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Stretchable Distributed Fiber Bragg Grating for Sensor Applications

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***Abstract*—Fiber Bragg Grating (FBG) sensors have been widely used due to their simplicity and high sensitivity. One of their distinct features includes their ability to allow distributed measurements for several arrays of FBG sensors. However, conventional FBGs have a limited strain range and poor performance due to their stiff nature, which makes them easy to break when overstrained and hence affects their practical applications. Besides, a single FBG sensor measurement at a time is inefficient and time-consuming, especially when measuring multiple parameters such as strain and temperature. In this work, distributed FBG sensor was successfully demonstrated along with embedded FBG coated with polydimethylsiloxane (PDMS) to enhance its stretchability. Comparison analysis showed the wavelength shift for FBG coated with PDMS was higher than the bare FBG. This PDMS-coated FBG strain sensor was tested in terms of straight-line and S-shaped, evaluated by angular displacement from 0 - 90º. Result reveals that the straight-lined shape of PDMS-coated FBG gives uniform red shifted wavelength as compared to the S-shaped. This study may contribute to the advancement of fiber sensing technologies and offers practical solutions for monitoring applications.**

Keywords*—*Stretchable, Distributed, Fiber Bragg Grating, Fiber optic sensor, PDMS.

I. Introduction

Fiber bragg grating (FBG) is an excellent sensor based on optical fiber which usually measure strain and temperature. However, FBG is known for its stiff nature and is easy to break when it bends past its limit. The FBG is usually applied in a structural environment and biochemical applications. It is also used in additive manufacturing for measuring the internal temperature of a products [1], [2]. Nowadays, researchers find that FBG can be further explored if the limitations related to stretchability and distribution are addressed. Some researchers started the experiment regarding stretchable and distributed FBG for monitoring devices of human movement [3], [4]. Wearable devices using FBG sensors, attract various researchers to investigate further. In [5], the high sensitivity of FBG sensor was reported to provide accurate and reliable information when it is mounted on the skin for sensing [5]. Fiber sensors are becoming more popular in the field of rehabilitation to monitor joint angles [6]. They provide a non-intrusive, dependable, and long-term option for recording human joint motion which is especially helpful in medical and rehabilitation field. For example, flexible (flex) FBG sensors focused on joint movement, vibration monitoring, and medical which related to monitoring movement or joint movement. Many have used flex sensors to measure the bending of certain human body parts. According to Abro et al., the flex FBG sensor offered various angle-joint measurements hence contributing to wearable sensing technologies [7]. In their work, wearable FBG sensors were stitched into the garments to measure the angle change for its joint movement or position. Then, each of the angles will be measured causing the wavelength to shift [7].

There are several reported works to cater the fragility of the fiber optic as reported in several literature [6], [8], however for the purpose of rehabilitation implementation, the distributed measurement is crucial for monitoring multiple parameters simultaneously at human body. Distributed sensors allow each FBG on the fiber, works as a separate sensor element, reflecting a specific wavelength that varies depending on the environment. In this case of rehabilitation, strain, bend, tactile and pressure are some of the parameters that needed for monitoring [9]. The distributed fiber optic sensor (DFOS) in literature focuses on telecommunication and becoming rapidly evolve field. The DFOS allows the existing optical fiber infrastructure for telecommunications to be reused for wide-area sensing, in which the distributed setup allows light propagates through the optical fiber being tapped out [10].

Apart from being used in telecommunication, the application of DFOS varies and ranges to a more promising industry application. According to [11]., DFOS enables measurement of many parameters such as intensity, phase, wavelength, and polarization [11]. The review focuses on the combination of Rayleigh, Brillouin, and Raman scattering mechanisms that integrate multiple DFOS system to govern the multi-parameter measurements. In another work by [12], they reviewed the generation of DFOS using acoustics from the vibration waveforms generated by Rayleigh back-scattering along the optical fiber. The detection and retrieval of multiple vibrations over a long distance and high sampling rate provides abundant information on the environment. Due to the multiple location of the sensor (distributed), all the phases of the sensing points are matched, therefore combining

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the acoustic response characteristics of the optical cable result in an increase of signal detection's sensitivity [12].

