

Fabrication of Highly Stretchable Strain Sensor Fiber by Laser Slitting of Conductive-polymer-coated Polyurethane Film for Human Hand Monitoring

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In the research field of virtual and augmented reality (VR/AR), a highly stretchable sensor fiber that can easily be integrated into a sensor glove or finger cot has been required for detecting human hand motions. In this study, we propose a fiber-type highly stretchable strain sensor by slitting an elastic polyurethane (PU) film coated with a conductive polymer of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS). A 100- μm -thick PU film coated with 100-nm-thick PEDOT:PSS was slit by a laser cutter with a spot diameter of 125 μm . The width of the sensor fiber was only 214 μm , which is equivalent to a conventional thin 205- μm -diameter fishing line. To investigate the strain sensitivity of the PEDOT:PSS-coated fiber sensor at high stretching (>30%), we evaluated the gauge factor as a function of the concentration of ethylene glycol (EG) in PEDOT:PSS solution. The PEDOT:PSS strain sensor fiber with an EG concentration of 0.75% under 37.5% tensile stretching exhibited the highest gauge factor of 0.16. Finally, the sensors were integrated with thin woven fibers using a flat weave method, and the bending movement of a human finger was detected. The manufacturing method proposed in this study is expected to contribute to the realization of a stretchable strain sensor by the use of a wearable polymer die coating and a slitting apparatus.

1. Introduction

Recently, new augmented reality (AR) and virtual reality (VR) systems toward realizing highly immersive games and aircraft pilot simulators, and industrial virtual training systems for sheet metal bending and welding have been developed owing to the rapid development of VR glasses.^(1,2) These AR/VR simulators and training systems require a motion sensor that is capable of sensing human body motions, such as those of the fingers, hands, and feet. Currently, data gloves that detect human hand motion are used,^(3,4) but these gloves are thicker than 5 mm, hard, and have low sensitivity.⁽⁵⁾ Since the skin of human joints, such as fingers or knees, is stretchable (>30%),⁽⁶⁾ the sensor is required to have high mechanical elasticity. Thus, a new

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thin, highly stretchable, and high-sensitivity strain sensor that is easy to incorporate into gloves is necessary for human hand motion detection in VR and AR systems.

Owing to recent advances in the downsizing and high-definition technology of liquid crystal displays (LCDs), organic light-emitting diodes (OLEDs), and other displays, a small, high-definition display can be easily placed on glasses, and many AR and VR glasses such as HTC VIVE and OCULUS have been developed and manufactured.^(7,8) Therefore, three-dimensional video projection technology that produces AR and VR spaces has been established owing to the widespread use of AR and VR glasses. To make AR and VR systems more realistic in the future, the development of wearable sensor technologies that incorporate the motion of the user's body into a three-dimensional video projection will become a significant technical challenge in the VR field.^(9,10) In particular, for realistic AR and VR games, aircraft pilot simulators, and skill training, a globe-type device with high detection accuracy of human hands is required. A motion capture technique using two cameras has been developed to detect large parts of the human body, such as arms and legs. However, since a human finger joint is only several cm in size, finger bending cannot be identified by two cameras. Therefore, in previous studies, at least five cameras and a depth camera were used to detect the angle of the finger.^(11,12) Because of the small detection range of cameras, appropriate motion capture camera setting is also tricky. Therefore, data gloves with optical sensors and bending sensors have been utilized to detect the rotation of human fingers. A data glove with an optical fiber has a structure where the optical fiber is bonded to a thin soft knit glove and a sensing mechanism based on the bending transmittance loss of the optical fiber.⁽⁵⁾ Although it is possible to detect bending with high sensitivity by using the optical fiber, the plastic optical fiber is thick (>1.5 mm) and rigid in comparison with a conventional yarn of thickness less than 300 μm , which leads to uncomfortable clothes. Many commercially available sensors such as the 5DT data glove, CyberGlove, and shape hand use optical fibers. On the other hand, a data glove with strain sensors has also been developed. Strain transducers such as flex sensors have a thickness of only 500 μm and are easy to place on data gloves. However, because a strain sensor is made of a polyimide film and has a large width of 7 mm and a length of 55 mm, the sensor is rigid and lacks stretchability. To incorporate human hand motion sensors into gloves that are comfortable to wear, a new strain sensor should be thin and elastic. Thus, a narrow fiber (<300 μm)-type sensor is an ideal candidate for a data glove for human hand motion sensors.

