Plastic optical fiber respiration sensor based on in-fiber microholes

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Abstract
This paper presents a novel respiration sensor based on multiple in-fiber microholes drilled along a plastic optical fiber (POF) that is stitched to a waist-band wrapped around the patient’s abdomen. The bending loss of a POF with a single microhole is analyzed in order to enhance the sensor sensitivity. Several sensors were fabricated using a 1.5 mm-diameter POF with different numbers and spacing of 0.7 mm-diameter microholes. The sensitivity of the respiration sensor increased when increasing the number and spacing of the microholes, where the POF respiration sensor with seven 0.7 mm-diameter in-fiber microholes spaced at 15 mm showed the highest sensitivity and sufficient strength for respiratory monitoring. Thus, the experimental results confirmed that a POF sensor based on in-fiber microholes can be effectively used to monitor the respiration of patients.

KEYWORDS
in-fiber microhole, optical fiber sensor, plastic optical fiber, respiration

1 | INTRODUCTION

Respiration is the process that moves varying volumes of air into and out of the lungs, thereby providing an adequate oxygen supply to meet the energy production requirements of the body and maintaining a suitable acid-base status by removing carbon dioxide from the body. The act of normal respiration has a relatively constant rate.1

Respiratory monitoring is important for assessing physiological state, and can provide valuable information related to cardiac, neurological, and pulmonary conditions. When a patient needs to be sedated or anesthetized during surgical procedures monitoring their respiration is very important2,3 as respiratory failure is difficult to predict and can quickly cause life-threatening conditions. Moreover, certain illnesses, such as apnea, tachypnea, hyperpnea, and hypopnea, can be diagnosed via monitoring.4 Thus, several methods and sensors, such as respiratory inductance plethysmography, transthoracic impedance plethysmography, strain-gauge transducers, and spirometers have already been developed for monitoring respiration.5–7 However, these electronic methods and sensors become ineffective when the medical treatment involves magnetic resonance imaging (MRI), radiation, or high electromagnetic fields due to the induction of interactive noise on respiration sensors. Therefore, the development of optical fiber-based respiration sensors has been attracting attention due to their advantage of electromagnetic immunity and remote sensing capability.8

Various optical fiber-based respiration sensors have already been developed. For example, fiber Bragg grating (FBG) sensors have been embedded into medical textiles.9,10 However, while showing a high sensitivity, they cannot be used inside an MRI system as the vibration and acoustic noise degrade the sensor performance. A plastic optical fiber (POF) respiration sensor with a plastic flap to transfer the force of the exhaled air onto the POF11 has also been developed. While cost effective and simple in structure, this sensor can only monitor normal expiration and exhibits cross sensitivity to vibrations associated with body movement. Another variation is an abdomen-attached POF sensor fabricated using a POF,12 polymethyl-methacrylate (PMMA) tubes, a mirror, and spring. While this sensor can measure respiratory signals in a magnetic resonance room, it has a low sensitivity, making it unsuitable for accurate respiration.
monitoring. U-shaped POF respiration sensors and glass optical fiber respiration sensors have also been studied, and while comfortable to wear with good sensing capabilities, the fabric-embedded U-shaped optical fibers and glass fibers are easily broken. POF sensors based on in-fiber microholes have recently been generating increasing interest, and have already been used for refractive index measurements and liquid level measurements. Accordingly, this study investigated the sensitivity and strength of an abdomen-attached POF sensor based on in-fiber microholes for monitoring the respiration of patients. The configuration of the proposed respiration sensor is a POF with multiple in-fiber microholes stitched to a waist-band wrapped around the patient’s abdomen, and the respiration measurement is based on the bending loss due to the abdomen circumference change induced by respiratory movement.

