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Research paper

Duplex Fiber Interferometer for Acoustic Wave Sensing

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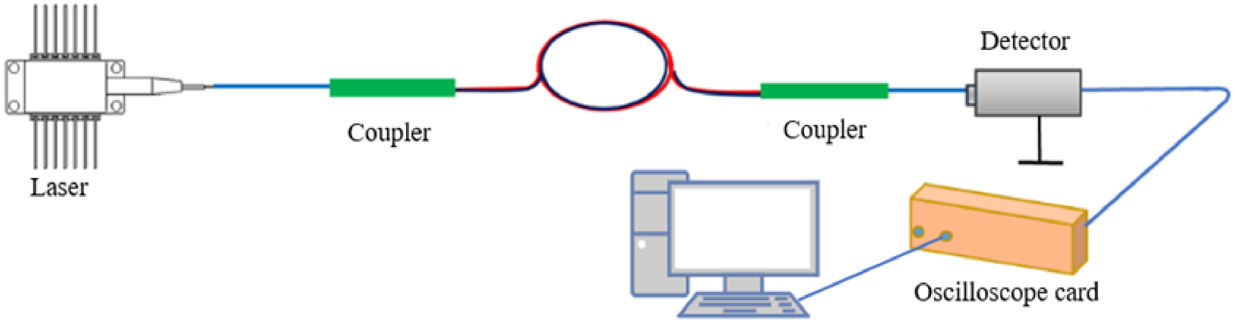
Abstract

Optical fiber sensors have played a significant role in the area of border security control and focal organization protection. In this article, a fiber Mach-Zehnder sensor based on the duplex fiber cable was proposed. Replacing two simplex fibers with duplex fiber cable in the Mach-Zehnder interferometer prevents the problem of fiber length mismatches in long fiber cable. The operating principle of the sensor is based on the fact that the acoustic wave induces strain in the fiber, and this strain changes the effective length or the refractive index of the fiber. As a result, the phase difference between the two arms changes, leading to a variation in the output light intensity of the interferometer. This intensity change is then detected and recorded by the photodetector. The acoustic wave with various frequencies was applied to the fiber cable, and the responses of the sensor were investigated. Then, a 150m cable was buried under the soil and the intrusion effects were considered.

Graphical abstract



1. Introduction

Acoustic wave detection is one of the most important issues in modern science and technology. Among its vast applications, we can mention the structural health monitoring and medical imaging. Piezoelectric crystal is one of the customary and commercial acoustic sensors. It possesses interesting characteristics such as small size, lightness, and high sensitivity. Despite these benefits, they suffer some limitations, especially when used in harsh environmental conditions, such as high temperatures and chemical pollution. Furthermore, the electromagnetic interference can interrupt these sensors. Cable link requirement for electrical transmission and signal attenuation in the higher cable length are considered to be some other disadvantages of these sensors [1]. However, fiber optic acoustic sensors have drawn a lot of attention due to their high sensitivity and simple usage, as well as the absence of the above limitations. Among the applications of these sensors, we can refer to the pipeline leakage detection and the intrusion detection [2-4]. Fiber optic acoustic sensors are based on various mechanisms such as Mach-Zehnder interferometer [5-8], Sagnac interferometer [9], Michelson interferometer [10], and phase-OTDR [2, 3]. Most of these sensors are based on the interference mechanism in order to detect the light phase change induced by the acoustic wave.

Nowadays, Mach–Zehnder-based acoustic sensors are continuously advancing. In [11, 12], the sensing fiber arm has been covered by a low elastic modulus composite to improve the acoustic sensitivity of the Mach-Zehnder sensor. Moreover, these fiber interferometer sensors have been employed as a microphone and hydrophone to record the voice due to their high sensitivity to acoustic waves [7, 8]. For all of the reported Mach-Zehnder acoustic sensors, one interferometer arm, called the sensing arm, was exposed to the acoustic wave, and the other arm, called the reference arm, was put in an isolated box away from the acoustic wave. In [13], the researcher employed the push-pull technique where both arms were wrapped around two individual tubes. The tubes were coaxial, and one of them was surrounded by the other one. The acoustic wave was loaded inside the tube with a smaller diameter. In this case, the difference in the induced phase shift between the two loops was 180°. Therefore, the sensitivity got twice as strong as it is in the traditional case. Under this condition, the tube is employed as a transducer, whereas the tube seems extremely difficult to employ, especially when the fiber arm needs to be buried under the soil to detect the intrusion. On the other hand, preparing two exactly equal-length fibers to employ as the optical paths of an interferometer is one of the significant challenges for the traditional interferometer, especially for the long sensing length. The length mismatch will increase the noise of the system. In this article, instead of using two simplex fibers for a Mach-Zehnder interferometer, we use a duplex fiber cable where two single mode fiber cables are stuck together. An infinitesimal difference in the fiber length can help record data by the detection system.

2. Theory

Figure 1 shows the configuration of the Mach–Zehnder fiber optic interferometer. In this structure, the output light from a continuous-wave laser is divided into two branches and propagates through two paths of equal length. In a Mach–Zehnder interferometer, the maximum optical path difference between the two branches must be smaller than the coherence length of the laser. The two paths are then recombined by another coupler at the photodetector. One branch acts as the reference arm, while the other serves as the sensing arm. Moreover, any optical path difference between the two arms or any change in physical parameters causes modulation of the output signal intensity, which is detected by the photodetector.