E-textiles are a manufacturing technology that integrates electric wires and sensors onto thin fibers.^(6,13) In the conventional e-textile research field, several types of conductive yarns have been developed by electroplating silver and copper on fibers or by coating conductive polymers on fibers.^(14,15) Plating is a technique of forming copper and silver on a fiber and forming electric wiring.^(16,17) The metal-plated fibers cannot be used as stretchable sensors because metal films have no elasticity. On the other hand, we have developed a technology for continuously coating conductive polymers on polyester fibers by a die-coating method.^(18,19) Conductive polymers (such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS)) have an advantage of rapid film formation by coating with a PEDOT:PSS water dispersion and drying.^(20,21) Since PEDOT:PSS is an elastic-plastic, conductive polymer, it is resistant to bending and stretching. However, because polyester fibers are not stretchable, a PEDOT:PSS-coated thread cannot

be applied to elastic sensors.⁽²⁰⁾ Also, it is difficult to uniformly coat fibers with conductive polymers because fibers have a complex three-dimensional shape. Therefore, a special coating jig called a three-dimensional die has been required.^(18,19) Consequently, it is necessary to develop a simple method of forming a simple conductive polymer film on a fiber that does not need a three-dimensional die. Therefore, in the e-textile research field, the development of a sensor, not a conductive thread, is challenging. Since conductive polymers can be considered as sensor materials for the development of an elastic sensor thread, a new technique for fabricating a stretchable strain sensor yarn of a conductive polymer should be developed as an alternative to three-dimensional die-coating.

In the VR/AR research field, a technology to incorporate a thin elastic sensor with 100 to 300 μm thickness into a sensor glove is required. A new hand motion sensor glove that does not limit finger movements and is comfortable to wear is highly desired. A narrow fiber (<300 μm)-type sensor is considered to be highly suitable for a data glove for human hand detection, and a new data glove should have an ideal structure woven with a small sensor fiber. On the other hand, in the research field of e-textiles, the development of a new sensor fabrication technique to make a stretchable strain sensor yarn with a conductive polymer as an alternative to three-dimensional die-coating is required. To meet these requirements of human finger motion sensors, we proposed a highly stretchable fiber-type strain sensor prepared by slitting an elastic polyurethane (PU) film coated with a conductive polymer. Conductive polymer strain sensor fibers were fabricated by laser slitting, and the cutting accuracy of the sensor fibers was evaluated. To investigate the strain sensitivity of a PEDOT:PSS-coated fiber sensor under high stretching (>30%), we evaluated the gauge factor as a function of the concentration of ethylene glycol in a PEDOT:PSS solution. Finally, after the sensor fibers were interlaced with thin cotton fibers to make a woven sensor fabric, the bending motion of a human finger was detected with our sensors.

2. Sensor Structure and Fabrication Process

2.1 Sensor cot using conductive polymer strain sensor fiber for VR/AR

Figure 1 shows the proposed sensor cot made of the PEDOT:PSS-coated strain sensor fibers for VR/AR applications. We aim to realize a system that detects the movement of a human finger by using the proposed sensor cot. Unlike conventional nonstretchable strain sensors (e.g., micro-electromechanical system (MEMS)-based semiconductor strain sensors and metal-composite strain sensors), a PEDOT:PSS-coated strain sensor can be easily integrated into the sensor fabric since the sensor fibers are flexible and elastic.

2.2 Conductive polymer coating of film and fabrication of conductive polymer strain sensor fiber by laser slitting

The proposed process is based on the method of manufacturing the gold yarn used in a kimono. In the manufacturing method of gold yarn, gold is first sputtered on a polyimide film.

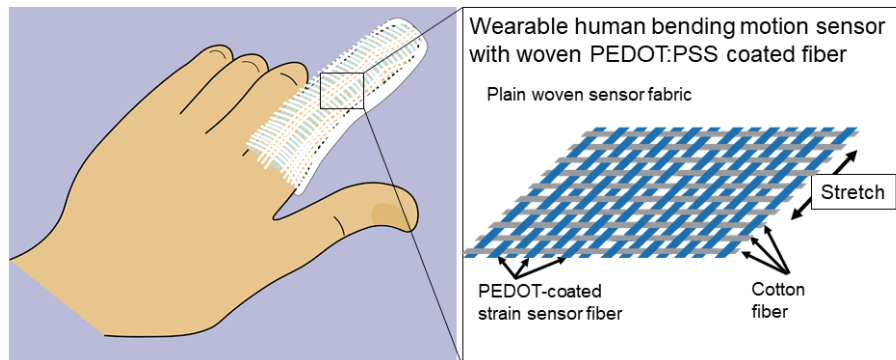


Fig. 1. (Color online) Sensor cot made of conductive strain sensor fibers for VR/AR applications.