In this work, to achieve the DFOS, 2 FBGs are used representing multiple location as distributed sensor. Since rehabilitation application is aimed in this work, stretchability of the sensor become crucial as it will monitor the change in mechanical and will then transmit the signal to be monitored. As for the stretchable FBG, a coating method for the FBG is needed to improve its flexibility, sensitivity, and protection [13]. Materials like polymer membranes or elastomers and thermoplastic polyurethane (TPU) can be an option, however according to [14], a material like a polyimide (PI) has the ability to withstand high temperatures while having a good linear expansion, therefore many research on PI coating were reported for temperature and humidity sensing [14]. TPU on the other hand exhibit insufficient information in the literature owing to their new discovery. According to [15], TPU demonstrate self-healing capabilities which correspond to their work on the latest developments in supramolecular which composed of many molecules, TPUs that can heal themselves [15]. This discovery might extend TPU's service life and increase its capacity for recycling. [13] demonstrates FBG sensors coated with TPU for FBG-strain sensor measurements. The work summarizes that the TPU embedded FBG strain sensor was able to increase the sensitivity by ~2.05 times higher than polylactic acid-based (PLA-based) coating [13].

For stretchability, polydimethylsiloxane (PDMS) is widely known due to its flexibility and withstand high-temperature properties. It is an elastomer with excellent optical, electrical, and mechanical properties, making it suitable for various engineering applications [16]. The work by Shin & Kim, reported on their observation that the PDMS-coated FBG provides a stable wavelength response for significant period of time [17]. This indicates that coating FBG with PDMS can improve the sensitivity of wavelength by providing a better stability of wavelength response. In this work, distributed stretchable fiber optic sensor was successfully develop using FBG to monitor the multiple positions simultaneously in combination with the stretchable FBG sensor coated with PDMS.

II. Experimental Setup

The stretchable FBG was fabricated before it was tested as a distributed sensor. A petri dish is used as a container to fabricate FBG coated with PDMS. Fig. 1 shows the process flow of making the PDMS substrate for the stretchable FBG sensor. The first step was to make a base or foundation for the FBG. The mixing ratio of 11:1 for PDMS (11g) and curing agent (1g) was determined after several tests. This ratio works well because it makes the PDMS become hardened while still flexible and reduces stickiness once hardened. After mixing, the PDMS was stirred for 10 minutes, then it was placed in a vacuum container for about 10 minutes to remove air bubbles. After the procedure of extracting the bubbles was done, the PDMS was poured into the petri dish with a dimension of 35mm radius x 10mm height, that had been cut as in Fig. 2. It is then put into the oven for one hour at 60 ºC.

For the clear picture, Fig. 2 explains the foundation of the FBG when coating, in which the depth represent the cut section of plastic petri dish to locate the FBG, if the PDMS is to pour into the petri dish, the excess PDMS will flow out of it. Therefore, the two step fabrication is needed. First, the base

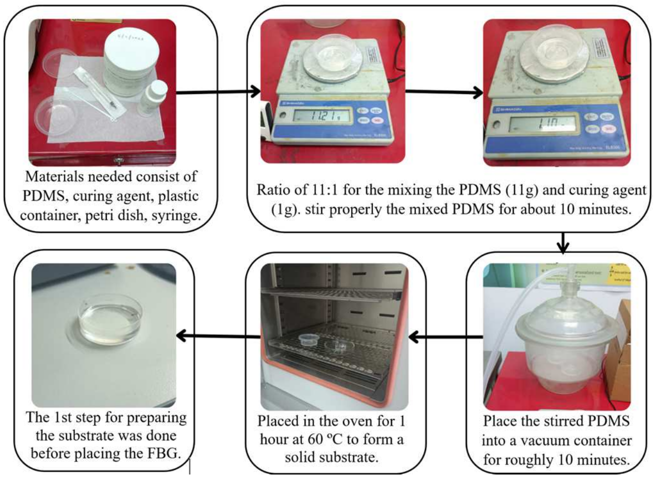


Fig. 1. The process flow of making the PDMS substrate for the stretchable FBG sensor.

