Applications and Future Developments of Flexible Organic Light-emitting Diode

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Abstract—With the rapid development of display technology, human beings have more and more stringent requirements for display products, e.g., their light weight, thinness, flexible performances, and versatility. Contemporarily, the flexible organic light-emitting diode (OLED) technology and its derived multi-layer structure tend to be wearable, light, and responsive in a short time. Although flexible OLED technology is popular, there are still many problems that needs to be addressed, e.g., new raw materials, rough flexible substrate, and low efficiency in workmanship, resulting in poor luminescence, rough and inflexible products. In this paper, a new type of flexible fiber display system is proposed by combining OLED with conductive optical fiber. This paper comprehensively introduces the mechanism, manufacturing technology and structure of this new type of flexible OLED. It covers various scopes like Internet information communication, real-time positioning, and medical assistance, etc. Despite some challenges and limitations, this product possesses a variety of advantages in terms of its convenience and flexibility, which makes the exploitation of a large range of applications probable. Therefore, it is highly expected that these promising prospects of development will stimulate the further progress in display fabrication, which helps to facilitate people’s lives in the future. These results shed light on the significance of developments of flexible OLED technology.

1. Introduction

With the progress of societies and the improvement of people’s living standards, one expects more and more high-tech display devices. Besides, it also makes the display technology develop by leaps and bounds in people’s earnest expectations. OLEDs are favored plenty of consumers owing to their advantages e.g., self-emission, low driving voltage, high response speed, high contrast, wide viewing angle, good temperature characteristics, ultra-thin, impact resistance, flexible display etc. They are regarded as the third generation display technology after cathode ray tube (CRT) display and liquid crystal display (LCD) [1], and have gradually become a research hotspot in the display field.

Flexible OLED is also called flexible display, which is a flexible display device which is made of soft materials. At present, OLED technology is divided into flexible OLED and printed OLED.
Additionally, the curved screens and folding screens used by stacked mobile phones are all made of flexible OLED as display screens, which replaces the driving circuit thin film transistor (TFT), flexible OLED and flexible OLED packaging film [2]. The flexible OLED device consists of flexible substrates, flexible electrodes, transmission references and luminescent materials. Flexible OLED possesses the advantages of light weight, thin shape, folding characteristics and usage of new energy, etc. Moreover, flexible OLED also uses an innovative display technology, which develops rapidly and has broad development prospects. Many scholars have investigated flexible OLED and done related research, since this is a hot topic in contemporary times, which will bring a lot of convenience to researchers. In the display field, OLED devices can be widely used in watches, mobile phones, televisions, computers, and many other products. Because of its independent light-emitting function, no backlight is required, making the product lighter and thinner. Additionally, each pixel works independently, which makes the OLED display more power-saving, possess higher contrast and finer image quality [3]. In the field of lighting, OLED devices are widely used in indoor decorative lamps, eye protection table lamps, vehicle lamps, medical shadowless lamps etc. However, there are still lots of conundrums that have not been solved yet, e.g., new access to raw materials, rough flexible substrate, and low process efficiency, resulting in poor luminescence, rough products, and inflexibility [4]. Therefore, it is urgent to develop a new flexible fiber display system, which can meet the gradually growing demand.

In view of the above problems, a new flexible optical fiber display system combining OLED with conductive optical fiber is investigated in this paper. Besides, its preparation process, mechanism, advantages and disadvantages as well as prospects are discussed in depth. In addition, its application fields, advantages and limitations existing so far are also explored.

2. Flexible OLED

2.1. Mechanism of OLED
OLED is driven by semiconductor materials and organic light-emitting materials in an electric field, through carrier injection and recombination technology that leads to luminescence [5-7]. The principle is that indium tin oxide (ITO) glass transparent electrodes and metal electrodes are used as the anode and cathode of the device respectively. Under a certain voltage, electrons are injected into the electron transport layer through the cathode, and holes are injected into the hole transport layer from the anode, and then migrate to the luminescent layer, respectively. Excitons are formed after meeting the excite luminescent molecules, which emit visible light after radiation. The radiation light can be observed from the ITO side, and the metal electrode film also acts as a reflector [8].