Then, the film is cut into a string with 100 to 300 μm width using a slit. In our study, instead of polyimide, we use an elastic PU film (Sheedom Corporation, SHM 101 – PUR 0.1 mm) as the yarn substrate. Instead of sputtering gold, a conductive PEDOT:PSS-based polymer solution is coated with a spin-coater. The solution is a mixture of the conductive polymer poly(3,4-ethylene dioxythiophene) doped with poly(styrene sulfonate) (PEDOT:PSS) (PH100, Clevios, Heraeus), ethylene glycol (EG) (99.8%, Sigma-Aldrich), dodecylbenzene sulfonic acid (DBSA) ($\geq 95\%$, Sigma-Aldrich), and (3-glycidioxypropyl)trimethoxysilane (GOPS) ($\geq 98\%$, Sigma-Aldrich). Before mixing, the PEDOT:PSS dispersion is filtered through a 0.45 μm filter (Whatman) to remove large particles. The proposed manufacturing process consists of the following steps (Fig. 2):

1. A nonstretchable polyethylene naphthalate (PEN) film (Teijin DuPont Film PEN film Q51 – A4) of 100 μm thickness is attached to a 100- μm -thick PU film for ease of handling.
2. The conductive PEDOT:PSS-based polymer solution is spin-coated on the PU surface at a rate of 500 rpm. The as-coated film is dried at 110 $^{\circ}\text{C}$ for 1 h to remove moisture and form a conductive film.
3. The PU film coated with the dried PEDOT:PSS film is slit into lines of 2 mm width by a CO₂ laser cutter (Universal Laser VLS 4.6 – 30), which has a spot diameter of 127 μm and power of 30 W. The PU film is slit at intervals of 100 to 600 μm .
4. The PEDOT:PSS-coated strain sensor fibers are detached from the PEN film.
5. The sensor fibers are interlaced in the same direction as thin cotton fibers to make a woven sensor fabric using a plain weaving technique.

The unique feature of the proposed technique is that thin fibers with strain sensor functions can easily be made from conductive-polymer-coated films. When a conventional metallic material is used as a sensor, the metallic film cannot be cut without a high-energy laser. In contrast, the conductive polymer is thin (100 nm) and can be cut easily by a low-energy laser with a power of less than 30 W. Recently, a low-energy laser has been used in digital fabrication methods. We previously developed a technique to coat a round thread with a conductive polymer.⁽¹⁹⁾ However, it was difficult to coat a thin conductive polymer on a thin fiber. A conventional thin film is flat and a spray coater is made of flat plates, making it difficult to coat cylindrical fibers with conductive polymer. Therefore, the method of cutting out of a flat plate is characterized by its compatibility with conventional functional film deposition techniques.

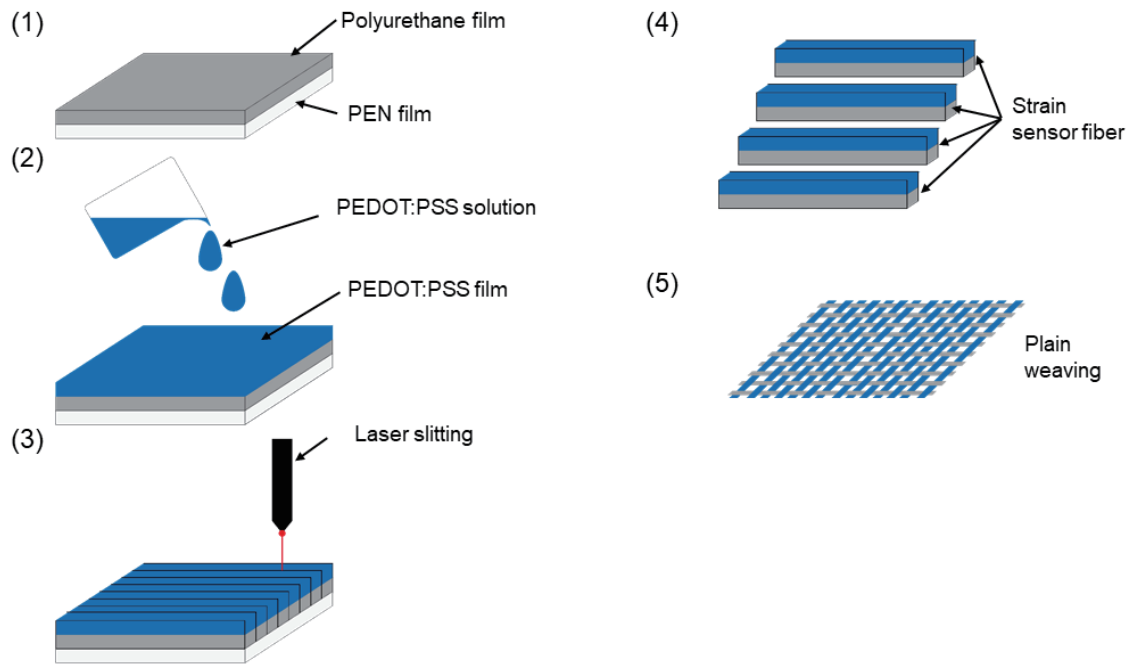


Fig. 2. (Color online) Fabrication process of conductive polymer strain sensor fiber by laser slitting.