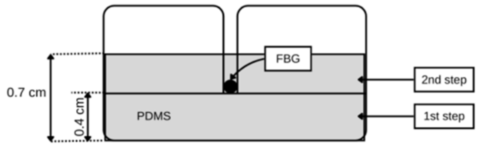


Fig. 2. The 2D view of two-step process foundation for coating FBG in petri dish.

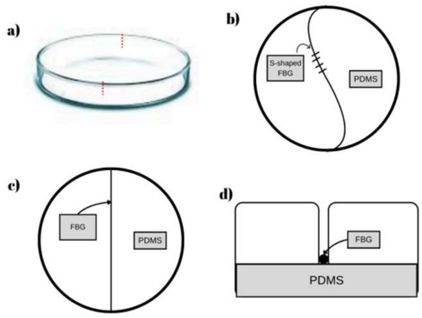
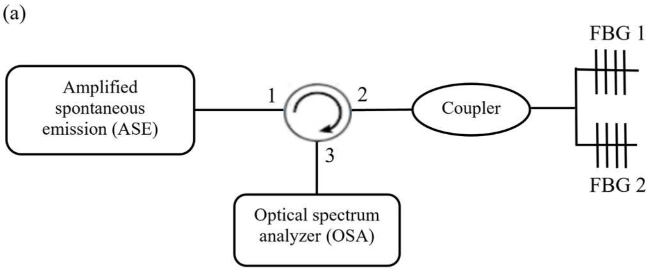


Fig. 3. Process flow for fabricating the stretchable FBG sensor (a) cutting section of petri dish, (b) S-shaped, (c) straight-line shaped, (d) location of the FBG placement before the second step for coating.

PDMS was poured roughly at 4 mm high to perform the PDMS substrate. Then, the petri dish was put in the oven for about one hour at 60º C. The high temperature can speed up the curing of PDMS. It is then took out from the oven to proceed with the second step.

For the stretchable FBG sensor, two different shape namely straight-line and S-shaped were fabricated, as shown in Fig. 3(b) and Fig. 3(c), respectively. The FBG was placed on top of the PDMS foundation made in the first step (Fig. 3(d)). Another PDMS and curing agent was mixed as in the first step for coating the FBG. It is then placed in the oven for about 40 to 45 minutes to ensure it reaches an almost-solid state. Next, the PDMS was immediately pour into two petri dishes that have FBGs placed in. In this state, the PDMS can still take form as it approaches solidity therefore unable to flow out at the cutting section on the petri dish due to its density (Fig. 2). Considering that the high-temperature oven would affect the sensitivity of FBG, we left out the coated FBG for about 24 hours at room temperature to allow the PDMS cured properly. After 24 hours, the PDMS-coated FBG

(a)



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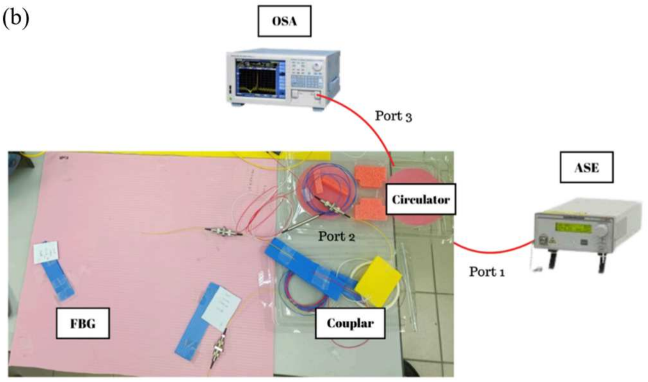


Fig. 4. The distributed FBG sensors, (a) diagram, (b) actual setup.

is ready to take out from petri dish. The dimension of the coated FBG was about 7 mm in thickness x 35 mm in radius and the FBG was located at a depth of about 4 mm as shown in Fig. 2.

After the fabrication of the stretchable FBGs, the experiment was setup (Fig. 4) to produce the distributed sensor consist of Amplified Spontaneous Emission (ASE), a circulator, a coupler, two homemade FBGs, and an Optical Spectrum Analyzer (OSA). The ASE is fed into port 1 of the circulator. The signal was then circulated to port 2 where the FBG was located. Before the FBG, the optical signal is split using a 50:50 coupler and once the signal reached the FBG, the reflection from the FBG at a wavelength of interest (also depends on their Bragg wavelength) was reflected and circulated back to port 3 for monitoring the signal at OSA. The circulator is responsible for avoiding the reflected signal from going back to the sources. The results of the combined reflection were displayed at the OSA.

