

Article

Novel Fabrication Method for Pressure-Sensing Polymeric Optical Fiber (POF) Fabric with Non-Direct-Contact Conductive System

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Abstract: Considering the current limitations of intelligent interactive in electronic integration and luminescent modes, this paper proposes a novel fabrication method for pressure-sensing POF fabrics with a non-direct-contact conductive system. In this system, conductive materials are concealed in the fabric structure to avoid direct contact with the human body. It was enabled by integrating layered weave structure, POFs, conductive yarns, and fabric patches within the fabric. Laser engraving was also applied on the fabric surface to achieve intricate pattern design. Experimental tests were conducted on sensing and luminescent properties of this POF fabric. The circuit module and software were developed to support the interactive function. The potential application of this fabric in the interior components of intelligent cockpits was envisioned. The research results show that the POF fabric integrated with conductive yarns and conductive fabric patches has good pressure sensitivity, enabling control of the fabric's luminescent color by pressing the fabric surface. The non-direct-contact conductive system developed in this study offers the advantage of electrical signal stability by avoiding interference from human body resistance and grounding conditions. The development of this type of interactive luminescent textile holds promising prospects for application and development in various fields, including intelligent cockpits.

Keywords: integrated fabrication method; interactive luminescent textiles; POF fabric; conductive materials; intelligent cockpits



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1. Introduction

Since the 21st century, with the continuous development of new textile materials and electronic information technology, the focus of the global textile industry has shifted from traditional apparel to high-tech textiles with multifunctionality and high added value [1]. Intelligent interactive textiles that incorporate conductive fibers or sensors into traditional textiles have emerged as a popular technology in recent years [2,3]. This technology endows traditional textiles with more proactive interactive functions, such as health monitoring, motion recognition, gesture interaction, virtual reality (VR) and augmented reality (AR) control, and smart home [3,4]. In the design of intelligent interactive textiles, the safety, durability, and stability of the electrical signals in the interaction with the human body are still of the utmost concern [5].

Currently, there is an increasing emphasis on the development of luminescent interactive textiles in various fields such as smart homes, intelligent cockpits, wearable technology, and healthcare [2,6]. In particular, the development of luminous interior components in cockpits has expanded beyond the traditional roles of lighting and decoration. It is poised to become a key window for human-machine interaction [4]. Huisheng Peng's team at

Fudan University presents a functional, large-area display textile which serves to bridge human–machine interactions by weaving conductive and luminescent fibers with cotton yarn to form electroluminescent units (EL units) directly within the textile [7]. At this stage, the following aspects can be studied to further develop interactive luminescent textiles: materials, manufacture, sensing, circuit, wearability, and intelligence [4]. The integration of multimodal sensing and flexible circuits in textiles is a new challenge for development. Meanwhile, artificial intelligence should also be used in such textiles [4].

Conductive materials play a crucial role as carriers of electronic circuits in the development of smart textiles [2]. Conductive materials are often integrated into smart textiles in the form of fibers, yarns, coatings, or fabrics to meet different performance requirements and application scenarios [8]. In addition to conventional spinning methods, the prefabricated preform-to-fiber thermal drawing technique, invented by Yoel Fink at MIT, has been utilized to produce multicomponent and multifunctional conductive fibers for constructing textile electronic devices [9]. Coating techniques provide a convenient method for endowing textiles with conductive properties. By using dip-coating, screen printing, or template printing, conductive materials can be coated onto textile substrates to achieve conductive and sensing functions [10]. For conductive fibers and yarns, traditional weaving techniques can be employed to integrate them into fabrics for connecting various electronic components. Xiaoming Tao's research group has extensive experience in designing and weaving textile flexible circuit boards (FCBs). These fabric-based FCBs have temperature-sensing networks with superior sensitivity, precision, and resolution compared to general coating composite materials [11]. Currently, smart textiles developed based on conductive materials generally possess excellent conductive and sensing performance. However, most interactive functions still rely on external electronic components for expression, lacking integrated and visualized interactive feedback. At the same time, conductive materials are usually exposed on the surface of fabrics in smart textiles so that the signal stability is susceptible to interference by many external factors such as human body resistance and grounding conditions.

Polymeric optical fibers (POFs) have been used to construct luminous clothing and various household textiles which occupy a certain market share due to their lightweight, flexibility, and ease of processing [12]. Several commercial POF fabric products have been developed by companies such as Luminex in Saluggia, Italy, XO Technology in the Concord, CA, USA, SEYANG in Seoul, Republic of Korea, and Shenzhen Fashion Luminous Technology (Shenzhen, China), and Fujian Deliang Jacquard Weaving (Fuzhou, China) [13]. In academic research, Bin Yang's team at Zhejiang Sci-Tech University mainly focuses on the structure and patterns of POF fabrics, developing POF fabrics with patterned color-changing effects [6,14]. Amy Chen's team at The Hong Kong Polytechnic University primarily conducts research on the interactivity and functionality of POF fabrics [12]. However, most existing POF fabric products on the market have a single luminescent mode and limited functionality. Even POF fabrics in academic research may have limited luminescence in bright environments.

