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Research Article

Polymer Optical Fiber-Based Respiratory Sensors: Various Designs and Implementations

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This research discusses the polymer optical fiber sensor for respiratory measurements. The infrared LED that produces light will propagate along the polymer optical fiber which will be received by the phototransistor and the differential amplifier. The output voltage in the form of an analog signal will be converted to a digital signal by the Arduino Uno microcontroller and displayed on the computer. The polymer optical fiber sensor is installed on the corset using a variety of configuration (straight, sinusoidal, and spiral), placed in the abdomen, and a variety of positions (abdomen, chest, and back) using only a spiral configuration. While doing the inspiration, the stomach will be enlarged so that the optical fiber sensor will have strain. The strain will cause loss of power, the resulting light intensities received by the phototransistor are reduced, and the output voltage on the computer decreases. The result shows that the highest voltage amplitudes were in the spiral configuration placed in the abdominal position for slow respiration measurements with the highest range, sensitivity, and resolution which are 0.119 V, 0.238 V/s, and 0.004 s, respectively. The advantages of our work are emphasized on measurement system simplicity, low cost, easy fabrication, and handy operation and can be connected with the Arduino Uno microcontroller and computer.

1. Introduction

Respiration is a process of oxygen entering the lungs and reaching the body's cells, as well as the processes that cause carbon dioxide out of the body through the nose and mouth. Respiration has a frequency taken within a certain time; this level may vary depending on the oxygen requirement. Respiratory rate measurement is one of the important physiological parameter in the medical field. Respiration will provide the pertinent information about the condition of the human heart, nerves, and lungs [1–3].

Several methods of measuring the respiratory rate using sensor systems have been developed, particularly using optical fiber [4]. The optical fiber can be applied as multipurpose sensors in various measurement fields with several advantages in terms of sensitivity, selectivity, reversibility, flexibility, accuracy, smaller size, and lightweight [5].

In the development, the optical fiber sensor can be used in various measurement fields such as measurement of an electric field, electric current, crack, load, strain, temperature, pressure, and vibration. This type of polymer optical fiber has advantages compared to silica optical fiber. Polymer optical fibers have a bending nature that is easily curable, while silica has a fragile and small size which require special treatment in its use [6].

Several researchers reported that the study of respiratory sensor using plastic optical fibers has been performed in Ref. [7] regarding plastic optical fiber sensors for measuring chest respiration using the Optical Time Domain Reflectometer (OTDR). Yoo et al. [2] reported the respiratory sensor by using plastic optical fiber which was placed in the front of the nose and stomach. Other researchers show good characteristics for the plastic optical fiber of respiration sensor with the Fiber Bragg Grating (FBG) system placed on the back [8] and also in the breast costume (textile) embedded with a sinusoidal configuration [9]. All reported studies show complicated fabrication, high cost, and low output voltage range [2, 7–12].

In this research, the respiratory sensors were made by using polymer optical fibers without a jacket placed on a

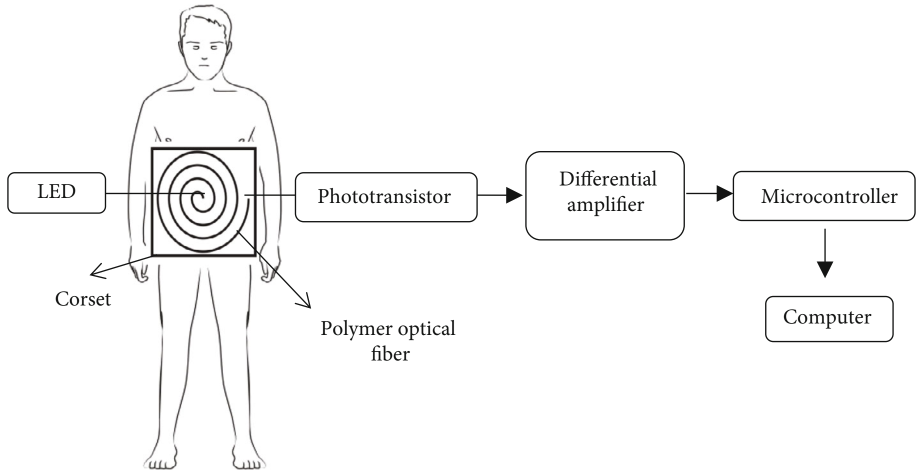

Figure 1: Scheme of the respiratory sensor uses a polymer optical fiber.

