ABSTRACT
In this paper, we proposed a hetero-core optic nerve pulse sensor made by softly silicone rubber sheet for unconstrained monitoring. An optical fiber has several advantages such as lightweight, minimal material, resistance to corrosion and electromagnetic interference. Additionally, a hetero-core optic fiber sensor is only sensitive to bending action of the sensing portion and the transmission line is unaffected to external disturbance as pressure and temperature fluctuation because of its single-mode stable propagation scheme. Therefore, the hetero-core optic fiber sensor could be suitable for the pulse pressure sensing in unconstrained human activities and be placed in various sites such as a sofa and bath, and wearable device at the wrist. The proposed pulse sensor was devised to have high sensitivity by means of adding two spacers to the both ends of a hetero-core portion. Additionally, the pulse sensor was devised to have detectable area in the pulse pressure to be relatively wide with high sensitivity due to several hetero-core optic fiber sensors arranged in the pulse sensor. We successfully demonstrated to be adjustable to sensitivity and the sensing area, and some participants could detect the pulse signal due to a hetero-core optic nerve pulse sensor.

KEY WORDS
Pulse monitoring, Fiber optic sensor, Unconstrained, Hetero-core, Minute pressure measurement

1. Introduction
In recent years, due to the aging of the population, unforeseen accidents are increasing at home. On the other hand, a number of people including elder and younger people are struck down by running and walking. Therefore, the demand for self-performed health monitoring techniques has increased, especially, pulse monitoring during daily life and sport activity.

The conventional sensing technique for pulse monitoring has mainly employed the photoelectric sensor. The pulse sensor based on the photoelectric device is attached at the end of the finger and ear lobe, and clipped in between the light emitted diode (LED) and photo diode (PD) [1, 2]. A transmitted light intensity varies with the blood oxygen saturation level corresponds to a pulse signal. However, this method can be fraught with low heat burning by the LED and constrictive pressure on the site. Additionally, the dirt and finger nail polish tends to affect the pulse signal as noise from the LED light beam.

In the fields of smart structure and human health monitoring, a variety of techniques have been developed using optic fiber sensors in the past few decades such as motion capturing and monitoring system of a human respiration. Since the optic fiber sensors have several advantages such as not being necessary to supply the power at the sensor itself, immunity of electromagnetic interference, flexibility, lightweight and high resistance to high humidity and water. Some examples have been reported such as fiber optic strain and pressure sensors such as fiber bragg grating (FBGs) [3] and plastic optical fibers (POFs) bending sensors. Especially, plastic optical fibers use the pulse monitoring technique in above-referenced conventional sensing technique [4]. However, plastic optical fibers have the limited stability of multi-mode (MM) fiber usage, and the FBGs have also several problems such as temperature dependency and low cost performance because the measurement system needs to wavelength shift detection performance such as a spectrum analyzer and wavelength filter.

In contrast to the conventional fiber sensors, we have proposed and developed hetero-core optic fiber sensors [5], which can detect moderate bending with high sensitivity based on optical-intensity operation. A displacement and pressure sensing for environmental monitoring, and wearable motion analysis [6, 7] have been developed using hetero-core optic fiber sensors. This is because hetero-core optic fiber sensor is only sensitive to bending action of the sensor portion and the fiber transmission line is unaffected to external disturbance as pressure and temperature fluctuation because of its single-mode (SM) stable propagation scheme. Therefore, the hetero-core optic fiber nerve sensor could be suitable for the pulse pressure sensing in unconstrained human activities and be placed in various sites such as a sofa and bath, and wearable device at the wrist.

In this paper, we proposed a newly pulse sensor employing the hetero-core optic fiber sensors made by softly silicone rubber sheet for unconstrained monitoring. In order to detect minute pressure change such as a pulse pressure at the wrist, we devised the structure of fiber sensor arrangement so as to change the minute pressure to the moderate bending action of hetero-core fiber sensing.
portion. On the other hand, for natural usage in daily life, it is desired that the pulse measurement could be achieved by means of only putting a hand without consciousness to the sensor on the pulse sensing instrument and sofa. For the daily usage, the pulse sensor needs to have the widely sensitive area of detecting the pulse pressure. The proposed pulse sensor was devised to have detectable area in the pulse pressure to be relatively wide with high sensitivity due to several hetero-core optic fiber sensors arranged in the pulse sensor. Finally, some participants tried to use the proposed pulse sensor.

2. Hetero-core optic nerve pulse sensor

2.1 Hetero-core optic fiber sensor

Fig. 1 shows the proposed pulse sensor with a hetero-core optic fiber sensor. A hetero-core optic fiber sensor consists of a single mode transmission fiber and inserted fiber with a length as short as a few millimeters by fusion splicing. The core diameter of the fiber transmission line and the inserted fiber are 9μm, and 5μm, respectively. The length of the inserted fiber is 2mm, as shown in Fig. 1. The trace of the light is lost as leakage by their core differences in the hetero-core portion. The optical loss of the hetero-core fiber-sensing element increases monotonically with bending action of the hetero-core portion. Inserting the hetero-core portion in a transmission line decreases the overall signal by less than 1 dB when unbent, which is a very small loss. Therefore, hetero-core optic fiber sensors have high sensitivities to detect pulse signals.