2 | BACKGROUND

Ray optics are used to theoretically analyze the characteristics of a POF respiration sensor with multiple in-fiber microholes. As such, the bending loss mechanism of a POF with a single in-fiber microhole is analyzed on the principle that the bending loss of a POF with multiple in-fiber microholes is approximately a multiple of that of a POF with one in-fiber microhole. Figure 1 shows a schematic diagram of a POF with a single in-fiber microhole. When the POF is unbent (Figure 1A), the transmittance of the POF with a single hole is given as

\[ T = \frac{\left[ \cos^{-1}\left(\frac{n_2}{n_1}\right) - \sin^{-1}\left(\frac{\alpha}{R}\right) + \tan^{-1}\left(\frac{n_2 \sin \theta_{\text{max}}}{R - n_2 \cos \theta_{\text{max}}} \right) \right]}{\cos^{-1}\left(\frac{n_2}{n_1}\right)}, \]

where \( n_1 \) and \( n_2 \) are the core and cladding refractive indices, respectively, \( r_h \) is the hole radius, \( \theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \) is the critical angle, \( L = \tan \theta_c \), and \( \theta_{h, \text{max}} \) is the maximum angle between the fiber axis and the point where the traversing ray reaches the microhole. Thus, if the POF has \( N \) in-fiber microholes along its axis, the transmittance becomes \( T_N = T^N \).

When the POF with a microhole is bent and the microhole is on the ascending slope (Figure 1B), the rays arrive at the microhole at \( \Delta \theta \approx L/2R \) below when compared to the unbent POF, where \( R \) is the bending radius. For the upper half of the fiber axis, the rays of the unbent POF that enter the hole at an angle less than \( \Delta \theta \) are included in the lower half of the fiber axis when the POF is bent. However, some of the rays propagated in the unbent POF without loss (passing through point P with an angle to the fiber axis less than \( \theta_B \) and greater than \( \theta_c \)) are lost when the POF is bent. These bending losses occur as some of the lossless propagated rays of the unbent POF enter the hole and go into the cladding at the core-cladding boundary when the POF is bent. Moreover, ray loss also occurs due to a reduced incident angle at the core-cladding boundary induced by the bending. As such, the unbent rays arriving at the boundary at critical angle \( (\theta_c) \) reach the boundary at angle \( \alpha \), which is smaller than the critical angle, when the POF is bent. Angle \( \alpha \) is

\[ \alpha \approx \sin^{-1}\left(\frac{R + a - x}{R + a} \sin^{-1}\left(\frac{n_2}{n_1}\right)\right), \]

where \( x = \sqrt{\frac{L^2}{1 - \sin^2 \Delta \theta}} \).

Therefore, more ray loss occurs in the upper half of the fiber axis when compared to a bent POF without a microhole. For the lower half of the fiber axis, the rays of the unbent POF that enter the hole at an angle less than \( \Delta \theta \) are included from the upper half of the fiber axis when the POF is bent. Simultaneously, the bending induces almost the same amount of losses of unbent POF rays in the lower half of the fiber axis. Thus, the ray loss induced when bending the POF with an in-fiber microhole is only produced by the incident angle change at the core-cladding boundary. The unbent POF rays arriving at the core-cladding boundary at the critical angle \( (\theta_c) \) reach the boundary at angle \( \beta \), which is smaller than the critical angle, when the POF is bent. Angle \( \beta \) is

\[ \beta \approx \sin^{-1}\left(\frac{R - a - x}{R - a} \sin^{-1}\left(\frac{n_2}{n_1}\right)\right). \]

When the microhole is on the descending slope, the ray loss is approximately the same as that for a microhole on the ascending slope. Plus, if the POF sensor has multiple microholes, the bending loss is approximately a multiple of that for a POF with a single in-fiber microhole. Consequently,
since a POF with multiple in-fiber microholes will have a higher bending loss than a POF without microholes. The bending sensitivity of a POF respiration sensor with multiple in-fiber microholes will also be higher than that of a POF sensor without any microholes.

3 | SENSOR FABRICATION AND EXPERIMENTAL RESULTS

The proposed POF respiration sensor (Figure 2) consists of a POF with multiple in-fiber microholes in the central part, a waist-band, and plastic buckle. When fabricating the POF respiration sensor, multiple in-fiber microholes were first created in the central part of the POF using an inexpensive drilling machine. Next, the waist-band was created by stitching elastic fabric to each side of an inelastic fabric centerpiece. The central part of the POF was then embedded in the inelastic fabric, while the remaining parts were merged into the elastic fabric on each side. The sensor operation was based on the bending loss due to abdominal movement induced by respiration. Toray PGR-FB 1500 POF was used to fabricate 9 kinds of POF respiration sensors with three, five, and seven 0.7 mm-diameter in-fiber microholes spaced at 5 mm, 10 mm, and 15 mm. The amplitude variations were proportional to the microhole diameter. However, POF respiration sensors with in-fiber microholes larger than 0.7 mm in diameter were easily broken. Thus, POF respiration sensors with 0.7 mm-diameter in-fiber microholes were determined as strong enough for respiratory monitoring. The core and cladding diameters are 1.48 mm and 1.5 mm, respectively, and the refractive indices of the core and cladding were 1.49 and 1.41, respectively.