corset. Respiratory sensors have a variety of configurations that are straight, sinusoidal, and spiral, which are only placed on the abdomen. In addition, variations of a position are also placed on the abdomen, chest, and human back. The polymer optical fiber sensor is connected to the Arduino Uno microcontroller and displayed on the computer. While doing the inspiration, the stomach will be enlarged, so that the polymer optical fiber sensor will have strain. The strain will cause loss of power, the resulting intensity of light received by the phototransistor is reduced, and the output voltage on the computer decreases. Some of the advantages of respiratory sensor using polymer optical fiber are the measurement system simplicity, low cost, easy fabrication, and handy operation and can be connected with the Arduino Uno microcontroller and computer.

2. Research Methodology

The polymer optical fiber which is used in this research is a multilayer fiber-index ladder with 1 meter optical fiber length. The specifications of polymer optical fiber used are jacket coat diameter, cladding, and core of 2.2 mm, 1 mm, and 0.98 mm, respectively. Core and cladding of polymer optical fibers are made from polymethyl methacrylate (PMMA) with a refractive index of the core and a refractive index of the cladding, each are $n_{\text{core}} = 1.49$ and $n_{\text{cladding}} = 1.402$, with a numerical value of the polymer optical fiber which is $\text{NA} = 0.5$. Respiratory sensors use polymer optical fibers in pairs on the corset.

At both ends of the polymer optical fiber sensor, the infrared LED light source and the phototransistor as the light receiver are connected. LED infrared IF-E91A type with a wavelength of 950 nm and phototransistor used IF-D92 type. The power supply that generates an electrical signal will be converted into a light signal when connected to the LED. While doing the inspiration, the stomach will be enlarged so that the polymer fiber optic sensor will experience strain. Thus, it will cause loss of power and make the light intensity received by the phototransistor reduce and the output voltage decrease. This light signal will be converted into electrical signals by the phototransistor. Electrical signals in the form of voltage will be enlarged by the difference amplifier. Then, the electrical signals in the form of analog signals are converted into digital signals by the microcontroller and are read by the computer. Respiratory sensor scheme using polymer optical fiber is shown in Figure 1.

Optical fiber as respiratory sensor is reported in Ref. [9] by using LED and phototransistor in sinusoidal configuration. The sensor was placed on the back side with the voltage output signal of 0.010 ± 0.03 V, and similar is reported in Ref. [7] for respiratory sensor using sinusoidal configuration on the chest position.

In this study, respiratory sensor using polymer optical fiber is made with two variations, configuration and position. Both sensor variations are used to measure fast, normal, and slow respiration. The measurement time used is one minute on each sensor test. Variations of sensor configuration in our study are straight, sinusoidal, and spiral as shown in Figure 2.

The variation change on the sensor configuration is expected to multiply bending occurrence and to increase power losses, so that the sensitivity and resolution of the sensor will be better. Measurement of variations in configuration is straight, sinusoidal, and spiral only performed on the abdominal position. Installation of respiratory sensors with spiral configuration variations is positioned on the abdominal, chest, and back position, as shown in Figure 3.

The measurement of position variation is only done on spiral configuration with optical fiber spacing distance in 1 cm, which is mounted on the corset.

3. Results and Discussions

The data obtained in the test is used to analyze sensor characterization which includes the calculation of output voltage range values, sensitivity, and resolution. The sensor range values equal to the respiratory amplitude values can be determined using the formula [6]:

$$\Delta V = V_{\max} - V_{\min}, \tag{1}$$

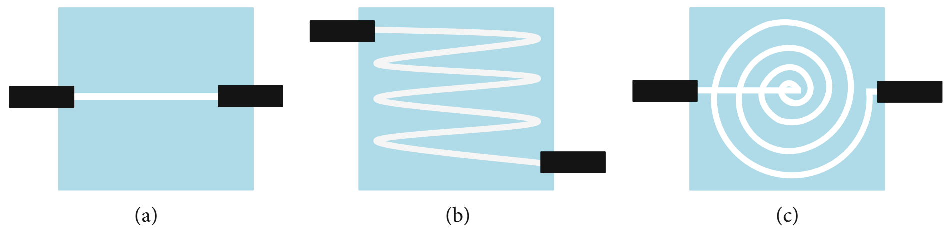

Figure 2: Configuration variations: (a) straight, (b) sinusoidal, and (c) spiral on the polymer optical fiber respiratory sensor.