The PEDOT:PSS film is highly stretchable but has sufficient hardness to be scratch-resistant. Therefore, PEDOT:PSS has been used as an antistatic coating on displays and photo papers.⁽²²⁾ However, to improve the resistance to scratching, a liquid PU film or another film should be coated on the PEDOT:PSS film.

2.3 Fabrication of sensor fiber by laser slitting and slitting resolution

Our proposed technique makes it easy to fabricate thin fibers that can be used as sensors. The conductive polymer layer in this study has a thickness of about 100 nm and a hardness equivalent to that of plastics. Therefore, our sample with a three-layer structure can be cut with a laser under the conditions used to cut a single PU film. In contrast, in the case of a conventional metal-coated film, the cutting must be performed with a high-output laser. In general, the diameter of a fiber used in cloth (e.g., T-shirt) ranges from 100 to 300 μm . In fishing line standards, the conventional diameters of the fibers are as follows: No. 1 = 171 μm , No. 1.5 = 205 μm , No. 2 = 235 μm , No. 3 = 285 μm . Our desired sensor fiber width should range from No. 1 to No. 3.

We investigated the film slitting accuracy and the conditions under which the fiber can be finely cut into widths ranging from 100 to 300 μm by a laser cutter. The samples were cut with a laser power of 20% and a speed of 50%. Laser slitting was performed to produce fibers with designed widths of 100, 200, 300, 400, 500, and 600 μm . Five fibers were cut by a laser for each designed width, and the actual width was measured with a microscope (LEICA DMS1000). The actual width of the experimental fibers is the average of the widths of the five samples.

Table 1 shows the designed and actual widths of the fabricated sensor fibers. Because the laser beam had a spot diameter, a cutting allowance was necessary, and the average fiber width was found to be 192 μm . In the case of a 100 μm designed width, the cutting was a failure. For the designed fiber widths of 200, 300, 400, 500, and 600 μm , the actual cut fiber widths were failure, 45, 83, 214, 314, and 387 μm , respectively. The widths of the slit fibers are significantly less than the designed widths. As shown in Fig. 3(a), the fibers with the designed fiber widths of 200 and 300 μm cannot be used as sensors because they are partially melted and burnt by the laser beam. The 314- μm -wide sensor fiber is too wide to match the standards of commercially used cloth fibers. It was found that the cut width of 214 μm is similar to the width of a No. 1.5 fishing line (205 μm). Figure 3(b) shows that the fiber is thin and smooth, similarly to a regular No. 1 fiber; thus, we considered it suitable for use as our sensor.

3. Strain-Sensing Mechanism and Gauge Factor Improvement by EG Addition

3.1 Strain-sensing mechanism of PEDOT:PSS and conductivity change upon EG addition

The conductivity of PEDOT:PSS was improved by changing the concentration of EG. The principle of PEDOT:PSS film conductivity is shown in Fig. 4(a). A PEDOT:PSS film has a

Table 1 Fiber widths of laser-slit PEDOT:PSS-coated polyurethane film.

Designed fiber width (μm)	100	200	300	400	500	600
Laser cut Fiber width (μm)	failure	45	83	214	314	383
Error of Fiber width (μm)		155	217	186	186	217