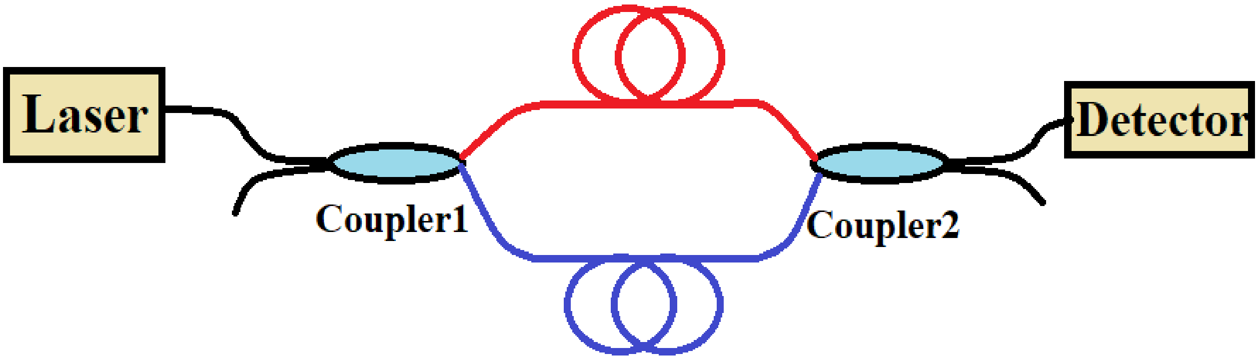


Figure 1. The schematic of the Mach-Zehnder interferometer

The operating principle of the fiber-optic Mach–Zehnder interferometric (MZI) acoustic sensor is based on the interference of two optical beams propagating through the reference arm and the sensing arm. Assuming that the light intensities in the two arms are equal ($I_1=I_2=I_0$), and ϕ_1 and ϕ_2 are the optical phase delays in the corresponding arms, the signal detected by the detector is as follows [14]:

$$I=2I_0[1+V\cos(\Delta\phi)] \qquad (1)$$

Where $\Delta\phi=\phi_1-\phi_2$ is the optical phase difference between the two arms and V is the interference visibility. The optical phase delay is defined as:

$$\varphi=2knL \qquad (2)$$

Where $k=2\pi/\lambda$ is the optical wavenumber, n is the effective refractive index of the fiber, and L is the length of the fiber arm. When an acoustic wave is applied to the sensing arm, mechanical strain is induced in the fiber, causing a phase change in the transmitted light. The induced phase difference change resulting from the acoustic wave is given by:

$$\Delta\Phi=2\pi nL\sigma\varepsilon / \lambda \qquad (3)$$

Where σ is the photoelastic coefficient, ε is the applied strain due to the acoustic wave, and λ is the operating wavelength of the optical source. Consequently, acoustic waves are converted into intensity variations through phase modulation, which are then measured by the photodetector.

3. Method and Results

In this article, instead of two simplex fibers, a duplex fiber cable was used as the arms of a Mach–Zehnder interferometer acoustic sensor. Therefore, both arms are similarly exposed to the acoustic wave. When an optical path difference on the order of micrometers exists between the two arms, the acoustic-wave-induced phase difference between the two similar arms can remain under special conditions. As a result, the output of the exposed interferometer exhibits intensity variations proportional to the applied acoustic wave. The experimental setup is shown in Figure 2. The optical output of a continuous-wave distributed feedback (DFB) laser with a wavelength of 1550 nm and an output power of 10 mW, having a spectral linewidth of 0.1 nm, is divided into two beams by a 50:50 optical coupler (Coupler 1). Each beam is then injected into one of the arms of the duplex fiber. The duplex fiber cable consists of two single-mode telecommunication fibers bonded together. The outer jacket diameter of each single-mode fiber is 2.8 mm, and the fiber length used in the experiment was 10 m. The light emerging from the two arms is recombined using a second 50:50 coupler (Coupler 2), and the output of this coupler is directed to an InGaAs photodetector with a bandwidth of 2 GHz and responsivity of 0.85 A/W. The electrical output of the photodetector, which contains the intensity fluctuations of the interferometer, is recorded using an oscilloscope card with a bandwidth of 15 MHz and 8-bit resolution. The sampling rate of the oscilloscope card is 10 kS/s for two channels. Considering the minimum required number of samples per cycle, the maximum detectable frequency for each channel is approximately limited to about 1 kHz. The oscilloscope card is connected to a computer, and the data are collected and stored using dedicated software. To investigate the system response, acoustic waves with known frequencies are applied to the fiber, and the corresponding responses are analyzed. The acoustic excitation is generated using a simple buzzer driven by a function generator. The buzzer has no calibrated control over the acoustic pressure level. It is placed approximately 1 cm away from the fiber cable, as shown in Figure 3. It is also noted that the fiber cable is not mechanically constrained on the surface, allowing free mechanical interaction with the acoustic field. All experiments were conducted under room temperature conditions of approximately 25 °C. At first, the buzzer is derived by a 100 Hz sinusoidal wave and the resultant acoustic wave is applied on the fiber.

The time scale signal was obtained and compared to that of the silent buzzer. We compared the duplex fiber cable with the traditional Mach-Zehnder interferometer in which two simplex fiber is used as interferometer arms.