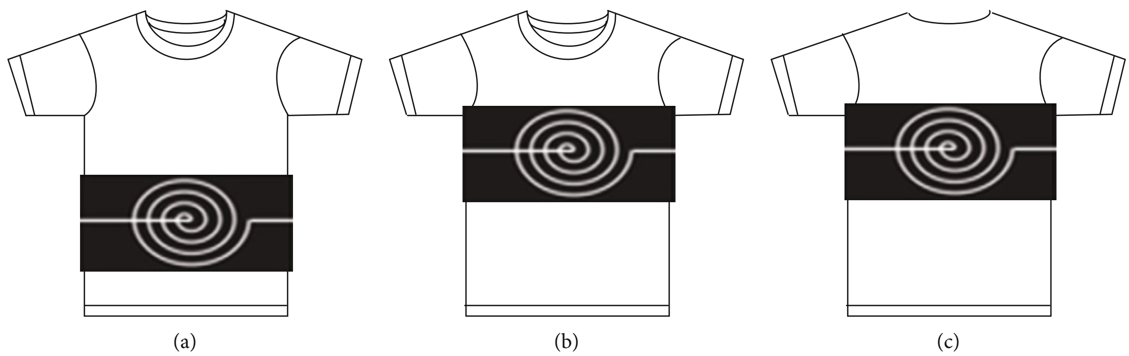

Figure 3: Position variations: (a) abdomen, (b) chest, and (c) back.

where ΔV is the value of range output voltage (V). V_{max} is the maximum (V) and V_{min} is the minimum output voltage (V) that is displayed on the computer. The sensitivity of the sensor shows how much sensitivity is affected to the measured quantity. Sensitivity of the sensor can be formulated as follows [6]:

$$S = \frac{\Delta V}{\Delta t}, \tag{2}$$

where S is the sensor sensitivity (V/s) and Δt is the value of the ratio of twice respiratory frequency to the time applied when measuring for the respiratory sensor (s). Resolution is the smallest value of the value that can be measured by the sensor. The sensor resolution can be formulated as follows [6]:

$$R = \frac{N}{S}, \tag{3}$$

where R is the sensor resolution (s) and N is the smallest scale of the measuring instrument used that is 0.001 volt.

The results of the polymer fiber optic sensor are obtained from fast, normal, and slow breathing. Respiratory measurements were performed for 1 min for each sensor test. The first measurement was performed on respiration using straight, sinusoidal, and spiral configuration. In this scheme, the configuration was placed on the abdomen. According to the Department of Health of Indonesia, the normal respiration for adult patients is about 16-20 times per minute number of breath. Our measurement of number of breath for fast, normal, and slow respiration is 27, 18, and 15 times per minute, respectively. These are shown in Figures 4(a)–4(c).

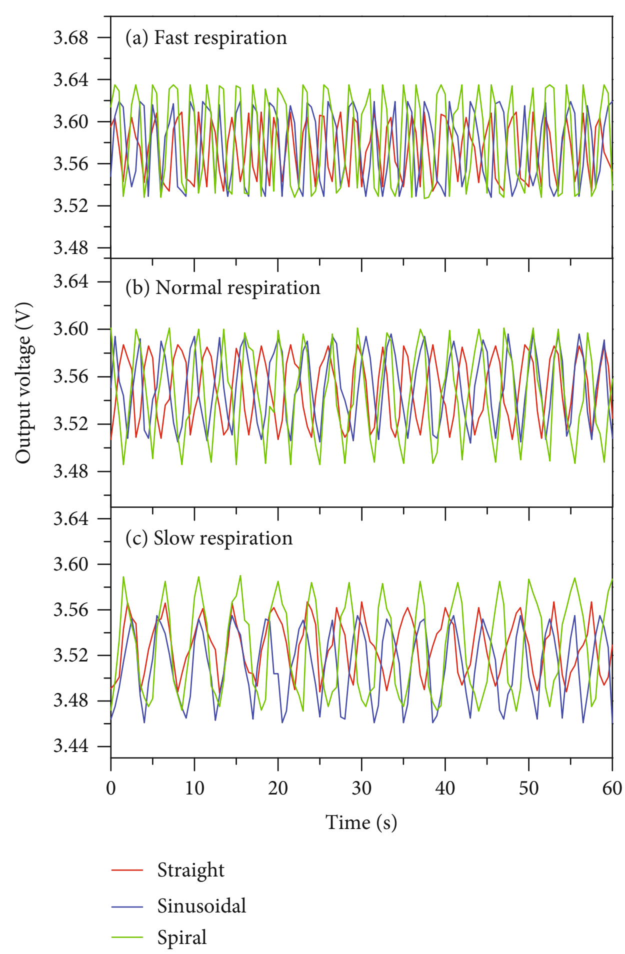

Figure 4: The output voltage of the respiratory sensor configuration variation on (a) fast, (b) normal, and (c) slow respiration.