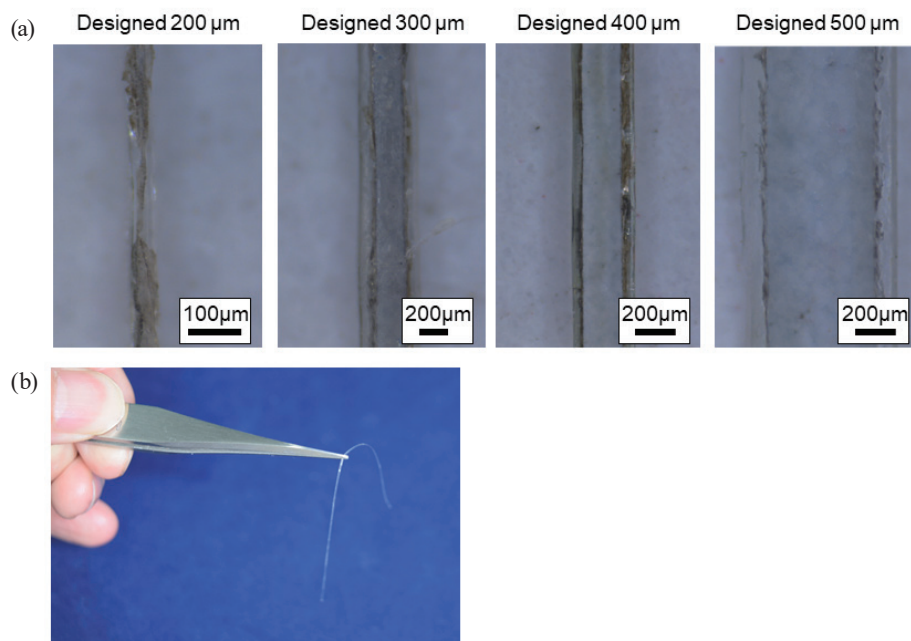


Fig. 3. (Color online) (a) Microscopic images of laser-slit sensor fibers. (b) Sensor fiber with a width of 214 μm .

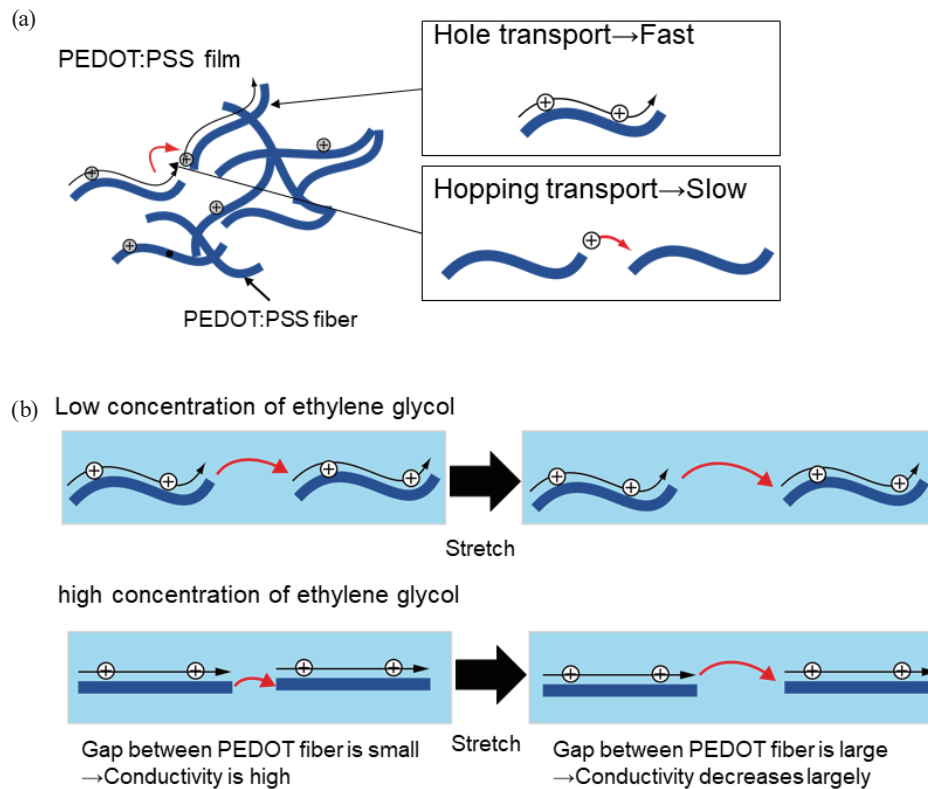


Fig. 4. (Color online) (a) PEDOT:PSS electric conduction mechanism. (b) Electric resistance under low and high concentrations of EG.

structure in which nanoscale PEDOT:PSS fibers are intertwined. The electrons of the PEDOT fibers are removed by PSS, and electric holes are produced. In the PEDOT fibers, current flows through the motion of the produced electric holes. The electric current flows between the PEDOT fibers by hopping transport as shown in Fig. 4. Hole transport conduction is fast, but it is known that hopping transport decreases the conductivity, because it takes a long time to transport holes between PEDOT fibers. Generally, the conductivity of organic electronic materials is low. Basically, their crystallinity is low, and the resultant long distance between fibers means that a long time is required for hopping conduction. It was previously reported^(18,23) that the conductivity of PEDOT:PSS is improved by adding EG. The improved conductivity is due to the decreased intermolecular distance between the molecules of the PEDOT polymer. As shown in Fig. 5, the conductivity (S/sq.) increases by more than three orders of magnitude when the concentration of EG reaches 3%. This is because a low concentration of EG is effective in reducing the distance between PEDOT polymers. This leads to a large strain gauge factor of the film. In principle, the conductivity by hopping conduction is generally proportional to the inverse of the square of the intermolecular distance. Therefore, it is possible to obtain a large decrease in conductivity by reducing the initial intermolecular distance. Thus, if the initial intermolecular distance of PEDOT fibers can be decreased by adding EG, the conductivity change of PEDOT fibers under an applied strain will be larger.