Hence, the duplex fiber cable is replaced by two simplex fibers with the length of 10m. One of the fibers was put in an isolated box away from the acoustic wave and the other arm is exposed by the acoustic wave.

Figure 4 shows the fiber arrangement on the table.

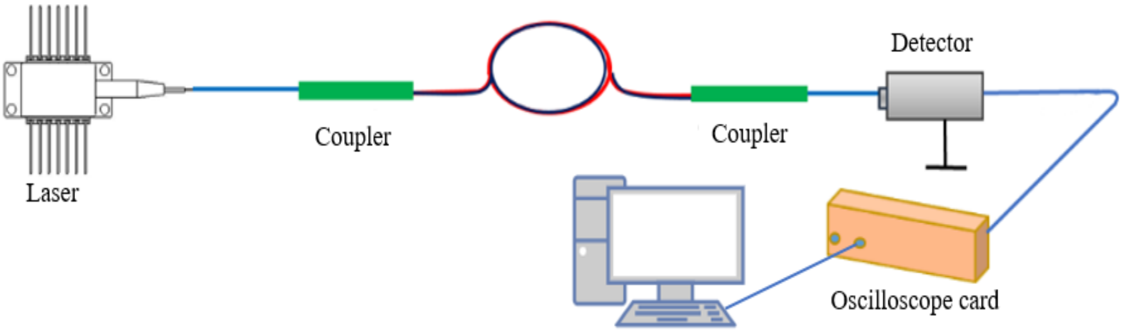


Figure 2. The schematic of the setup

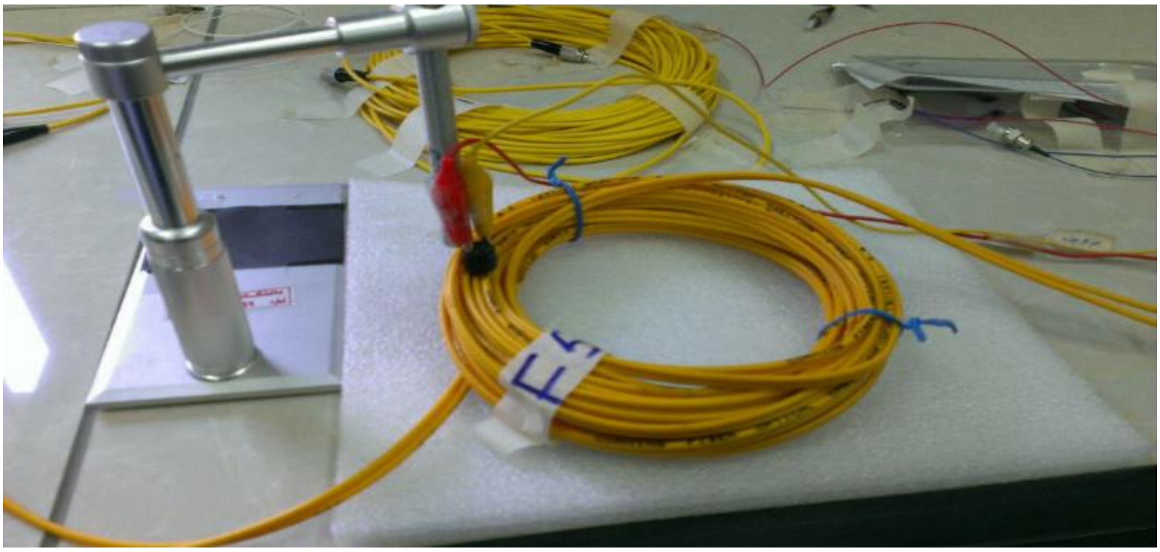


Figure 3. The position of the buzzer near the fiber cable

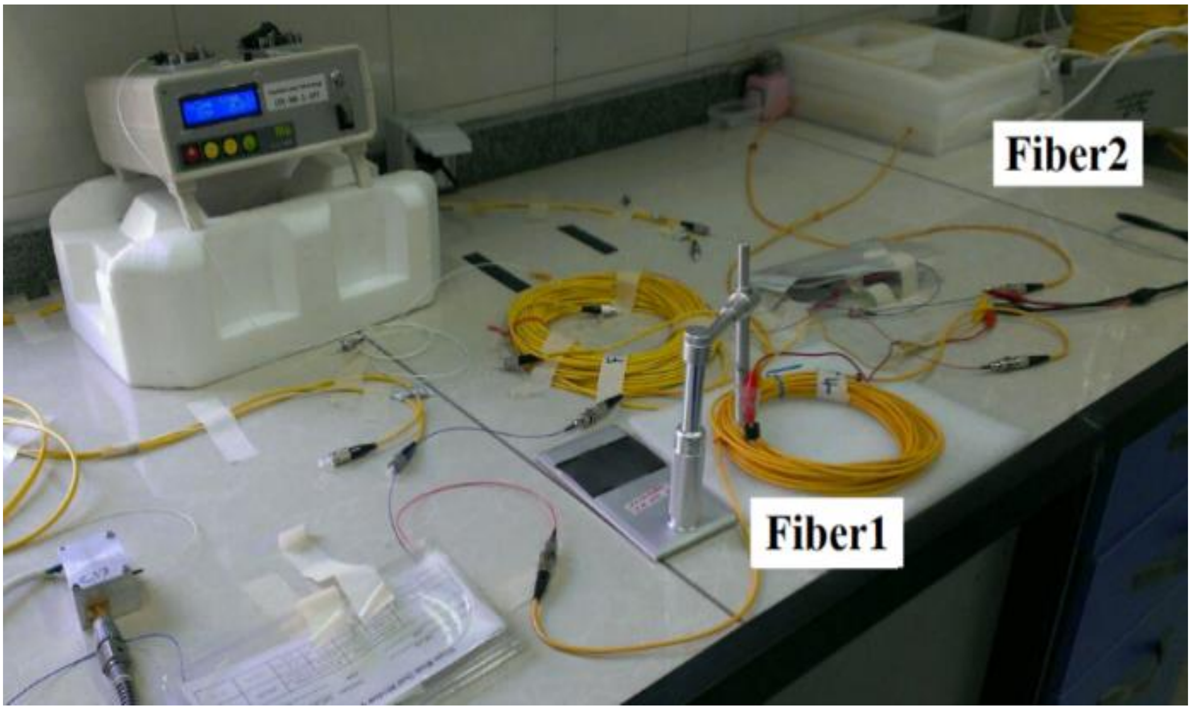


Figure 4. The fiber arrangement on the table

The time scale signal in two cases, duplex fiber and two simplex fibers, are shown in Figure 5.

It can be seen that, in both cases, the time scale signal is affected significantly by the buzzer. It is noteworthy that the buzzer generates some frequency components in order of 2 kHz. When the buzzer is derived by a constant voltage, these frequency components will be generated. When the buzzer