Table 1: Respiratory sensor characterization of the configuration variations on fast, normal, and slow respiration.

Configuration	Fast respiration			Normal respiration			Slow respiration		
	ΔV (V)	S (V/s)	R (s)	ΔV (V)	S (V/s)	R (s)	ΔV (V)	S (V/s)	R (s)
Straight	0.075	0.083	0.012	0.080	0.133	0.008	0.080	0.160	0.006
Sinusoidal	0.091	0.101	0.010	0.092	0.153	0.007	0.094	0.188	0.005
Spiral	0.108	0.120	0.008	0.115	0.192	0.005	0.119	0.238	0.004

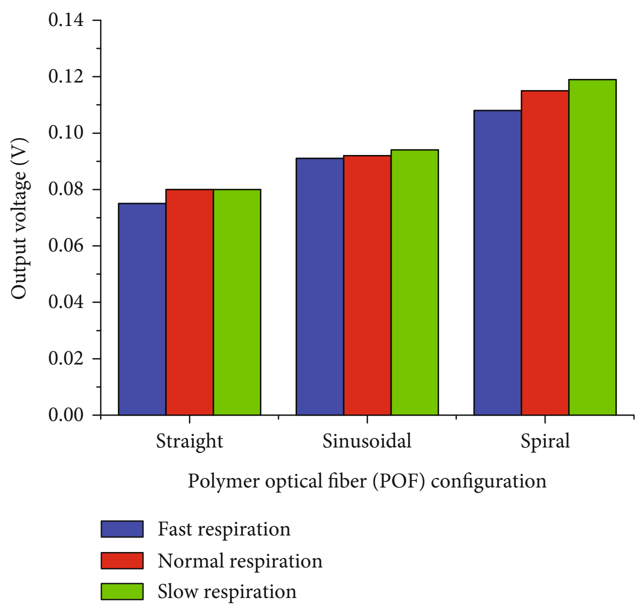

Figure 5: Chart diagram of output voltage range for various configurations.

Results from the calculation of respiratory sensors consist of values of output voltage range, sensitivity, and resolution of respiratory sensor configurations in fast, normal, and slow respiration. Calculation results of respiratory sensor characterization using equations (1)–(3) are shown in Table 1.

Data from the calculation of respiratory sensor characterization are shown in Table 1. These results indicated that the more bending applied produces the higher sensor sensitivity and the smaller sensor resolution. These indicated that the sensor characteristics were improved with more bending [13, 14]. The best sensitivity and resolution for the fast, normal, and slow respiration are obtained in spiral configuration. Values of the range, sensitivity, and resolution of the sensor obtained for each fast respiration are 0.108 V, 0.120 V/s, and 0.008 s. For each normal respiration, we get 0.115 V, 0.192 V/s, and 0.005 s, while the slow respiration records 0.119 V, 0.238 V/s, and 0.004 s. Results of this work indicate that the spiral configuration sensor has a higher result than the sinusoidal configuration as obtained from other researchers [9] with value of range obtained that is 0.06 ± 0.01 V. Comparison chart diagram of output voltage range for various configurations is shown in Figure 5. It shows the results of output voltage to configuration variations in fast, normal, and slow respiration. The spectrum indicated that the highest output voltage range for each respiratory conditions is spiral configuration.