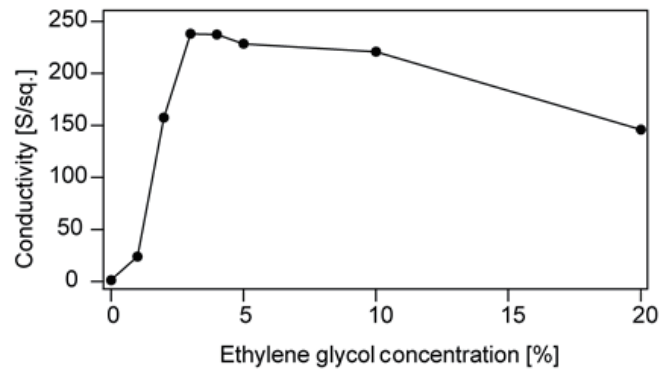


Fig. 5. Relationship between electric conductivity of PEDOT:PSS film and EG concentration.

On the other hand, if the concentration of EG is too high, hole conduction between PEDOT polymers is suppressed owing to their insulating properties. Thus, when the EG concentration is more than 5%, the conductivity gradually decreases and the gauge factor of the film also decreases at the same time.

Therefore, in this study, the change in the PEDOT strain sensor characteristics as a function of EG concentration was experimentally investigated. The preparation of PEDOT:PSS solutions with various concentrations of EG is described below. First, a water dispersion of PEDOT:PSS (Heraeus CLEVIOS PH 1000) is filtered through a filter of 0.45 μm , and large particles of PEDOT:PSS in PEDOT:PSS solution are filtered. Then, conductive polymer solutions of EG, DBSA, and GOPS are mixed. The volume of EG in the mixed solution was varied between 0 and 25%. The resistivity of PEDOT:PSS films with different EG concentrations was measured with a sheet resistance meter (Republican Institute, K-705 RS). The reciprocal of the measured sheet resistance is the sheet conductivity (S/sq.). As shown in Fig. 5, the conductivity of the PEDOT film increased up to an EG concentration of 3%, then was almost constant, consistent with the above theoretical discussion.

3.2 Change in gauge factor of PEDOT:PSS strain sensor fiber with EG concentration

Tensile tests were performed on 5-mm-wide PEDOT:PSS strain sensor fibers with different concentrations of EG (0–20%). A single sensor fiber was attached to a tensile machine (FTN-3001, AIKOH Engineering Co.) and was subjected to cycles of stretching at 12.5, 25, and 37.5% (tensile lengths of 5, 10, and 15 mm, respectively). For each tensile length, the sample was stretched 10 times. The resistance was measured simultaneously using a Keithley 2400 source meter, and the data were collected in the Labview program. The testing speed was 30 mm/min.

Figure 6 shows the change in resistance during the stretching cycles for three different EG concentrations. The strain sensors with 0 and 0.75% EG exhibit high gauge factors when utilized for repeated stretching. When the concentration of EG was 0 and 0.75%, the resistance strongly depended on the cycle number. However, even in the case of repeated elongation, the resistance returned to its initial value. Note that the change in resistance was larger when the