Based on the above research, this paper proposes a design scheme for a pressure-sensing POF fabric with non-direct-contact conductive system to address the shortcomings of relatively low integration level, poor signal stability, and limited luminescent modes in current intelligent interactive luminescent textiles. The design scheme mainly consists of two parts: fabric and circuit design. In fabric design, conductive materials are integrated into the POF fabric through double-layer weave and fabric patch process, allowing the intelligent interactive luminescent textile to have the pressure sensitivity and signal stability. Laser engraving is employed to create luminous patterns that remain highly visible in bright environments. Sensing and luminescent properties of the POF fabric will be verified in this study. In circuit design, the electrical signals from the fabric can be converted into digital signals for judgment by electrical signal conversion modules, PCB design, and software development, thereby controlling the luminescence of the light source.

2. Materials and Methods

2.1. Material Selection

In the design of integrated pressure-sensing POF fabrics, both good conductivity and luminescent effects need to be considered simultaneously. For the conductive materials, silver-plated nylon sewing threads (referred to as “conductive yarns”) and copper–nickel-plated polyester plain woven fabric patches (referred to as “conductive fabric patches”) are chosen. Silver, copper, nickel, and other metals have excellent conductivity, while nylon and polyester have higher strength, ensuring the fabric’s weaving, processing, and subsequent use. POFs have certain requirements for the diameter and hardness when constructing fabrics. Generally, POFs with a diameter of about 0.25 mm are selected. These POFs are fine and soft, and are suitable for weaving flexible luminescent fabrics. POFs and regular yarns can be woven into luminescent fabrics by using techniques such as weaving, knitting, and embroidery [6]. When using traditional weaving techniques, POFs are generally inserted as weft yarns into the fabric, while warp yarns often use high-strength yarns such as polyester sewing threads to withstand the high tension during the weaving process [14]. The detailed information and specifications of the mentioned materials are shown in Table 1.

Table 1. Material specifications.

Material	Placement	Content	Color	Specifications	Manufacturer ¹
Conductive yarn	Face weft	Silver-plated nylon fiber	Silver grey	Diameter: 260 D; Resistance: $3.0 \pm 0.3 \Omega/\text{cm}$	Dongguan Shengxin Special Rope Co., Ltd., Dongguan, China
Conductive fabric patch ²	Sensing area	Copper–nickel-plated polyester plain fabric	Silver	Thickness: $0.02 \pm 0.005 \text{ mm}$; Surface Resistance: $\leq 0.05 \Omega$	Qingdao THINGER Textile Co., Ltd., Qingdao, China
Polymeric optical fiber (POF)	Face and back weft	Core PMMA, skin fluorine resin	Transparent	Diameter: 0.25 mm	Hubei Senwo PHOTOELECTRIC Technology Co., Ltd., Yichang, China
Sewing thread	Warp	Polyester fiber	White	Diameter: 40 S/2	Qingdao Liuqing Thread Industry Co., Ltd., Qingdao, China

¹ All manufacturers are from China. All material characteristics are provided by the manufacturer. ² The conductive fabric is not sticky. It is given stickiness with double-sided tape during fabrication.

2.2. Process Design

2.2.1. Fabrication Method

In fabric weaves, the interchanging double weave is employed for electronic integration in POF fabrics. Both the face and back layers are plain weave. The fabric’s looming drafting is shown in Figure 1, where 1 and 2 represent the face warp and weft, and I and II represent the back warp and weft. The configuration of warp and weft yarns can be seen in Table 1. To ensure the luminescent effect and aesthetics of the fabric surface, POFs are used for all face weft yarns. The conductive yarn is only present as weft yarns in the back layer, which better protects the conductive yarn from being damaged by subsequent laser engraving processes. Similarly, to prevent damage to the conductive yarn during the interchanging of face and back layers, the fabric structure near the interchanging area does not contain conductive yarns. The back layer of the fabric has conductive areas, where the POF and conductive yarn are arranged in an alternating pattern in a ratio of 1:1. This arrangement effectively prevents the contact between the conductive yarn in the back layer, which may cause a short circuit.

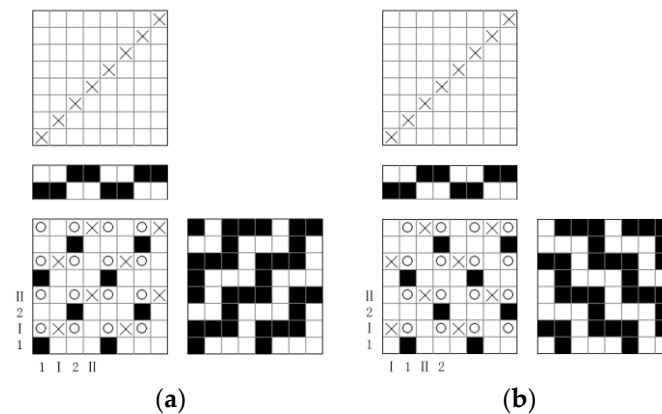


Figure 1. Looming drafting of the interchanging double weave (1 and 2 represent the face warp and weft and I and II represent the back warp and weft, marked boxes in the weave diagram represent warp floating-point and blank boxes represent weft floating-point): (a) Pre-interchange; (b) post-interchange.