is derived by a frequency generator, the buzzer is modulated by the desired frequency. In this section, the acoustic signal generated by the buzzer, is recorded through a microphone and the time scale signal is compared with the result of the Mach-Zehnder acoustic sensor.

The recorded signal by the microphone is shown in Figure 6.

Now, the time scale signal generated by a special frequency of buzzer, is converted using Fourier transform to obtain the detected frequency by the sensor.

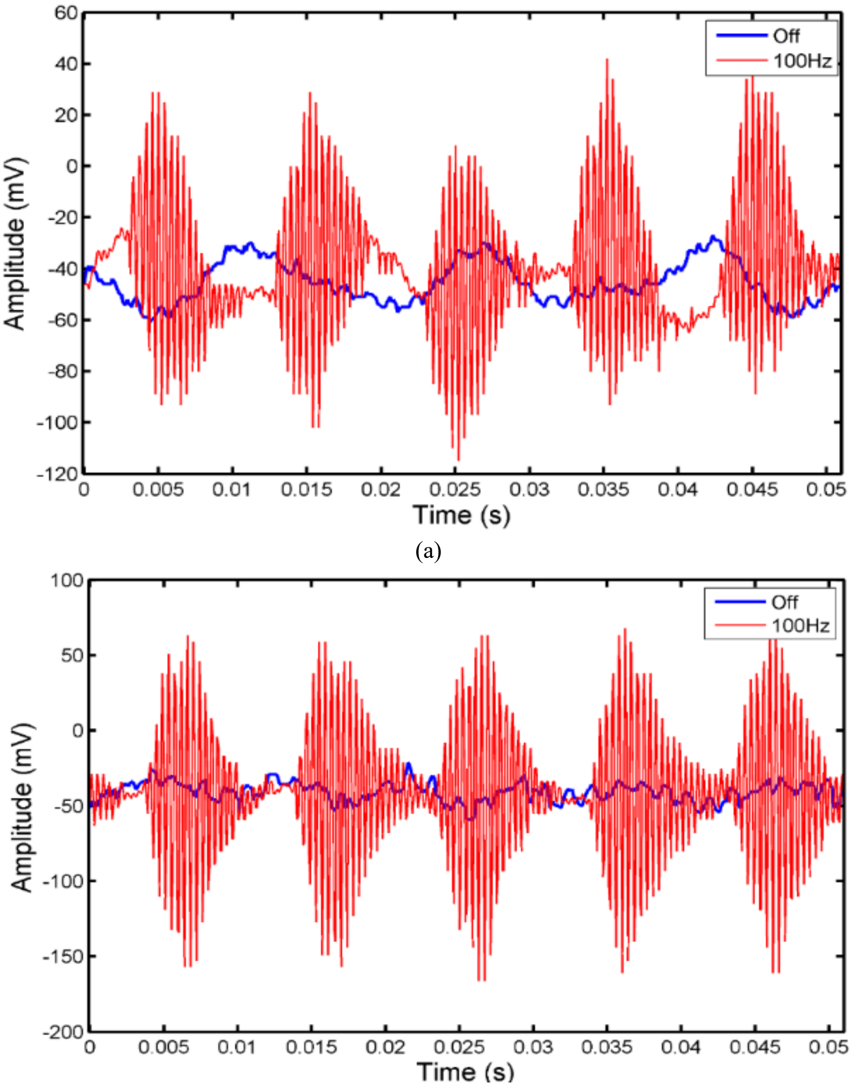
The results of the frequencies between 100 to 500 Hz for two state of duplex fiber and two simplex fibers are compared in Figures 7 and 8. The comparison between the generated signal by buzzer in two state of duplex fiber and in two simplex fibers shows that the sensor works properly in different frequencies. However, there are some peaks in different frequencies in the case of a silent buzzer.