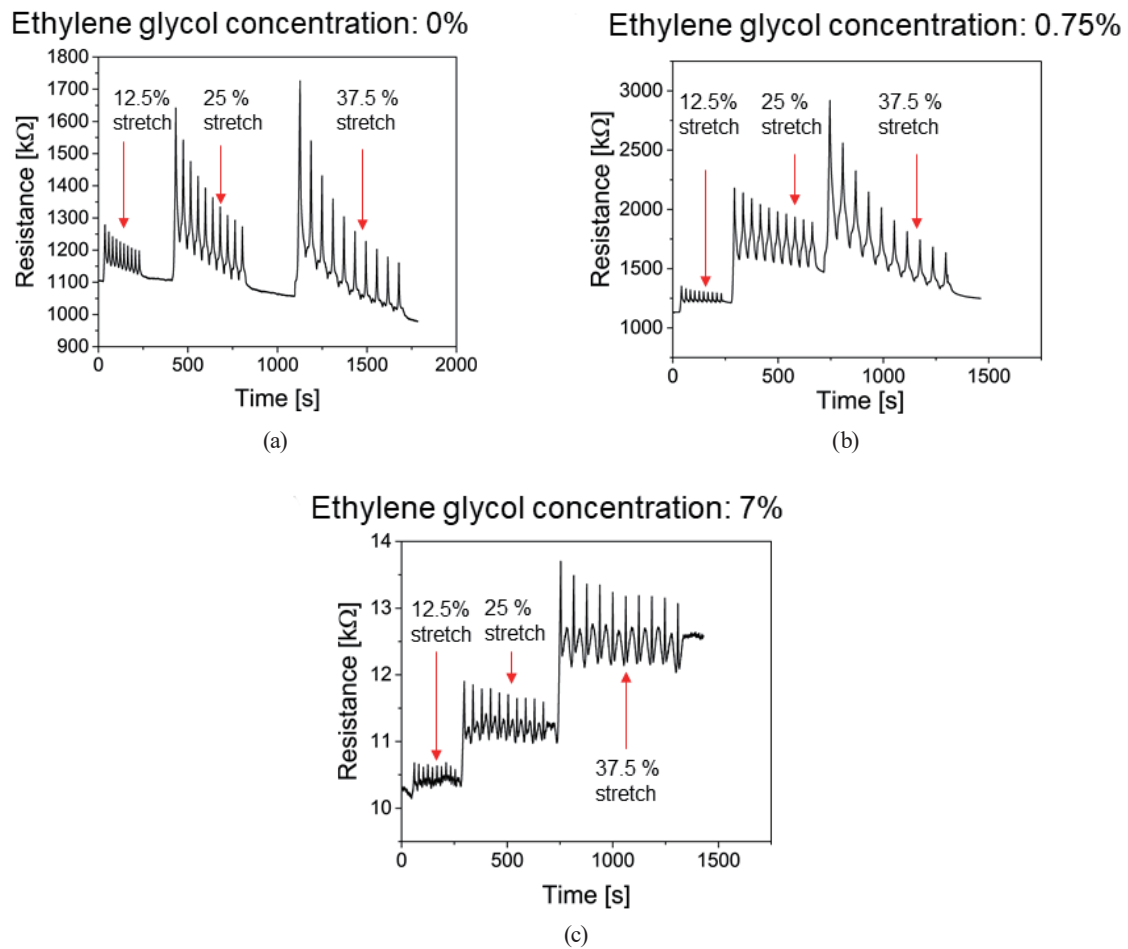


Fig. 6. (Color online) Results of cyclic stretch tests of PEDOT:PSS films with EG concentrations of (a) 0%, (b) 0.75%, and (c) 7%.

concentration of EG was 0.75%. On the other hand, when the concentration of EG was 7%, the change in resistance under fixed stretching was constant regardless of the cycle number [see Fig. 6(c)], but the resistance did not return to its initial value. Therefore, it was found that the strain sensor with 0.75% EG is optimal for applications with repeated stretching such as finger-bending sensors. The change in resistance was highly linear for the strains up to 12.5, 25, and 37.5% given in this study. However, after repeated large strains of approximately 37.5%, the resistance did not return to the initial value, which may have been caused by cracks or other flaws in the PEDOT itself. Therefore, when the sensor is used as an actual sensor, it should be changed to a structure having cracks and other flaws by first applying a large strain. It is considered that the strain sensor can be used at a large strain when the initial resistance of the sensor is increased by a structural change. The linearity of the sensor needs to be evaluated to determine the maximum percentage of strain it can withstand.

Figure 7 shows the relationship between the concentration of EG and the gauge factor. Cyclic tensile tests of the strain sensor fibers with EG concentrations of 0 to 5% were carried out at stretching of 12.5, 25, and 37.5% for ten cycles of stretching. It was found that the PEDOT:PSS

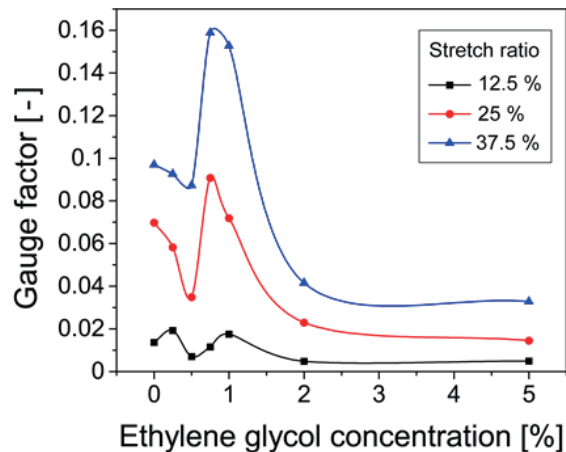


Fig. 7. (Color online) Gauge factors of PEDOT:PSS films with different EG concentrations.

film with an EG concentration of 0.75% could withstand stretching of 37.5% and exhibited a high gauge factor of 0.16. Under large stretching ($\geq 25\%$), the resistance varied greatly. The gauge factor (K_s) reached its maximum (0.09 for 25% stretching and 0.16 for 37.5% stretching) at the EG concentration of 0.75%. When the EG concentration was larger than 0.75%, the gauge factor decreased. Moreover, when a sensor is attached to the joint of a human finger to measure bending, it is necessary to withstand repeated stretching of more than 30%. In accordance with the sensing mechanism of the PEDOT:PSS strain sensor as mentioned in Sect. 3.1, the addition of EG increased the distance between PEDOT polymers. Because conductivity is maximum at 3% in Fig. 5, it was expected that the gauge factor would be maximum at 3%. Figure 7 shows that the gauge factor was maximum at 0.75%, which is less than 3%. This may be because the distance between polymers is minimized at about 0.75%, and above 0.75%, the conductivity may be improved for reasons other than distance.