Based on the aforementioned fabric weave design, a sampling process was conducted on the SGA598 Semi-Auto Sampling Loom (Jiangyin Tongyuan Textile Machinery Co., Ltd., Jiangyin, China). During the weaving process, attention was paid to reserving extra length at both ends of the weft yarns (POFs) to facilitate bundling and coupling with light sources (Figure 2c) after the fabric is removed from the loom. Similarly, extra length was also reserved for the conductive yarn at both ends for future connection to the circuit module. After the fabric is removed from the loom, the structure of the fabric's face and back layers is shown in Figure 2a,b. The warp density of both the face and back layers is 96 ends/10 cm, and the weft density is 256 ends/10 cm. The fabric has a width of 24 cm and a length of 20 cm, with an interchange interval of 5 cm. Due to the inherent rigidity and brittleness of POFs, the fabric sample that integrates POFs as weft yarns is stiffer than ordinary fabrics and has limited shear resistance in the weft direction. At the same time, excessive wear of the conductive yarn should be avoided during use in order to ensure the conductivity of the fabric's back layer.

Two conductive fabric patches with the dimension of 1.2 cm × 3.8 cm are placed between the face and back layers of the fabric, tightly adhered to the back of the "sensing area" (Figure 2a) of the face layer. Figure 2d shows the electrical schematic in the fabric sample. The conductive yarn has a resistance of about 3.0 Ω/cm, so the conductive yarn interwoven into the fabric's back layer can be equated to four constant-value resistors R in series. The two conductive fabric patches tightly adhered to the back of the sensing area can be equated to switches K_1 , K_2 due to their very small surface resistance ($\leq 0.05 \Omega$).

The structural design of the fabric's sensing area is shown in Figure 3. These two sensing areas are essential for touch interaction on the fabric. When the user presses the sensing area on the fabric's surface, it causes the conductive fabric patches on the backside to come into contact with the conductive yarn in the back layer, resulting in a significant change in the resistance value of the conductive region (Figure 3c). In conjunction with Figure 2d, the user pressing the sensing area is equivalent to closing the switch K_1 or K_2 , causing a portion of the conductive yarn's resistance to be shorted, which ultimately affects the resistance value of the conductive region.

In this way, users do not directly touch the conductive yarn, effectively avoiding interference from human body resistance and grounding conditions on the electrical signal changes during the interaction process. To prevent the conductive fabric patches from making contact with the conductive yarn before interaction, an insulated flexible support material can be added between the face and back layers (Figure 3b).

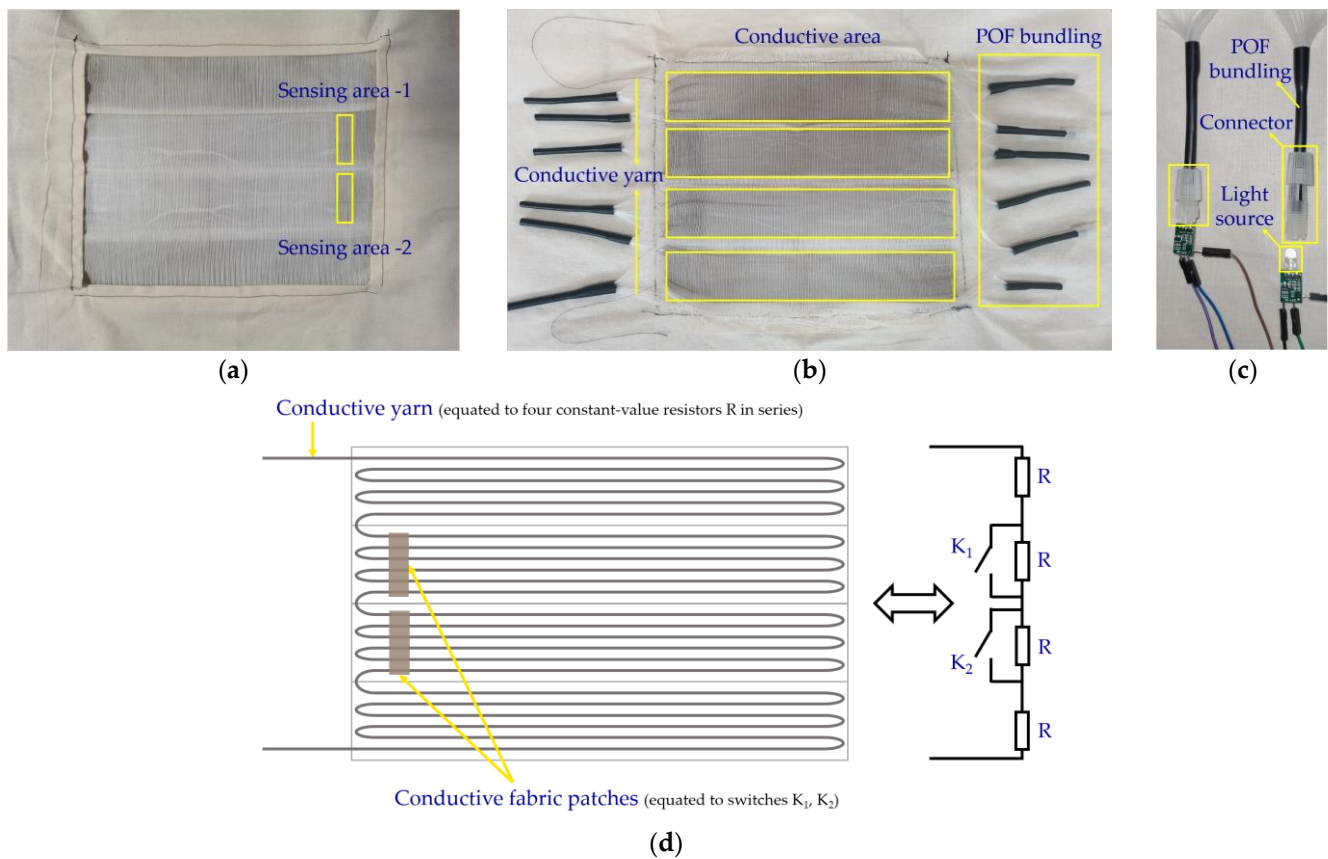


Figure 2. Sample of the double-layer POF fabric: (a) Face layer; (b) back layer; (c) light source coupling; (d) electrical schematic.