2.2 Structure of a pulse sensor

Fig. 1 (a) and (b) shows a cross-section and front views of the pulse sensor, respectively. The hetero-core portion was arranged at the center of silicone rubber seats. The square silicone seat was 5cm on a side. Three spacers placed at the center and both ends of hetero-core portion at 0.5 – 1.0cm intervals in order to induce efficiently-transformed bending to the hetero-core portion in the pulse pressure. Silicone seats were adhered by silicone glue. In addition, a pulse sensor equipped with a curved hetero-core portion as shown in Fig. 1 (b), in order that the sensor has high sensitivity. Fig. 1 (a) shows a cross-section view of a pulse sensor. The spacer located at center has thickness and width of 1.0mm. The spacers at both ends have thickness and width of 0.5mm and 2.0mm, respectively. The spacers at both ends of the hetero-core portion with the angle, θ deg., between two spacers corresponded to the distance of the two spacers. In other words, the angle of θ becomes smaller with decreasing the distance of the two spacers.

Fig. 1 (c) show a pulse sensor of three hetero-core optic fiber sensors arranged in the sensor device. Three hetero-core optic fiber sensors were lined up on the spacer located at center, such as sandwich in the hetero-core optic nerve sensor in Fig. 1 (b) between the other two hetero-core optic fiber sensors. The optical loss changes of three hetero-core optic fiber sensors were interrogated by three channels power meter simultaneously.

3. Experimental configuration

Fig. 2 shows schematic drawing of experimental setup for the pulse monitoring in terms of the optical loss of the hetero-core optic fiber sensor by an LED and a PD measurement system in the condition that the wrist is put on the base, which is equipped with the pulse sensor in order to exert pressure on the place of pulse in the subject. The incident light from an LED at the wavelength of 1.31 μm was put through the SM transmission line to be equipped with the hetero-core portion. The PD detects the transmitted light from the fiber line, which is converted to an current. The current is transformed into voltage by means of an I-V circuit. The voltage change is proportional to the transmitted light power. The analog voltage change is fed into a PC through an A/D converter.

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Fig. 1. Structure of a hetero-core optic nerve pulse sensor; (a) a cross-section view of a pulse sensor, (b) a photo of a pulse sensor equipped with a curved hetero-core portion, (c) a photo of a pulse sensor with three hetero-core optic fiber sensors.

Fig. 2. Experimental setup for pulse pressure measurement.
4. Characteristics of a hetero-core optic nerve pulse sensor

4.1 Sensitivities properties of the distance of the two spacers

Fig. 3 shows real-time responses of optical loss change and its differentiation of the hetero-core optic nerve pulse sensor. The optical loss change was produced by pulse pressure, which could give the bending action of hetero-core portion. Under the condition that the wrist was put on the base incorporation of the pulse sensor, the baseline of optical loss was defined as 0dB. The optical loss, $x$, can be calculated as follow:

$$x[\text{dB}] = 10 \log \left( \frac{V_f}{V_0} \right)$$

where $V_0$ and $V_f$ are the voltages of baseline condition and current condition of pulse pressure giving to the hetero-core portion, respectively. The differentiation value was obtained by means of subtracting optical losses in time. As a result, it is possible to extract peak of optical loss from the differentiation value. In this experiment, the waveform between two peaks was defined as a single pulse signal. Additionally, the threshold level of pulse detection was defined as continuous pulse signals over 20 times. The pulse sensor response was analyzed in respect to its period and amplitude in the pulse signal waveform [8]. The period means the time interval between the peaks of optical loss. The amplitude expresses the optical loss change in a period of pulse response. The sensitivity of the pulse sensor was defined as averaged amplitude among 20 pulse signals over 30 seconds.

Sensitivities properties of hetero-core optic nerve pulse sensors with the angle, $\theta$, of 45-, 60-, 75- and 90-degrees between the two spacers corresponded to the distance of the two spacers as shown in Fig. 4. The pulse sensor is fixed at wrist by a stretch belt in order to examine characteristic of pulse sensor. In the case of the angle 45-degrees, the pulse sensor had higher sensitivity than the angle of more than 60-degrees. This is because that the distance of the two spacers was so short as to be subjected to bending in hetero-core portion.

4.2 Sensitivities properties of relative position

The angle of the spacers is defined as $\theta$ [deg.] in the pulse sensor as shown in Fig. 1(a). The angle corresponded to the distance of the two spacers, in other words, the angle becomes small with decreasing the distance of the two spacers. In the case when distance between the two spacers was short, the sensitivity was improved. This is because the distance of the two spacers was so short which resulted in bending of the hetero-core portion. On the other hand, in the case when distance between the two spacers was large, the sensitivity was low. However, the pulse sensor area became wider. Because, the area between two spacers can play the role of a membrane that transmits the pulse pressure to the hetero-core portion since this portion is not glued down by adhesive. Therefore, as the distance of the two spacers increases, it can be inferred that pulse monitoring is available in a relatively wider area.