III. Discussion and Analysis

The FBG serves as a sensing measurement that responds to applied strain by shifting its Bragg wavelength. From the results shown in Fig. 6, distributed sensing was achieved when conducting the experiment as mentioned in the setup of Fig. 4. The homemade FBGs display the various Bragg wavelength ranging from 1537 nm to 1555 nm resulted from the broadband ASE input signal. The stretchable FBG was done by conducting two experiments, firstly, on testing the bare FBG, and secondly, stretchable PDMS-coated FBG. The FBG sensor was tested on the armguard for various angle between 0º to 90º to imitate the rehabilitation application (Fig. 5). For the bare FBG, only a straight-line shaped was applied during the experiment. From the result of Fig. 6, the bare FBG was observed to has a slight shift of wavelength when different angle was implemented on the FBG. This is due to the low sensitivity of bare FBG and causing a small difference in shifting. It is also challenging for the bare FBG to bend at the armguard when it passed 50º angle.

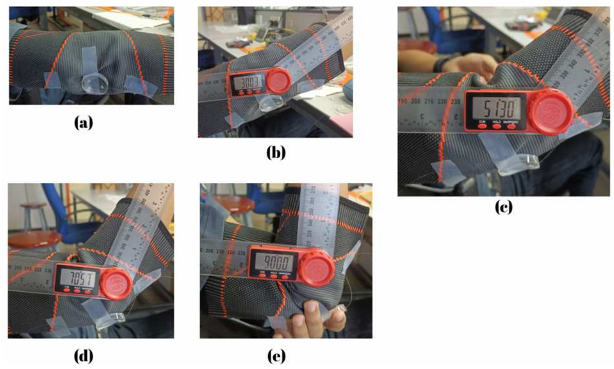
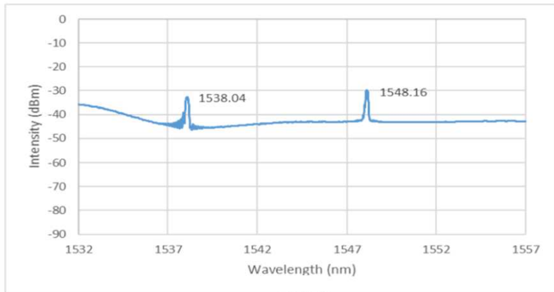
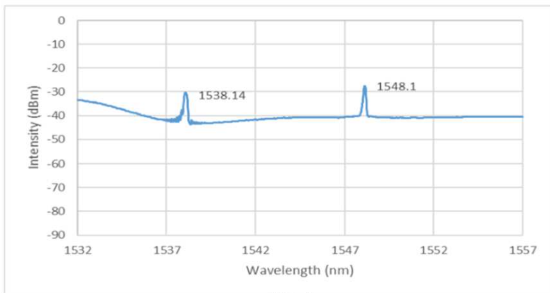


Fig. 5. Armguard configuration to evaluate the stretchable distributed FBG at (a) 0°, (b) 30°, (c) 50°, (d) 70°, (e) 90°.



(a)



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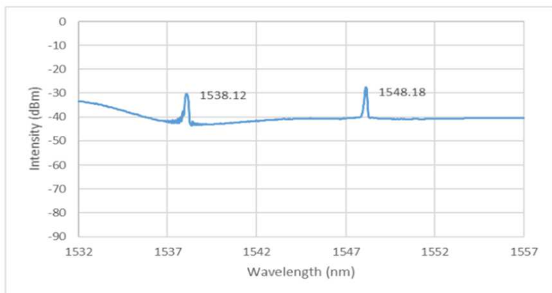

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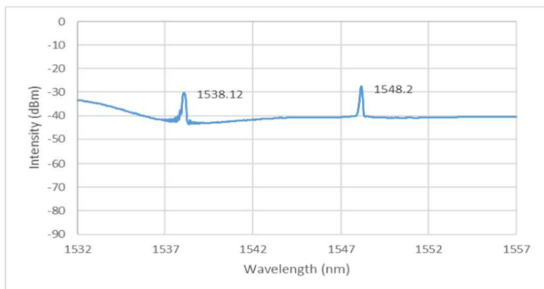