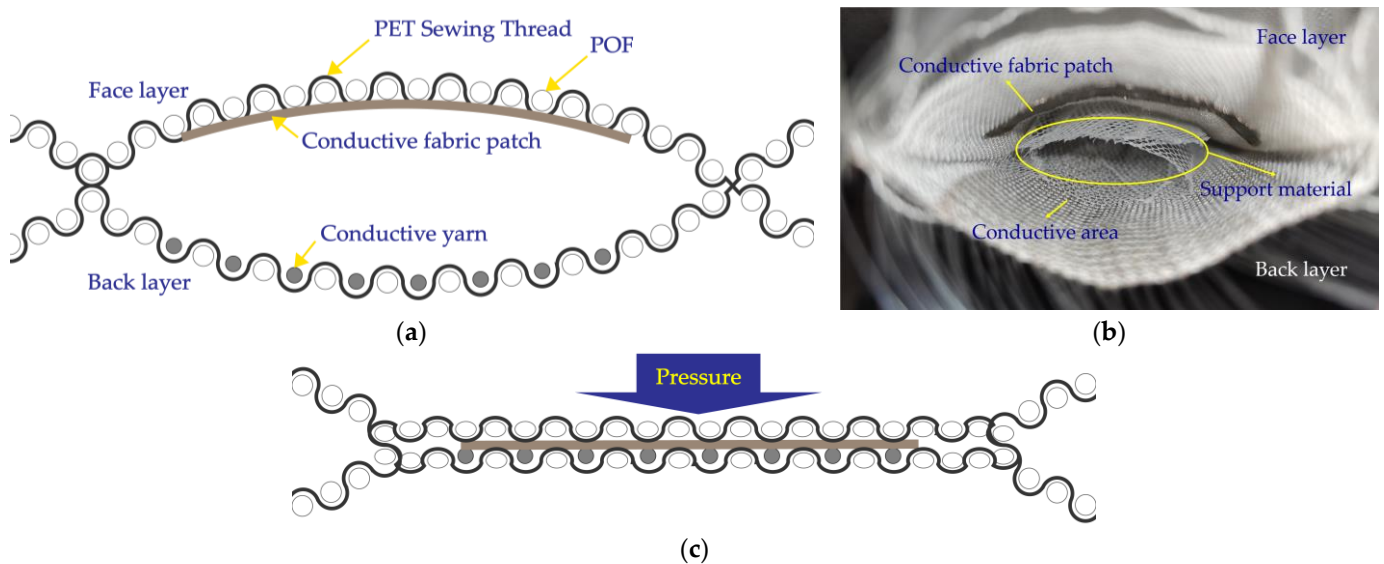


Figure 3. Structural design of the fabric's sensing area: (a) Schematic (before pressing); (b) POF fabric sample; (c) schematic (after pressing).

2.2.2. Laser Engraving

In this paper, fabrics are woven with fine and soft POFs which usually have an end-glowing effect, but not a side-glowing effect. At present, the commonly used methods to improve the POF's side-glowing effect are destroying the POF's core-skin structure and bending the POF. The principle of both methods is to destroy the total reflection of light

in the POF, so that the light is well scattered from the side of the POF, to improve the side-glowing effect of the POF [15].

Currently, laser engraving technology has been widely applied in the textile industry [16]. Based on the structural characteristics of POFs, laser engraving can be applied to the surface of POF fabrics to enhance the side-glowing effect of POFs and create bright luminescent patterns on the fabric by destroying the core–skin structure [17]. In order to achieve better interactivity of this smart textile, combined with the aforementioned fabricating process, the patterns and positions for laser engraving are designed.

As shown in Figure 4a, a “sun” pattern with a size of 5 cm × 5 cm is laser-engraved on the sensing area-1 of the fabric, and a “mountain peak” pattern with a size of 12 cm × 6 cm is laser engraved in the middle area of the fabric. Because the laser engraving of the sun pattern is on the press-sensitive area of the fabric, the electrical control function is given to the “sun” pattern. Through the subsequent circuit module design, this pattern design could help the fabric achieve the interactive effect of pressing the “sun” pattern to control the luminescent color of the “mountain peak” pattern.

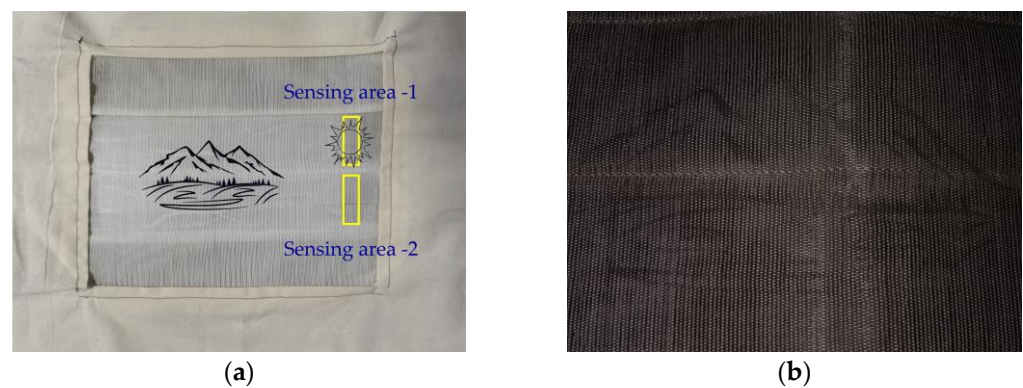


Figure 4. Laser engraving on the fabric surface: (a) Pattern design; (b) after laser engraving effect (unlit).