4. Sensor Cot and Detection of Human Finger Bending

The purpose of this study was to detect the bending of a human finger with a sensor fiber. Therefore, finger cots were woven by a plain weave using a sensor fiber and cotton yarn. The sensor uses the high strain sensitivity of a PEDOT:PSS film with 0.75% EG. Figure 8(a) shows a flat weave using a 2-mm-wide sensor fiber woven by hand to demonstrate the detection of human finger bending. Figure 8(b) shows the relationship between the angle of finger bending and the change in electric resistance of the sensor fibers. The sensor was mounted around a 10-mm-diameter cylinder instead of a finger joint, and the angle was varied. The angle of the joints of the fingers was changed from 0 to 90°. The change in the sensor resistance is the increase in the sensor resistance divided by the initial sensor resistance. The change in the sensor resistance varied from 0 to 1.2 as the angle was changed from 0 to 90°. Therefore, it is possible to measure the angle of the finger joints. However, one of the issues is that the change in resistance with the angle is not linear. Nevertheless, our sensor can be stretched repeatedly because the resistance of the sensor is stable even if the bending is carried out many times.

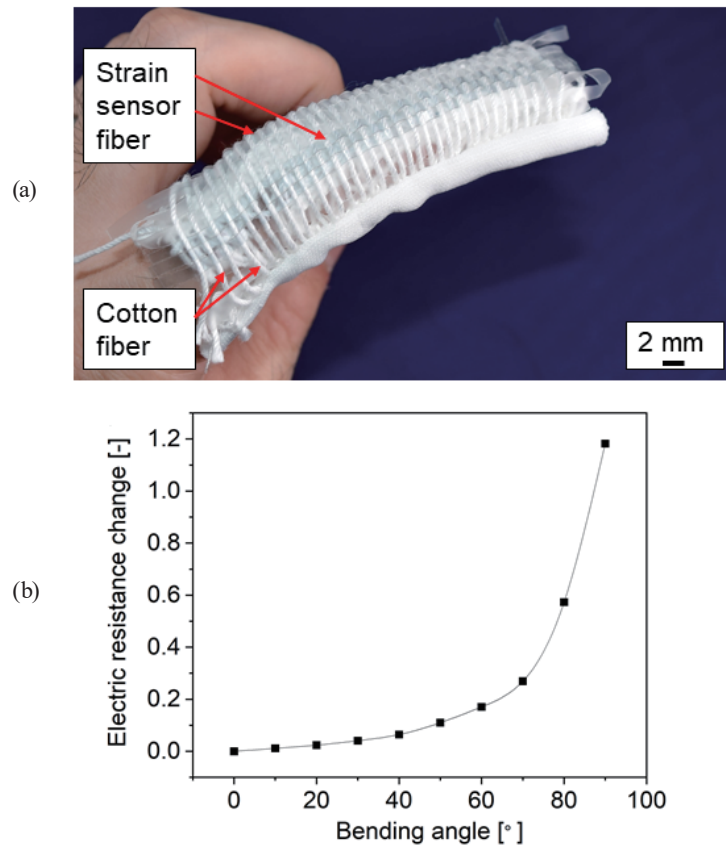


Fig. 8. (Color online) (a) Woven sensor cot with stretchable sensor fiber and cotton fiber and (b) relationship between bending angle and change in electric resistance of sensor fiber under bending.

5. Conclusions

In VR/AR research fields, it is necessary to have gloves and cots with a highly stretchable strain sensor that can be easily integrated with the fabric. We proposed a simple method of fabricating a new sensor fiber by laser slitting. A sensor fiber was formed by coating PEDOT:PSS on a 100- μm -thick PU sheet and laser-slitting the film with a CO_2 laser. The width of the slit sensor fibers can be narrowed down to 214 μm ; thus, the fibers can be easily integrated into thin and flexible fabrics. The strain sensitivity of the PEDOT:PSS strain sensor was improved by changing the concentration of EG. The PEDOT:PSS film with an EG concentration of 0.75% exhibited a high gauge factor of 0.16 under large stretching of 37.5%. Finally, PEDOT:PSS-coated sensor fibers were interlaced with cotton fibers to form a sensor cot, and finger bending was detected with our sensor cot. Our proposed manufacturing method is expected to contribute to the production of stretchable strain sensor fibers for many applications.

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