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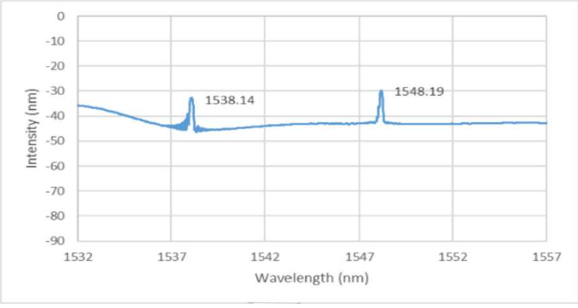


(e)

Fig. 6. Evaluation of bare FBG at (a) 0°, (b) 30°, (c) 50°, (d) 70°, (e) 90°.

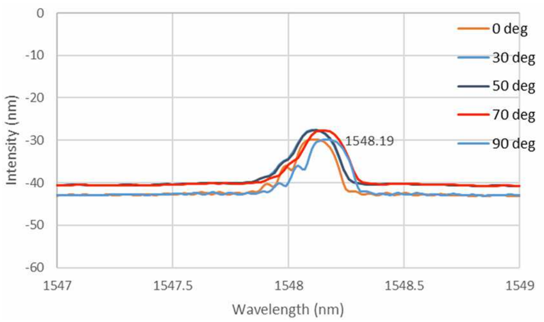


Fig. 7. A comparison of peak wavelengths at each angle.

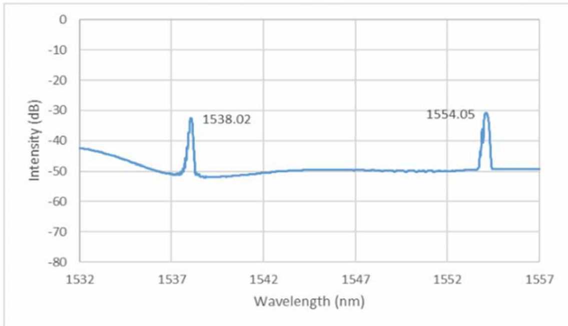
TABLE I. THE WAVELENGTH SHIFT OF BARE FBG FOR ACTUAL PEAK OF 1548.172 NM

Angle (°)	Actual Peak (nm)	Wavelength shift (nm)	Difference (nm)
0	1548.172	1548.16	0.012
30	1548.172	1548.10	0.072
50	1548.172	1548.18	-0.008
70	1548.172	1548.20	-0.028
90	1548.172	1548.19	-0.018

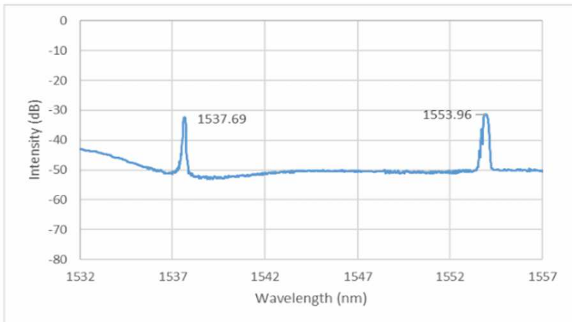
Fig. 7 shows the comparison of peak wavelength for each angle when bending armguard is applied. The shifting for each angle was low because the bending process did not affect the bare FBG but fractured it. Table 1 shows the summary of wavelength shifting for bare FBG. From the table, we can observe the minimal shifting of wavelength, hence wavelength differences are small. The sensitivity of FBG is low as it has difficulties detecting the deformation of elbow.

Next, the analysis of the distributed stretchable PDMS-coated FBG was done for the two FBGs which has a different shaped. S-shaped FBG was peaking at 1538.02 nm (left reflection signal), while straight-line shaped FBG emission peaking 1553.79 nm (right reflection signal), at its actual peak, as denote in Table 2. This shape plays an important part in strain sensing when the bending experiment starts. Fig. 8(a-e) show the wavelength shift when both coated FBGs started bending from 0 degrees to 90 degrees. As we can see, the FBG wavelength experienced a big shift compared to the bare FBG. This proved that coating FBG with PDMS can improve the sensitivity of FBG. Apart from that, coated FBG exhibit significant advantage due to its enhanced protection, as it can withstand the bending process up to 90 degrees, while most bare FBGs break once they exceed 50 degrees bending, as observed in the previous experiments.