This pattern design scheme was implemented on the Feihong Laser Inkless Printing Equipment of Suzhou BeaM Optoelectronics Technology Co., Ltd., Suzhou, China. The equipment uses a CO₂ laser and is based on the flying marking technology to perform high-speed laser marking on the surface of POF fabrics. The optimal power for laser engraving is 30 W, the laser wavelength is 9.3 μm, the engraving speed is 2000 mm/s, and the filling density is 0.2 mm. Figure 4b shows the effect after laser engraving on the POF fabric surface with the “mountain peak” pattern.

2.3. Circuit Design

2.3.1. Design Ideas

In order to achieve the pressure-sensing and luminescent interactive function of the POF fabric, the circuit module needs to convert the resistance value changes in the fabric caused by pressuring the surface into different colors of the LED light source coupled with POFs. The circuit module required for interactive luminescent fabric is shown in Figure 5, including signal conditioning circuit and light control circuit. In signal conditioning circuits, the resistance signal R_X from the fabric’s conductive yarns is input to the signal conversion module, which converts R_X into a voltage signal U_0 and outputs U_0 to the STM32 microcontroller (STMicroelectronics Investment Co., Ltd., Shanghai, China). In the microcontroller, U_0 is further converted into a standard digital signal $VOLTAGE_AO$. In the light control circuit, the STM32 microcontroller determines the value of $VOLTAGE_AO$ and outputs a corresponding pulse width modulation (PWM) pulse signal to the WS2812B module (Shenzhen Magic Lamp Technology Co., Ltd., Shenzhen, China). This module then outputs an RGB-LED light signal, ultimately controlling the color of the POF fabric’s

light source. The design of the circuit part mainly includes the signal conversion module, printed circuit board (PCB) design, and software development.

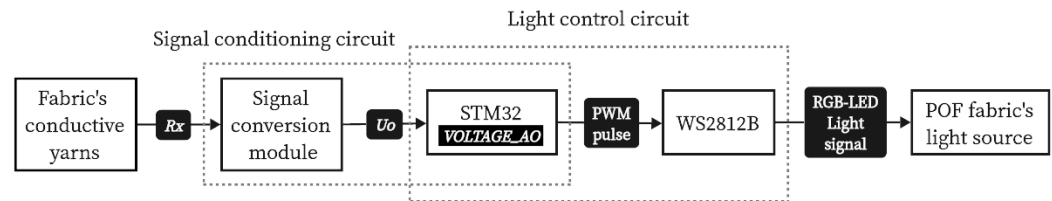


Figure 5. Fabric's circuit module.

2.3.2. Electrical Signal Conversion Module

The conductive yarn interwoven in the back layer of the fabric acts as a dual-port variable resistor. By pressing the sensing area on the fabric's surface, the resistance value of the conductive yarn can be significantly changed. However, the resistance value cannot be directly input into the printed circuit board (PCB). Therefore, an electrical signal conversion module is needed to convert the varying resistance value into a measurable voltage signal that can be processed.

The most common method currently used is the resistive voltage divider. However, resistive voltage dividers have drawbacks such as poor linearity and compatibility issues with different sensor models. On the other hand, an electrical signal conversion module based on operational amplifiers offers high linearity in signal output. It also provides adjustable amplification and high measurement accuracy, making it suitable for various fabric sensors. The structure of the operational amplifier-based electrical signal conversion module is simple and plug-and-play, as shown in Figure 6. It outputs a voltage signal ranging from 0 to 3.3 V, making it compatible with both 5 V and 3.3 V control systems.

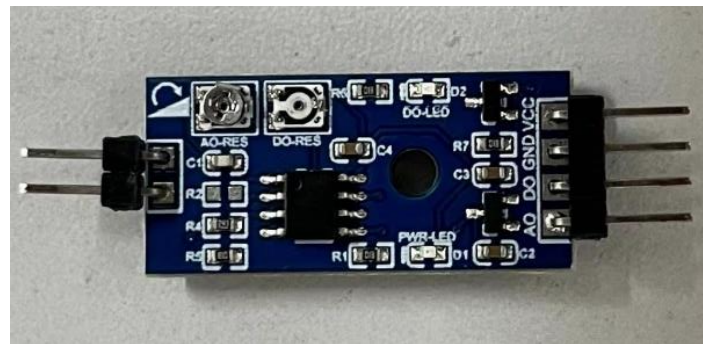


Figure 6. Operational amplifier-based electrical signal conversion module.

Its electrical signal conversion calculation curve is given by Equation (1):

$$U_0 = \left(1 + R_{AO-RES} \times \frac{1}{R_X} \right) \times 0.1, \quad (1)$$

where U_0 is the output voltage value of the module, R_{AO-RES} is the feedback resistance value, and R_X is the output resistance value of the fabric conductive part.