The origin of the observed spectral peaks was not explicitly investigated in this work. Possible contributors include environmental perturbations, mechanical vibrations of the experimental setup, laser frequency/intensity fluctuations, and electronic noise in the interrogation system.

To quantitatively evaluate the performance of the proposed sensing configuration, the signal-to-noise ratio (SNR) was calculated and compared with that of a conventional simplex fiber configuration.

The SNR was defined as the ratio between the amplitude of the acoustic signal peak at 100 Hz and the average noise floor in the surrounding frequency band.

For an applied acoustic signal with a frequency of 100 Hz, the measured SNR of the proposed duplex fiber configuration was 10.1 dB, while the simplex fiber configuration yielded an SNR of 4.6 dB.



(a)

(b)

Figure 5. Time scale signal for (a) duplex fiber cable (b) two simplex fibers

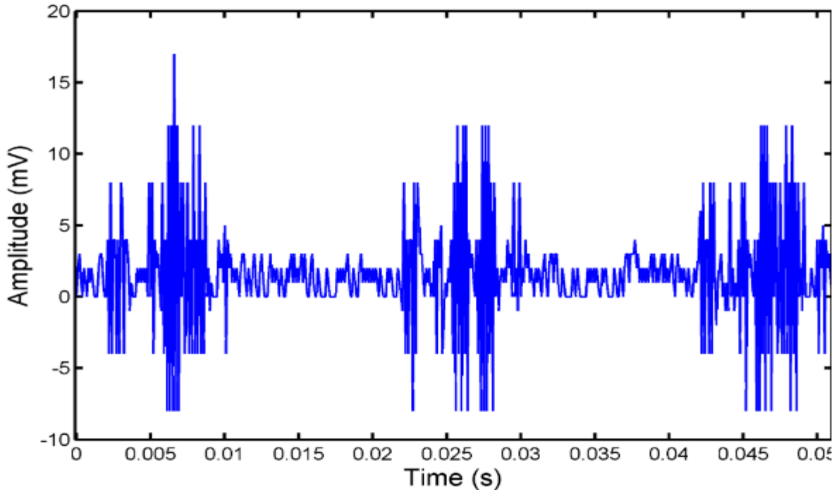
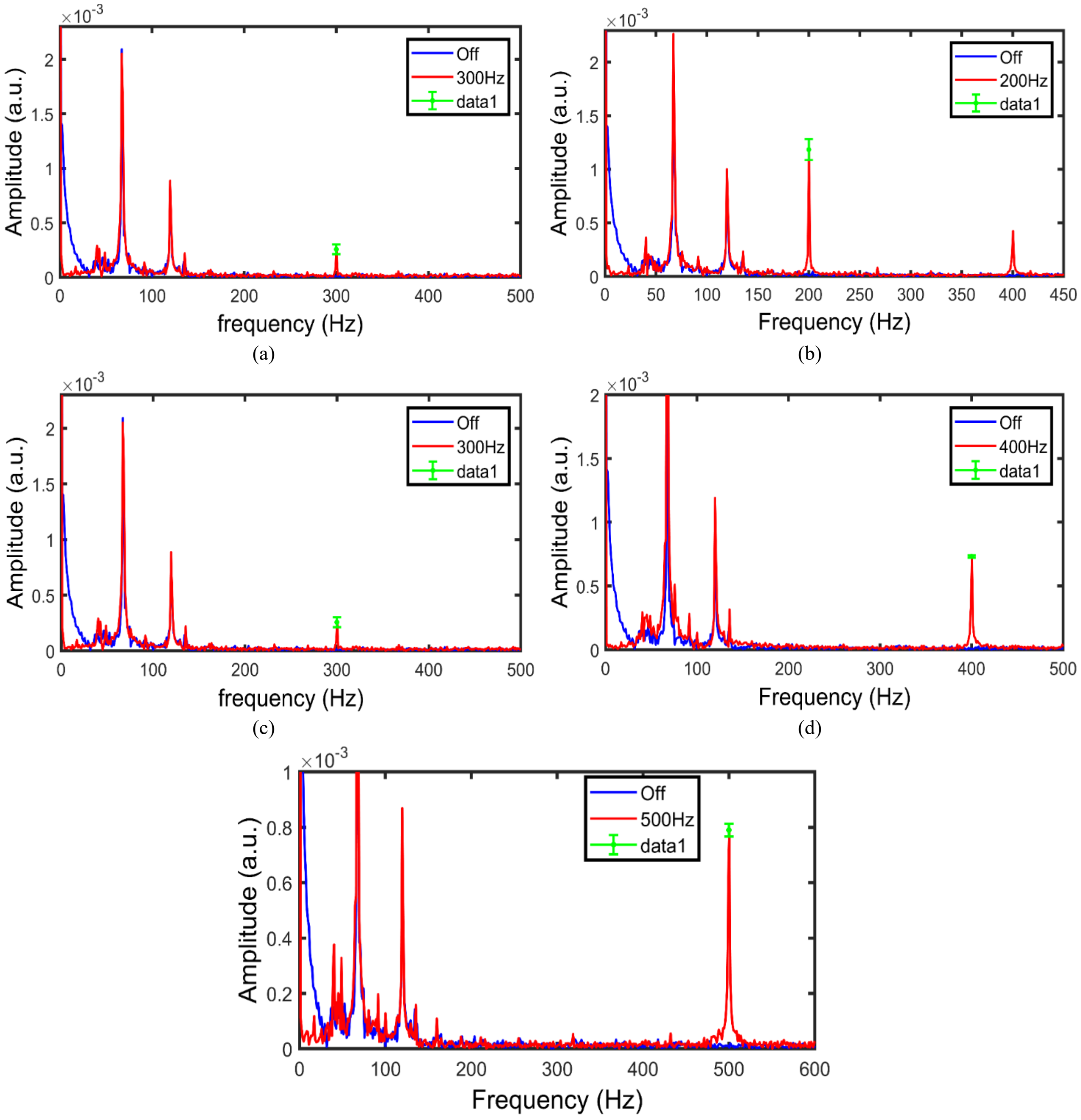