Furthermore, the two coated FBGs were observed to identify the shifting trends. Fig. 9(a) shows a compilation of FBG reflection spectrum displays at the OSA. The FBG peak wavelength shift with Fig. 9(b) shows FBG sensing elements for S-shaped and Fig. 9(c) displays a straight-line shape. Table 2 summarize the wavelength shift for PDMS-coated FBG from its actual peak of 1538.02 nm (S-shaped) and 1553.79 nm (straight-line). From Table 2 and Fig. 9(b), the S-shaped FBG showed inconsistent wavelength shifts; at 30 degrees, a blue shift was observed, while at 70 degrees, the shift was in the opposite direction. This irregularity could be attributed to the placement of FBG not being proportional to the applied bending during the experiment. Meanwhile, the straight-line shape shows a consistent shifting with each angle causes the wavelength to exhibit red shift. Generally, a higher bending angle results in a greater wavelength shift. However, as shown in Table 2 and Fig. 9(c), the shift at 70 and 90 degrees is less than that of 50 degrees. This irregularity may be caused by the inconsistent strain distribution during the experiment. The straight-line shape demonstrates better strain sensing performance as compared to the S-shaped due to the applied strain is more uniform along the entire surface of the FBGs.



(a)



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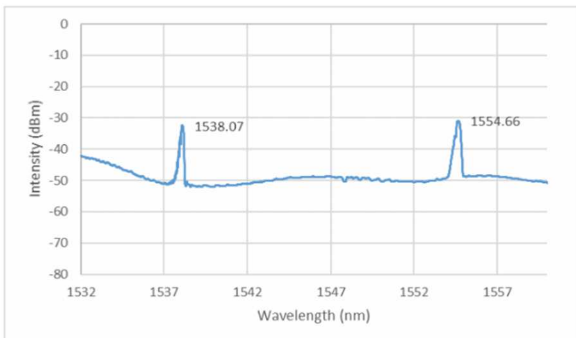

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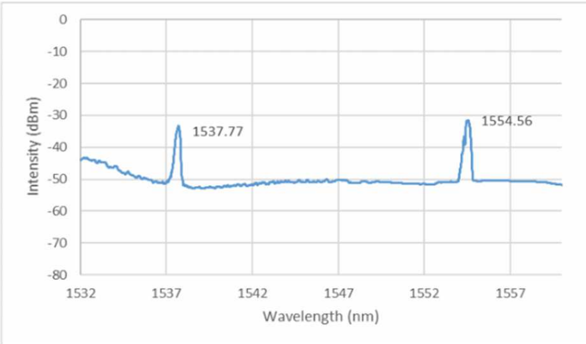

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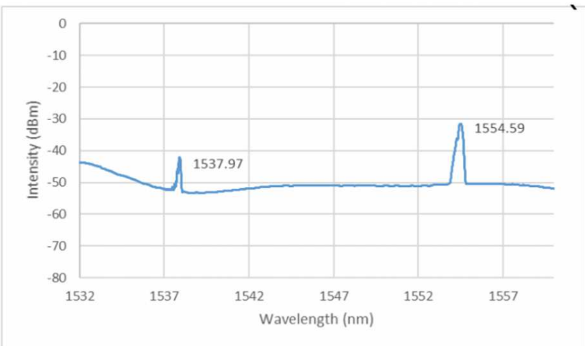

(e)

Fig. 8. Evaluation of coated FBG with PDMS for S-shaped (left side with actual peak at 1538.02 nm) and straight-line shaped (right side with actual peak at 1553.79 nm) at (a) 0°, (b) 30°, (c) 50°, (d) 70°, (e) 90°.