2.3.3. PCB Design and Software Development

Through PCB design and integrated electronic components, we can develop module circuits that are more suitable for use in fabrics. The hardware electronic circuit typically consists of several components, including a system power supply, voltage-stabilizing circuit, reset circuit, USB interface circuit, SWD debugging circuit, download circuit, sensor system circuit, microcontroller circuit, and WS2812B driver circuit. The PCB design may resemble the one shown in Figure 7, with the microcontroller model used in the circuit

being STM32. It is programmed in C language for control and is characterized by its compact size, allowing it to control the entire circuit board.

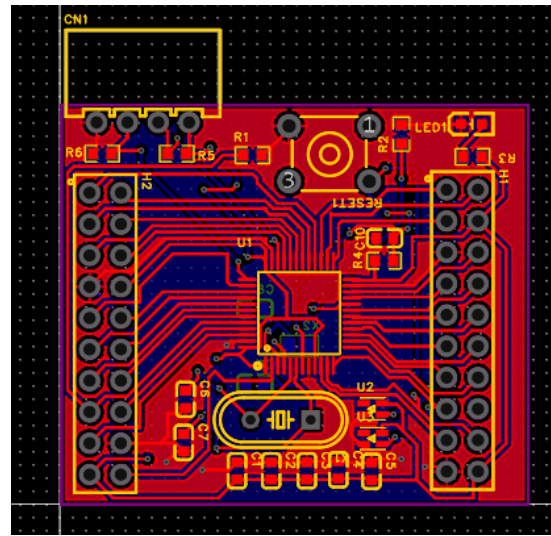


Figure 7. Printed circuit board (PCB) design.

The software control logic is shown in Figure 8. After the microcontroller is powered on, it performs initialization operations. The ADC peripheral detects changes in external signals and converts the voltage signal output by the electrical signal conversion module into a digital signal using the following formula:

$$VOLTAGE_AO = 4096 \times \frac{U_0}{3.3}, \quad (2)$$

where $VOLTAGE_AO$ is the digital signal value and U_0 is the output voltage value of the module. Subsequently, the microcontroller performs a judgment program on the digital signal value and delivers the judgment result to the WS2812B module through PWM pulses. The RGB-LED connected to this module expresses the digital signal value. In this study, the PWM pulses are encoded into data frames using a bipolar zero code, as shown in Table 2. The WS2812B module can extract the required 24-bit data for light emission from each data frame, and the connected RGB-LED expresses the data in red, green, and blue color values.

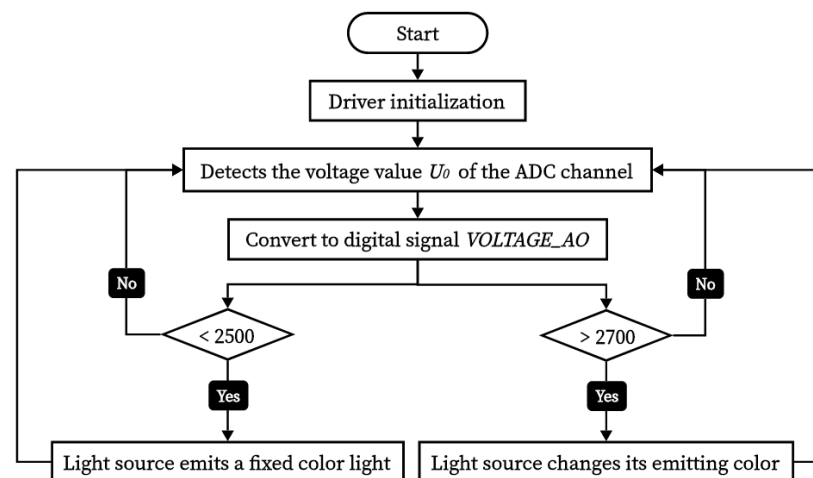


Figure 8. Software control logic diagram.

Table 2. Control data for different light colors.

24-Bit Data		0~7	8~15	16~23
Portion		Red	Green	Blue
LED	Red	11111111	00000000	00000000
	Green	00000000	11111111	00000000
	Blue	00000000	00000000	11111111