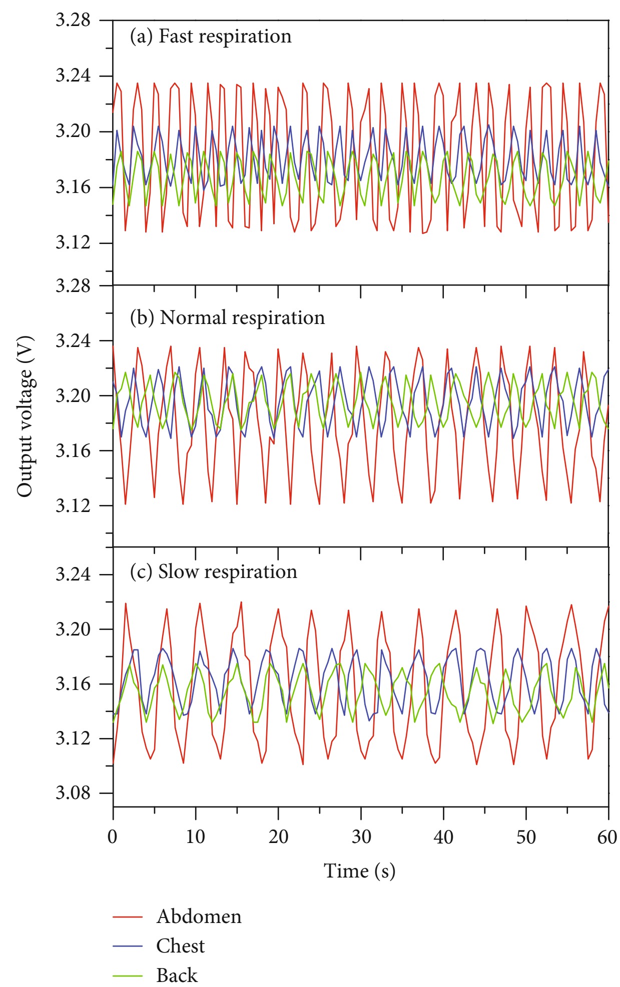

Figure 6: The output voltage of the respiratory sensor for the spiral configuration position with respiration was varied: (a) fast, (b) normal, and (c) slow.

Further measurement is performed on a variation of the position, with the respiratory sensor placed in the back, chest, and abdomen. Position variation is only used in the spiral configuration. Measurement of position variation in fast, normal, and slow respiration is shown in Figure 6.

The calculation results of respiratory position variation sensor characterization that is placed on the back, chest, and abdomen in fast, normal, and slow respiration are shown in Table 2.

Table 2: Respiratory sensor characteristics of position respiratory were varied: fast, normal, and slow respiration.

Positions	Fast respiration			Normal respiration			Slow respiration		
	ΔV (V)	S (V/s)	R (s)	ΔV (V)	S (V/s)	R (s)	ΔV (V)	S (V/s)	R (s)
Back	0.039	0.043	0.023	0.042	0.047	0.021	0.044	0.088	0.011
Chest	0.047	0.052	0.019	0.052	0.058	0.017	0.053	0.106	0.009
Abdomen	0.108	0.120	0.008	0.115	0.128	0.008	0.119	0.238	0.004

The best sensitivity and resolution results in fast, normal, and slow respiratory sensors are abdomen positions. Range values, sensitivity, and resolution of the sensor that were obtained at each fast respiration are 0.108 V, 0.120 V/s, and 0.008 s. Each normal respiration is 0.115 V, 0.128 V/s, and 0.008 s, while the slow respiration was 0.119 V, 0.238 V/s, and 0.004 s each. The results of this study indicate that the respiratory sensor placed on the abdomen has a higher value than the sensors placed on the chest and back. From Ref. [9], the range value obtained at the chest position was 0.036 ± 0.002 V and at the back position was 0.025 ± 0.004 V. Both variations show that the more bending and magnitude of respiratory movement in the human body, the higher sensitivity value gained and vice versa. These indicate that the sensitivity and resolution values are linearly correlated [13, 14]. Polymer optical fiber is suitable for respiratory sensor with high range, high sensitivity, low cost, and easy fabrication and can be connected with the Arduino Uno microcontroller and computer.

4. Conclusion

The results of the respiratory sensor research using polymer optical fibers show that the more bending applied to the sensors and the magnitude of the respiratory movement in the human body, the loss of power becomes large and the output voltage on the computer becomes small. This causes the sensitivity and resolution of the sensor to be better. The result shows that the best sensitivity and resolution of sensors with configuration variations, both normal and slow respiration, are the spiral configuration. Meanwhile, in the position variations placed on the abdomen, chest, and back, from the results showed that the best value lies in the variations of sensors placed on the abdomen. Both variations of the sensors indicate that the value of range, sensitivity, and higher resolution at fast respiration is 0.108 V, 0.120 V/s, and 0.008 s and at normal respiration is 0.115 V, 0.192 V/s, and 0.005 s, while the slow respiration is 0.119 V, 0.238 V/s, and 0.004 s, respectively.

Data Availability

Data available on request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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