Figure 6. The recorded signal by the microphone

The improvement in SNR indicates that the dual-fiber structure enhances the acoustic signal detection capability and suppresses background noise more effectively. In addition, the repeatability of the sensing system was investigated by repeating the measurement several times under identical experimental conditions. The mean response and the corresponding standard deviation were calculated and represented as error bars in the measurement results, confirming the stability and repeatability of the proposed sensor.

It should be noted that the acoustic excitation was generated by a buzzer driven by a signal generator, and the absolute sound pressure level produced by the source was not independently calibrated.



(a)

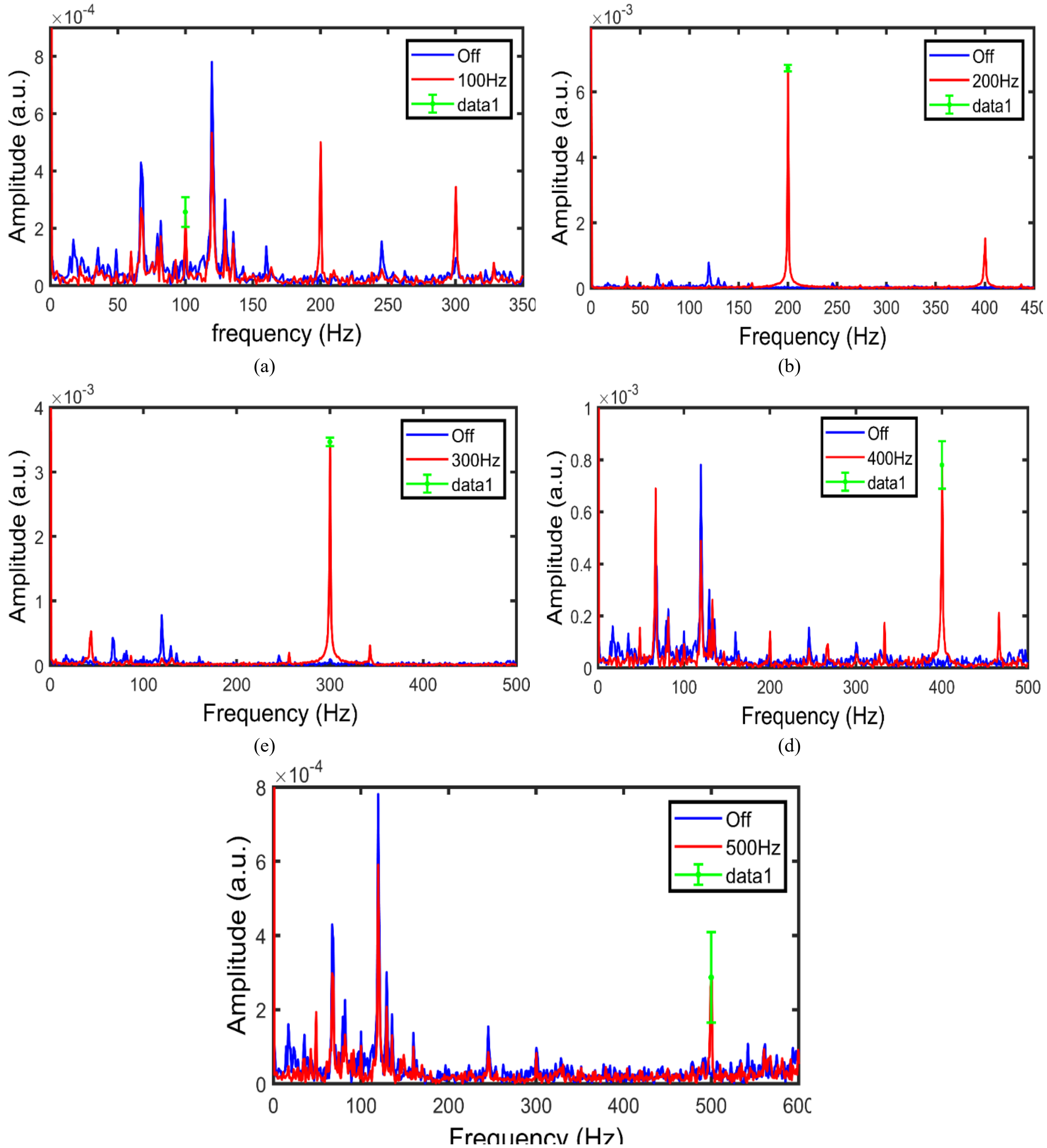
(b)