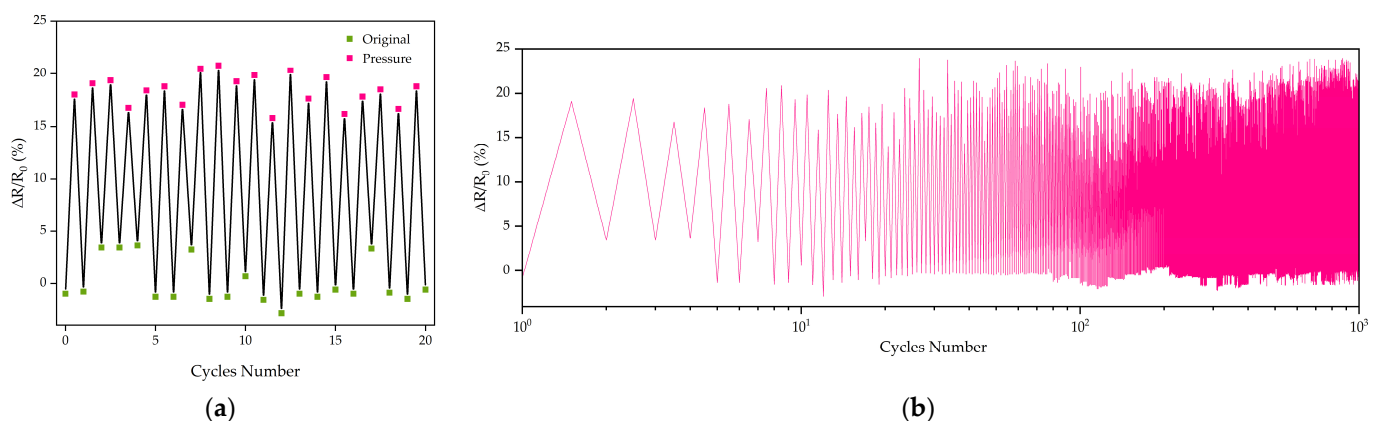
As shown in Figure 8, when the fabric sensing area is not pressed, the fabric's resistance remains unchanged. When the digital signal value $VOLTAGE_AO < 2500$, the LED light source emits a fixed color light. When the fabric sensing area is pressed, the fabric resistance decreases. When the digital signal value $VOLTAGE_AO > 2700$, the LED light source changes its emitting color. If the fabric is pressed for more than 2 s, the LED light source alternately emits different colored lights. When the fabric sensing area is no longer pressed, the digital signal value $VOLTAGE_AO$ will return, and the LED light source will emit a fixed color light again.

3. Results and Discussion

3.1. Experimental Verification

3.1.1. Sensing Properties

To verify sensing properties in the fabric, the main approach is to measure the resistance value of the fabric's conductive part when the sensing area on the fabric surface is pressed. The VC890D multimeter (Shenzhen Yisheng Victory Technology Co., Ltd., Shenzhen, China) was set to the resistance measurement mode (range: 20 k Ω), with the red and black probes connected to the ends of the conductive yarn shown in Figure 2b. At this point, the resistance value of the conductive part of the fabric was measured to be 10.48 k Ω . When the sensing area-1 shown in Figure 2a was pressed with a finger, the resistance value was measured to be 8.51 k Ω . After removing the finger from the fabric, the resistance value returned to 10.46 k Ω . This process was repeated 1000 times, and the resistance value measurement results of the fabric's conductive part are shown in Figure 9.

**Figure 9.** Fabric's sensing area pressing response: (a) 20 cycles; (b) 1000 cycles.

The experimental results indicate that through the fabricating process mentioned above, pressing the sensing area on the fabric surface significantly reduces the resistance value of the conductive part of the fabric. Moreover, this electrical signal change demonstrates stability and repeatability, providing a foundation for the subsequent design of circuit modules.

3.1.2. Luminescent Properties

Laser engraving is applied on the fabric surface to achieve intricate pattern design. Based on the light-transmitting characteristics of POFs, these patterns could present a

bright luminescent effect when the fabric is connected to the light source. The brightness values of this POF fabric sample after coupling with light sources were measured below to show its luminescent effect across the surface.

The TES-137 Luminance Meter (Taishi Electronics Industry Co., Ltd., Taipei, China) can be used to measure brightness values of the luminescent fabric's surface. The fabric is placed flat in a dark room and connected to a light source. The luminance meter's photo detector captures real-time brightness values of the fabric's luminescence. The multiple-point sampling method is employed during the process to ensure the feasibility of the final results.

The measurement involved sampling multiple points in the intricate patterned area (laser-engraved) and the other area (non-engraved) of the fabric. The box plot of luminescence values for each area is shown in Figure 10. The luminescence value of the intricate patterned area is significantly higher than the other area. The average values of luminescence in the intricate patterned area and the other area are about 62.06 and 21.21 cd/m^2 , respectively. The measurement results provide evidence for the bright luminescent effect of the intricate pattern in this study.

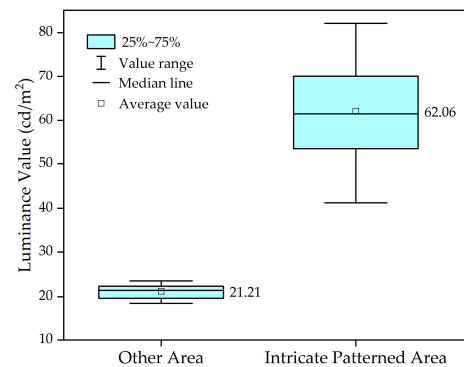


Figure 10. Measurement results of the luminescence value in different areas.

3.2. Interactive Luminescent Effect

The conductive yarn, intertwined within the fabric's back layer, is connected to the electrical signal conversion module at both ends. The POF in the fabric is coupled with the LED light source in the circuit module. When the power is turned on, lightly pressing the sensing area on the fabric surface can change the luminescent color of the POF fabric. By long-pressing, the luminescent color can continue to change. Figure 11 illustrates the process of changing the luminescent color from red to green when the fabric surface is pressed. Video S1 demonstrates the dynamic interactive luminescent effect.