In order to estimate the detectable area for relative position to the pulse origin, the hetero-core portion of pulse sensor is considered the $x$ – $y$ origin as shown Fig. 2. Then, the installation position of pulse sensor changes in steps of 2mm from the origin in the range of -20mm to 20mm in both $x$ and $y$ directions. Fig. 5 shows the sensitivities of hetero-core optic nerve pulse sensors with the relative position to the pulse generated place toward $x$-direction and $y$-direction as shown in Fig. 5 (a) and (b), respectively. The pulse sensor is put on the top of the base without being fixing at wrist using the stretch belt. As shown in Fig. 5, in the case that the angle between two spacers of 45-degrees in the pulse sensor, the sensitivity of pulse sensor was indicated to be highest near the pulse generated place in all of the relative position. As the sensor was gradually apart from the pulse generated place, especially the relative position of more than 14 mm, the
sensitivity of pulse sensor was decreased to 0dB. On the other hand, in the case that the angle between two spacers of 90-degrees in the pulse sensor as indicated in Fig. 5 (b), the pulse sensor was totally low sensitivity with the relative position to the pulse generated place, however, available in a relatively wide area even though there were the position difference between the hetero-core position and the pulse generated place. This is because the pulse pressure has a difficulty of being transmitted to the hetero-core portion as the angle, of \( \theta \) become narrow. The experimental results showed that there was trade-off between sensitivity and the angle of two spacers.

5. Experimental results

Table 1 show the experimental results of pulse monitoring employing ten subjects, which indicates that the number of detectable times of pulse signals. This experiment used two type sensors such as sensor A and B shown in Fig. 1 (b), and (c), respectively. In these experiments, subjects tried to use two kinds of sensors – A and – B with 10 trials in unawareness to the sensor position, which is the hetero-core position. A pulse signal was interrogated through 10 seconds for one trial. The first type of the sensor – A could detect pulse signals for one or a few times by seven subjects, as a result, have difficulty in being used by three subjects for pulse monitoring, as shown in Table 1. This is because the position of the hetero-core sensor position shifted from the pulse pressure position in the wrist, and additionally, the cuff pressure could not be effectively given to around the pulse position in the wrist so as to generate the pulse pressure. On the other hand, the second type of the sensor – B could detect pulse signals for two or more than two times by nine

<table>
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<th>Subject4</th>
<th>Subject5</th>
<th>Subject6</th>
<th>Subject7</th>
<th>Subject8</th>
<th>Subject9</th>
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<td>6</td>
<td>6</td>
<td>7</td>
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Fig. 5. Sensitivities of hetero-core optic never pulse sensors with the relative position to the pulse generated place toward (a) x-direction and (b) y-direction.

The hetero-core optic fiber sensor has excellent flexibility of the fiber optics with stable transmission line due to single-mode transmission basis, multiple sensors as the sensor – B can be arranged in the thin and rubbery materials such as silicone rubber sheet. Therefore, the proposed pulse module using hetero-core optic fiber sensors could have possibility of detecting the pulse signal in relatively wide detectable area. Subject - 5 was difficult to gauge, because subject with a low pulse pressure to the cuff pressure.

Experimental result of pulse monitoring using the hetero-core optic fiber sensor for the detectable frequency with ten trials for ten subjects.
core sensors bending out differently due to pulse pressure, however the pulse signal with out of phase could detect the cyclical peaks. Therefore, if the sensor – B indicate the pulse signal with out of phase, it can be regard the signal as the pulse signal.

Fig. 8 shows the real-time responses in the optical loss changes of the sensor – B for subject – 8. As shown in Fig. 8, hetero-core sensor – 1 and – 2 detected pulse signals at around 1.5 second. However, peaks of hetero-core sensor – 2 were 0.05 seconds behind the hetero-core sensor – 1. The temporal difference caused by fluctuation of thin silicone rubber sheet. The pulse pressure was transmitted to hetero-core portion via spacers of the sheet, and the transmissibility dependent on the pulse generated place-to-spacers distance. In addition, the relative position of the hetero-core portion and distance of the spacers at both ends of the hetero-core portion. Therefore, the temporal difference was effected that bending of hetero-core portion different each position.

6. Conclusion

In this paper, we indicated the characteristics of a practical hetero-core optic nerve pulse sensor. The pulse sensor with the angle 45-degrees between two spacers, which were added to the both ends of a hetero-core portion due to increase its sensitivity, had higher sensitivity than the angle of more than 60-degrees. On the other hand, the larger the angle between two spacers was, which corresponded to the area between two spacers, the wider the area of detectable pulse pressure was. The experimental results showed that there was trade-off between sensitivity and the angle of two spacers. Additionally, we successful achieve the pulse monitoring of some participants.

In conclusion, these results show the hetero-core optic nerve attractively useful for pulse monitoring, and the proposed sensor have several advantage of sensitivity property. These sensors could be useful for the practical usage such as wearable device for health management in sport activity, and human health monitoring in bathroom and at home.

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