(c)

(d)

(e)

Figure 7. Frequency signal of duplex fiber for (a) 100Hz (b) 200Hz (c) 300Hz (d) 400Hz and (e) 500Hz



(a) (b)

(e) (d)

(e)

Figure 8. Frequency signal of two simplex fibers for (a) 100Hz (b) 200Hz (c) 300Hz (d) 400Hz and (e) 500Hz

Consequently, performance parameters that require a calibrated acoustic pressure reference, such as sensitivity (V/Pa or rad/Pa), minimum detectable acoustic pressure, dynamic range, and absolute frequency response, could not be accurately determined within the scope of the present work

Therefore, this study is primarily intended as a proof-of-concept demonstration of the proposed fiber-optic acoustic sensing approach. A complete quantitative characterization using a calibrated acoustic source will be carried out in future investigations. In this section, the performance of the new method is investigated in a real condition. Therefore, a 150m duplex fiber cable is used as the two branches of Mach-Zehnder interferometer. One hundred and twenty meters of the middle section of the cable was buried under the soil and two free ends of the cable were placed into a pipe to protect the cable against the acoustic fluctuation. The cross section of the hole in which the cable was placed, is a rectangular with 30cm width and 20cm deep. At first, the sensor output resulting from a person walking on the optical fiber cable was investigated. The time scale of the detected signal for the case of a walking person on the buried fiber was recorded and the result was compared with the case of the intruder's absence. The result is shown in Figure 9. Then, a motorcycle passed near the buried optical fiber cable, and the generated acoustic waves were investigated. Figure 10 shows the output of these waves. Comparison between Figures 9 and 10 shows that the recorded signal for the case of a walking person and a motorcycle are different. In other words, they have their special fingerprint. It can be used to find the kind of intruder when this system is used as an intruder sensor.

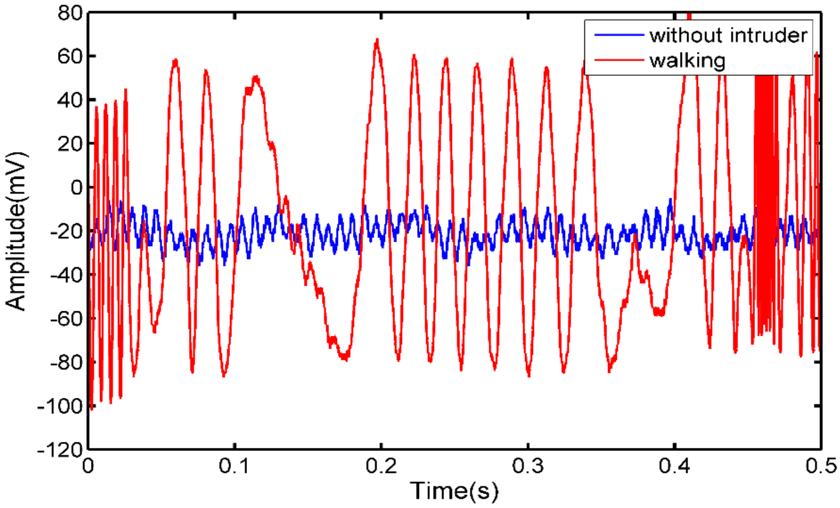


Figure 9. The time scale of the detected signal for the case of walking person on the buried fiber

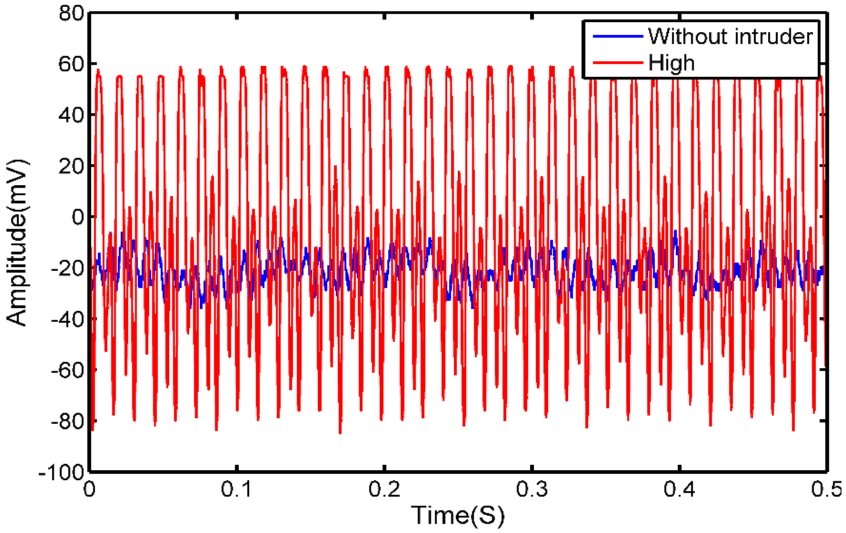


Figure 10. The effect of acoustic wave produced by a motorcycle near the buried fiber cable

Then, the time-domain signals generated by the motorcycle near the optical fiber were analyzed using the Fourier transform in two cases of low and high speeds, and the results were compared. The results are shown in Figure 11. As it was shown above, the motorcycle affected significantly on the frequency signal. Finally, the effect of distance between the motorcycle and buried fiber was considered and the frequency signals for three cases of 1m, 2m and the very small distance were compared to each other. The results are shown in Figure 12. As demonstrated by the results, duplex optical fiber represents a highly suitable option for acoustic wave detection. This advantage becomes particularly significant in applications where the sensing fiber must be buried underground and extends over long distances. In such cases, achieving precise matching between the lengths of the sensing and reference fibers is challenging, and any mismatch can weaken or eliminate the interference effect, thereby degrading the quality of the sensor output.