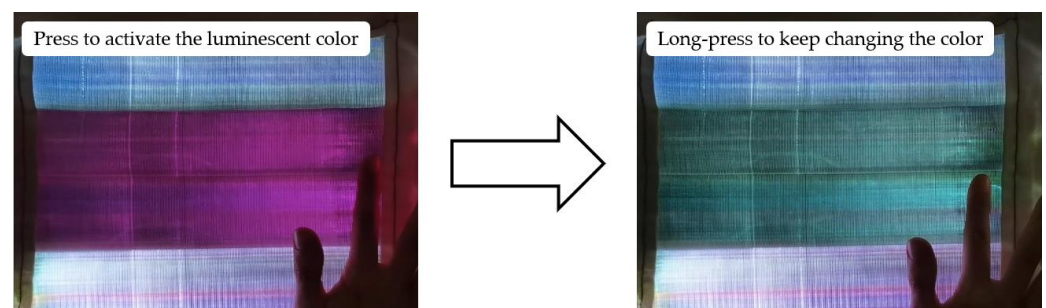


Figure 11. Interactive luminescent effect.

Combined with laser-engraving technology, patterned luminescent effects can be achieved on the fabric surface. As shown in Figure 12, the laser-engraved "sun" and "mountain" pattern on the POF fabric surface emit bright light. Additionally, fabric interaction effects will be achieved by pressing the "sun" pattern, which is also the sensing area, as a button to control the luminescent color of the "mountain" pattern.



Figure 12. Patterned luminescent effect.

3.3. Application in Intelligent Cockpits

In recent years, automobiles have been gradually transforming into intelligent terminals, and the concept of “intelligent cockpits” has been proposed. The user’s “emotional experience” has also been given increasing importance by car manufacturers. From the perspective of textiles, interior components undoubtedly serve as excellent carriers for human–machine interaction. With the innovative development in the automotive industry, interior lighting has been endowed with important functions for human–machine interaction. It can provide users with a pleasant driving experience through adjustments in color, brightness, and the application of rhythmic patterns. It can also enhance the user’s sense of involvement and belonging through customization, emotional linkage, and intelligent interaction.

Therefore, this developed pressure-sensing POF fabric holds great potential in the field of intelligent cockpits. Users can directly control the luminescent component or interact with other interior components by touching such POF fabric components, thus achieving more diverse interaction modes. Figure 13 simulates the effect of applying the luminescent POF fabric in automotive interior components.

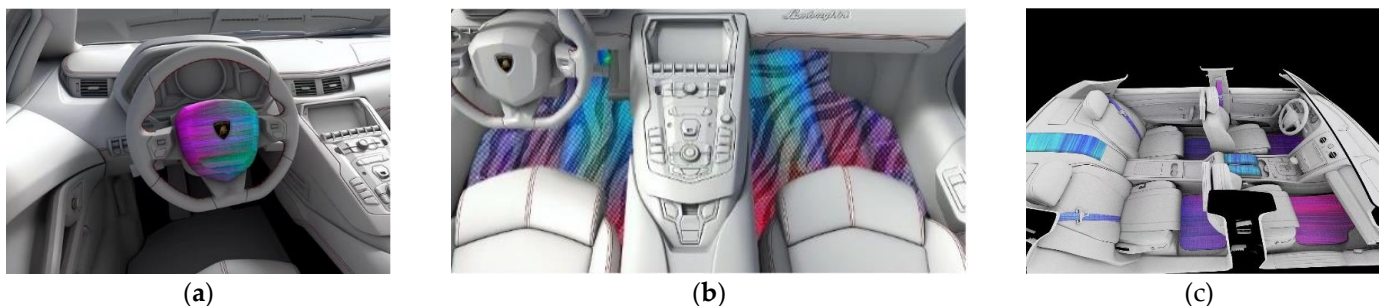


Figure 13. Simulation effect of luminescent interior components in automobile: (a) Steering wheel; (b) footrest; (c) combination.

4. Conclusions

This paper presents a fabrication method based on layered weave structure for a pressure-sensing POF fabric with a non-direct-contact conductive system. The POF fabric sample designed with this method ensures the controllability and stability of the fabric’s interactive process, which overcomes the limitation of low integration level and poor signal stability in the existing research.

The interaction among conductive materials can cause significant changes in the fabric’s electrical signals. Through circuit module processing, this paper also achieved the effect of controlling the fabric’s luminescent color by pressing the sensing area on the fabric’s surface, thus enhancing the functionality of the POF fabric.

Additionally, this paper applied laser-engraving technology to POF fabrics, making the fabric exhibit prominently visible patterned luminescent effects, even in bright environments. In the circuit, the changes in resistance values of the fabric are processed and expressed through the luminescent color of the light source, which is displayed on the POF fabric. By integrating and debugging both fabric and circuit modules, this paper successfully developed a pressure-sensing POF fabric with obvious visual interactive effects, which can be used in the development of intelligent cockpit interiors.

There is still space for improvement of this study. Currently, the fabric's interactivity is relatively limited, and the pressure-activated color-changing effect is similar to a fabric switch. Through the exploration of fabricating processes, it is possible to construct textile-based flexible pressure sensors within the POF fabric to achieve linear pressure-sensing luminescent effects with regular and predictable patterns. Additionally, further research can be conducted on the relationship between fabric luminescent patterns, colors, brightness, rhythm, and user emotional interaction, aiming to design fabric pressure-sensing luminescent solutions for application in intelligent cockpits.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app14062284/s1>, Video S1: Dynamic interactive luminescent effect.

Author Contributions: Conceptualization and methodology: M.L. and L.G.; validation, formal analysis, and writing—original draft preparation: M.L. and K.H.; investigation and data curation: M.L. and Q.T.; writing—review and editing, and funding acquisition: L.G.; visualization and supervision: W.X. and A.D. All authors have read and agreed to the published version of the manuscript.

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