF-28 for different acoustic pressures and frequencies. The obtained results showed that for the same applied acoustic pressure and frequency the sensitivity to acoustic pressure of the HC-1550 is higher than that of LMA-5 and SMF by 23.5 dB and 22 dB, respectively. In [10], a MZI strain sensor was constructed and used to compare the normalized strain responsivity (NR) of the HC-PBF with the conventional SMF by interchanging the optical fibers under test as a sensing arm of the MZI. The experimental results showed that the NR of the HC-PBF is about 3.6-5.3 dB better than that of the SMF depending on the frequency in the frequency range 500 Hz to 2 kHz. The results were important to judge the necessity of using the HC-PBF for sensing applications. As a result, it is expected that the HC-PBF stethoscopes have better performance than its conventional SMF stethoscopes counterparts. In this paper, we propose an experiment to preliminary study the use of HC-PBF stethoscopes to improve the performance of the existing conventional stethoscopes and provide even better performance than using conventional SMF. The aim of the experiment is to implement the concept of using the HC-PBF in the optical fiber interferometric stethoscope system, how it can interact with the applied signals, and how the measurand's relevant information is extracted by the PGC demodulation technique. The experiment is performed to test the system before realizing the HC-PBF stethoscope. The experiment is performed using a Mach-Zehnder interferometer in which light from a single-mode laser diode is split by an optical fiber coupler into the sensing HC-1550 arm which is wrapped around the piezoelectric transducer cylinder (PZT) and a reference SMF fiber that is isolated from the PZT strains. Simulation of the applied heart beats to the optical fibers is controlled by changing the PZT voltage amplitude and frequency. By modulating the input voltage of the PZT, the PZT cylinder is deformed, stretches the sensing optical fiber, and thus modulates the optical path length of the light to introduce phase shifts. The two optical signals are recombined by a fiber coupler into a single fiber where subsequent detection and demodulation of the relative phase shift is performed passively using the PGC. The high sensitivity of HC-PBF stethoscope allows it to replace the conventional piezoelectric crystal used in the electronic stethoscopes and the conventional SMF in the existing optical fiber stethoscopes.

2. The Experimental Setup

The experimental setup is shown in Figure 1. Unbalanced Mach-Zehnder interferometer is used where the HC-1550 and the SMF-28 form the interferometer arms wrapped around a PZT tube and an isolated aluminium tube, respectively. The HC-PBF acts as a measuring arm while the SMF

FIGURE 1: Block diagram of the experimental setup.

forms the reference arm of the interferometer such that the PZT signals apply to the measuring arm while the reference arm is isolated from the PZT strains. A single wavelength distributed feedback (DFB) fiber laser system with relative intensity noise (RIN) < -115 dB/Hz @ 1 MHz is used. The laser light source emission at 1550 nm is frequency modulated by a carrier sine wave of $\omega_o = 80$ kHz and injected into the interferometer through an optical isolator. In this case, a finite known path imbalance must exist between the two arms of the interferometer, so that the frequency variation of the laser light causes a linearly proportional phase variation. The material of the used PZT cylinder is lead zirconium titanate. The PZT cylinder dimensions are 5 cm (long), 4 cm (diameter), and 3 mm (thickness). The HC-1550 is used as a measuring arm by wrapping it around the PZT tube with number of 21 turns which forms a length of 2.5 m. The reference arm is formed by wrapping a single-mode optical fiber around an aluminium tube with the same number of turns and isolation from the effect of the measurand. When a voltage signal is applied across the PZT cylinder, it will experience dimensional change that increases the tension of the optical fiber. Since the optical path length of the fiber is a function of its strain, light transmitted through the optical fiber will experience a phase change. An electrical modulating signal of sine waveform is applied to the PZT and the output optical interference is detected by a PIN diode. The experiment is performed by varying the amplitude of the voltage applied to the PZT while the frequency of the signal is kept constant and vice versa. The phase information is extracted by a phase-generated carrier homodyne technique. A digital storage oscilloscope is used to display the results.

3. Measurement Results

In this experiment the strain-induced phase shift of the HC-1550 is measured where the HC-1550 is considered as the sensing arm of the MZI and the SMF as the reference arm. Signals with different amplitude and frequencies are applied to the PZT cause dimensional change in the sensing arm then the output voltage signal from the PGC for each reading is recorded. The input signal amplitude is swept from 2V to 5V while the frequency is swept from 500 Hz to 5 kHz. Samples of the results are shown. The output from the PGC circuit is interfaced with MATLAB for easier

FIGURE 2: Output signal from the PGC when the measuring arm is the HC-1550 for input V_{p-p} of 2.5V @ 900 Hz.

FIGURE 3: Single-sided amplitude spectrum of the output PGC signal for input signal of 2.5 V at 900 Hz.

dealing, displaying, transforming the output signals from time domain to frequency domain, and performing noise analysis. Figure 2 shows the output waveform from the PGC displayed on the Oscilloscope for input signal to the PZT of peak-to-peak voltage amplitude of 2.5 V and frequency 900 Hz. This output signal represents the output V_{p-p} signal of the PGC circuits after the demodulation process which is proportional to the strain-induced phase shift of the HC-1550.

Figure 3 shows the single-sided amplitude spectrum of the output signal in the frequency domain by applying fast Fourier transform (FFT).

The power spectral density of the output signal from the PGC of the HC-1550 interferometric sensor is also measured as shown in Figure 4.

It can be seen the presence of the fundamental frequency and its harmonics. If the level of these harmonics is high such that it can contribute to signal distortion which can be calculated or measured by total harmonic distortion, then it should be attenuated or rejected. To reject or to set the harmonics to acceptable limits, a band pass filter is designed using the filter design and analysis tool in MATLAB to improve the signal to noise and distortion ratio as shown in Figure 5.

The same results are obtained when the input signal frequency to the PZT is changed. For example, the power

FIGURE 4: Power spectral density of the output signal for input signal of 2.5 V at 900 Hz.

FIGURE 5: Power spectral density of the output signal after rejecting the harmonics by band pass filter.

spectral density of the output signal from the PGC when the input signal frequency to the PZT is 1.6 kHz is shown in Figure 6. These results show the ability of the proposed system to correctly detect, reconstruct, and analyze the input signal; thus it can be used as a high-performance optical stethoscope.

4. Conclusion

In this paper, an experiment shows the concept of using the high sensitive HC-PBF stethoscope is proposed. In the experiment, the HC-1550 is used as a measuring arm of a Mach-Zehnder interferometer and the conventional SMF-28 is used as an isolated reference arm. Detection and demodulation of the relative phase shift is performed passively using the PGC. The ability of the system to detect and to reconstruct the input signal in time domain and the ability to transform it to frequency domain using FFT for further analysis are shown. The experimental results prove the ability of using the system to measure and analyze the heart beats and the patient's condition. As a future work, the system will be realized, and we will use the obtained power spectral density to provide information about the cardiac activity. A library can be built to directly inform the doctor or the staff about the patient's condition.

FIGURE 6: Power spectral density of the output signal for input signal of 3.5 V at 1.6 kHz.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that they have no conflicts of interest.

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