The experimental setup (Figure 3) included a laser with a wavelength of 633 nm, photodiode (PD) with a peak wavelength of 670 nm, POF respiration sensor, interface circuit composed of an amplifier with a gain of about 300 and low pass filter with a cutoff frequency of about 1 Hz, DAQ board, and personal computer (PC). The rays from the laser were guided by the POF with multiple in-fiber microholes. When the rays reached the multiple in-fiber microholes, ray loss occurred, where the amounts depended on the inhalation and exhalation. After passing multiple in-fiber microholes, the rays arriving at the PD were then converted into electronic signals. At the interface circuit, these signals were filtered and amplified, converted into digital signals by the DAQ, and displayed on the PC, where the amplitude variations indicated abdomen changes caused by respiration.

FIGURE 2  Configuration of POF respiration sensor based on multiple in-fiber microholes [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 3  Experimental setup [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 4  Output signals of respiration sensors with (A) 3, (B) 5, and (C) 7 microholes
When a POF without microholes was used for measuring respiration signals, the output signal of the respiration sensor disappeared, indicating that the bending effect was insignificant. Figure 4 shows the output signals of the POF sensors with three, five, and seven of 0.7 mm-diameter microholes spaced at 15 mm, respectively. The amplitude variation was highest when using the POF respiration sensor with seven in-fiber microholes, and lowest when using the POF with three in-fiber microholes. These results indicate that the sensor sensitivity was proportional to the number of microholes in the POF.

Figure 5 shows the output signals of the respiration sensors with seven 0.7 mm-diameter microholes spaced at 5 mm, 10 mm, and 15 mm. The output signal variation was highest when using the POF with seven 0.7 mm-diameter microholes spaced at 15 mm. The amplitude variation of the respiration sensor output also increased when increasing the microhole spacing. Figure 6 shows the amplitude variation according to the number and spacing of the microholes. From Figure 6, the POF respiration sensor with seven 0.7 mm-diameter in-fiber microholes spaced at 15 mm showed the highest amplitude variations of the output waveform. Thus, all the experimental results confirmed that the POF respiration sensor with seven 0.7 mm diameter in-fiber microholes spaced at 15 mm has a high sensitivity and sufficient strength monitor respiration signals.

Figure 7 shows the respiration signals from the POF respiration sensor with seven 0.7 mm-diameter microholes spaced at 15 mm (top waveform) and an MP150WSW Biopac respiration measurement device (bottom waveform). As shown, the POF respiration sensor based on in-fiber microholes produced a similar response to the Biopac respiration measurement device, confirming its effectiveness for respiration monitoring. The experimental results also confirm that a POF respiration sensor based on in-fiber microholes can be used for monitoring respiration of patients.

4 | CONCLUSIONS

This paper presented a novel respiration sensor based on multiple in-fiber microholes drilled along a POF stitched to a waist-band wrapped around a patient’s abdomen. The sensitivity of the proposed POF respiration sensor with multiple 0.7 mm-diameter in-fiber microholes was shown to be proportional to the number and spacing of the microholes. The
Experimental results for the POF sensor with seven 0.7 mm-diameter in-fiber microholes spaced at 15 mm showed the highest sensitivity and sufficient strength for monitoring respiration along with a comparable response to a Biopac respiration measurement device. Therefore, the research results showed that a POF respiration sensor based on in-fiber microholes can be effectively used for monitoring respiration of patients, including potentially inside a MRI system. If a POF respiration sensor with more than seven microholes is used, higher sensitivity will be expected.

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How to cite this article: Ahn D, Park YJ, Shin J-D, Lee J, Park J. Plastic optical fiber respiration sensor based on in-fiber microholes. Microw Opt Technol Lett. 2019;61:120–124. https://doi.org/10.1002/mop.31524