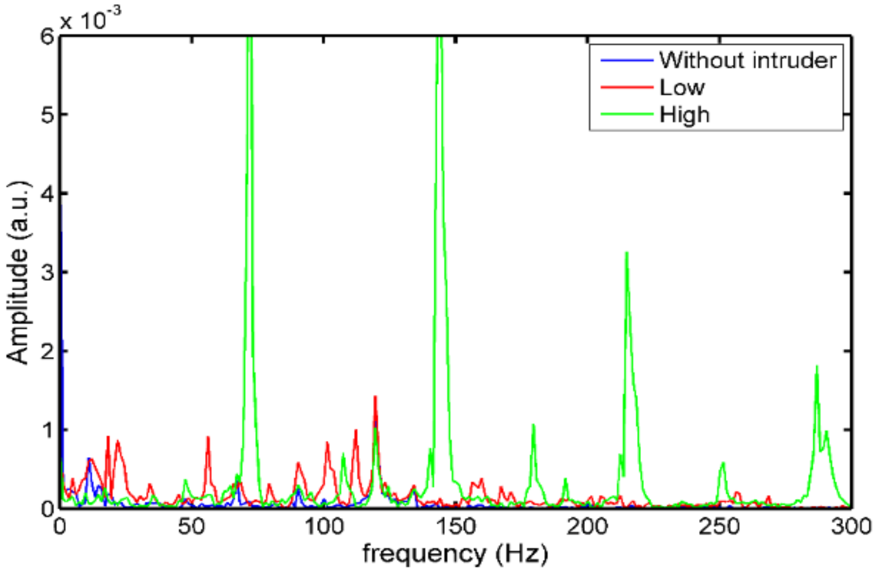


Figure 11. The frequency response of the system for two cases of low and high speed of motor

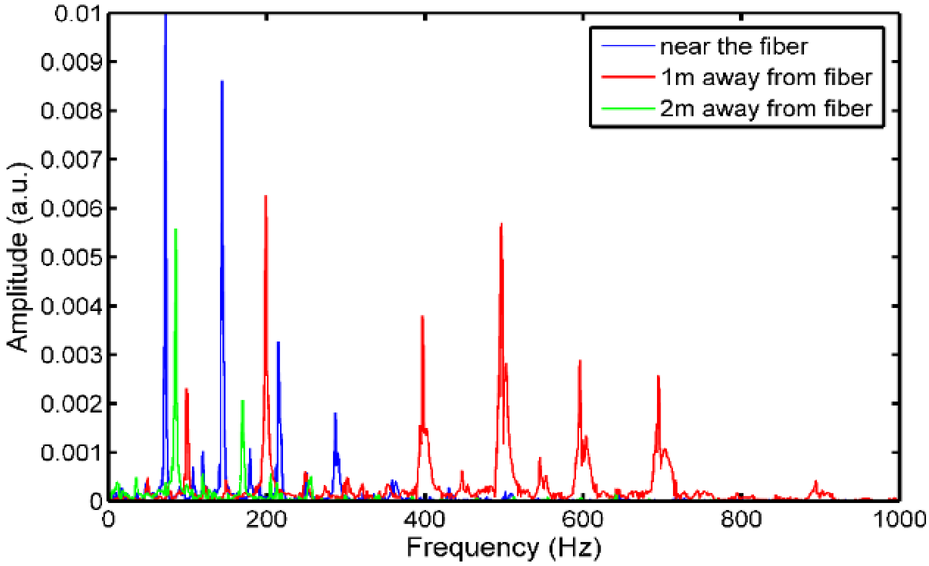


Figure 12. The frequency signal for three cases of 1m, 2m and very small distance between motorcycle and buried fiber

Employing duplex fiber effectively mitigates this difficulty by inherently maintaining the required correspondence between the two optical paths. Moreover, the sensor's appropriate response to events such as human movement and vehicle passage indicates that the proposed approach is capable of distinguishing between different sources of vibration.

4. Conclusion

This study proposes a Mach–Zehnder optical fiber acoustic wave sensor based on a duplex fiber cable, in which acoustic waves in the 100–500 Hz range were applied to the fiber. The results have shown that the frequency response of the proposed system was comparable to that of the Mach-Zehnder acoustic fiber sensor based on two simplex optical fibers. Analysis of the system response showed that the proposed sensor is sensitive to a person walking on the buried fiber as well as to a passing motorcycle at different distances from the buried fiber.

Competing interest

The authors declare that they have no competing interest.

Author's Contributions

S. Nouri carried out the optical and mechanical studies, participated in design and fabrication of the sensor and drafted the manuscript. S. Khoshi participated in design and fabrication of the sensor and carried out the data processing. I. Esmaili participated in the electronic section. All authors read and approved the final manuscript."

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