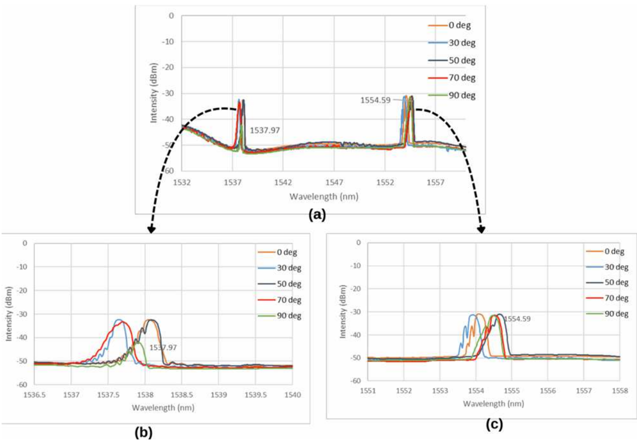

Fig. 9 (a) The OSA spectrum of the FBG peak wavelengths at each angle, (b) Wavelength shift for S-shaped, (c) Wavelength shift for straight line-shaped.

TABLE II. THE WAVELENGTH SHIFT COATED FBG FOR ACTUAL PEAK OF 1538.02 NM (S-SHAPED) AND 1553.79 NM (STRAIGHT-LINE)

	S-SHAPED		**STRAIGHT-LINE**	
Angle (º)	**Wavelength shift (nm)**	**Difference (nm)**	**Wavelength shift (nm)**	**Difference (nm)**
0	1538.02	0	1554.05	-0.26
30	1537.69	0.33	1553.96	-0.17
50	1538.07	-0.05	1554.66	-0.87
70	1537.77	0.25	1554.56	-0.77
90	1537.97	0.05	1554.59	-0.8

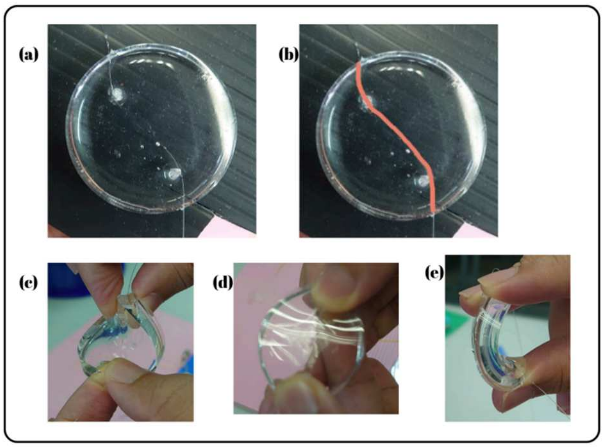

Fig. 10. The FBG coated PDMS with different types of mechanical deformations/strain a) The coated FBG, b) S-shaped FBG c) twist d) stretch e) bend.

Finally, the PDMS-coated FBG was tested in terms of stretchability and protection. The fiber was coated to minimize the likelihood of breakage and to offer improved mechanical protection. Fig. 10 illustrates the PDMS-coated FBG with different types of mechanical deformations/strain applied to the FBG. The coated FBG can endure a high bending process until 90 degrees compared to a bare FBG, which breaks once the angle surpasses 50 degrees. The coated FBG is still functioning when twisted as shown in Fig. 10(c) and stretched as in Fig. 10(d). Overall, it is proven that coating FBG with PDMS improved mechanical deformations/strain to the FBG.

IV. CONCLUSION

In conclusion, a stretchable distributed FBG sensor has successfully demonstrated, mounted to the armguard to imitate the angle measurement of both elbows. The stretchable FBG sensor was made up of an S-shaped and a straight line-shaped, coated with a stretchable material, PDMS. The advantage of PDMS coating allows the FBG to deform until 90 degrees, unlike the bare FBG which typically limited to a maximum of 50 degrees. The distributed FBG sensor was achieved owing to the coupler's function of merging the two reflected FBG signals. The analysis showed the wavelength shift for PDMS-coated FBG was significant than the bare FBG. The strain sensor was tested in terms of straight-line and S-shaped for FBG coated with PDMS, ranging from 0 - 90º bending angle. It has been confirmed from the experiment that the straight-lined shape of PDMS-coated FBG gives uniform red shift as compared to the S-shaped. To conclude, coating the FBG with PDMS is considered beneficial for improved performance in terms of sensitivity, protection, and to withstand mechanical deformations or strain applied to the FBGs.

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