2.2. Mechanism of flexible OLED
The polymer composite fiber loaded with luminescent active materials and transparent conductive polymer gel fiber are interwoven in the weaving process to form an electroluminescent unit (as shown in Fig.1), and a new flexible display fabric is realized by effective circuit control [9]. The display fabric presents a unique overlapping structure, which is formed by interlacing luminous warps and conductive wefts. Seen from the cross-sectional direction, one of them is a conductive yarn coated with luminescent material, and the other transparent conductive fiber is overlapped with its warp and weft by weaving. After alternating voltage is applied, the polymer composite luminescent active layer on the luminescent fiber is excited by the electric field in the lap joint area, forming luminous pixels one by one. Under the excitation of the electric field, the electrode and the light-emitting layer can emit light effectively by physical bonding. This method can unify the preparation of light-emitting devices and the weaving process of fabrics, and can initially meet the resolution requirements of some practical applications [10]. By changing luminescent materials, multi-color luminescent units can be realized and colorful display fabrics can be obtained.
2.3. Manufacturing process of flexible OLED

The fabrication process of flexible fiber display system is mainly divided into three steps. They are the preparation of conductive fiber, OLED lattice and fibrotic grid [11]. The first is the preparation of conductive fiber. In order to make the display fabric adapt to the changes of the external environment, and even resist repeated friction, bending, stretching or other external forces, one needs to prepare a kind of polymer conductive fiber. The polymer conductive fiber can be selected from polyaniline, polypyrrole and other conductive polymers [12]. This kind of conductive fiber is used as the matrix of luminescent materials. The preparation method involved in the first step is melt spinning, which is a molding method using a melt spinning machine with polymer melt as raw material. The advantage of this method is that it can prepare fibers on a large scale. Fig. 2 presents schematic diagram of melt spinning principle. Using this method, even thousands of meters of fiber can be prepared.

The second part is the most critical step. We need to conduct some etching on the conductive fiber prepared in the previous step to obtain the dot matrix like pits as shown in Fig. 3. In the pits, one can fill some flexible and small OLED materials. These OLED array structures constitute the pixels of the display, which is the key to flexible display [14]. Small OLEDs combined with conductive fibers can give full play to their respective advantages and further improve the flexibility of light-emitting devices.
The third step is to interconnect the functional fiber, the OLED loaded polymer composite fiber and the transparent conductive polymer gel fiber, and form the electroluminescence unit by the weft and warp. The collocation of the two fibers form the positive and negative poles of the fiber network. The principle of fiber luminescence (illustrated in Fig. 4) is divided into four steps. Firstly, the holes and electrons injected by anode and cathode. Then, the holes and electrons transport to emission layer (EML), need to keep high conductivity, block reverse transport [15]. Subsequently, the electron meets a hole in the EML, let exciton formation. In the last step, the electron falls to a lower energy level to fill the hole emitting a photon in the process, and tries to minimize defects to prevent loss of light. The power required by fiber display system can be supplied by battery, photovoltaic or piezoelectric materials [16]. With the designed circuit combination, one obtained the required text or pattern by programming, which is a unique lapping structure of interlaced weft and warp as exhibited in Fig.5.
2.4. Flexible OLED structure
For both multi-layer and a single-layer OLED, they are composed of a base layer, an anode, an organic layer, a conductive layer, an emission layer, and cathode composition. The structure of flexible OLED devices can be roughly divided into single layer structure, double layer structure, three layer structure and multi-layer structure [7].

Single-layer structure means that only one organic semiconductor thin film is prepared between the anode and the cathode as the light-emitting layer. Although this preparation is simple and low in cost, it is inefficient and often cannot meet the application criteria. Nevertheless, the double-layer structure solves this problem.

The double-layer structure consists of two specific ways: one is to insert an anode, a hole transport layer, a luminescent layer with electron transport capability and a metal cathode, and the other is to insert an anode, a luminescent layer with hole transport capability and a metal cathode in turn [13]. This double-layer structure greatly improves the working path and makes the device operate faster.

The three-layer structure is based on the single-layer structure, and hole transport layer and electron transport layer are added. With this structure, the carrier movement rate in the device can fluctuate within the controllable range, and the device will not be damaged and the material will not be lost. The multi-layer structure is based on the three-layer structure, with further hole injection layer, hole blocking layer or electron injection layer and electron blocking layer.

Multi-layer structure can not only improve the allocation and limitation of carriers, but also accelerate the flow and injection rate of carriers. Multi-layer structure is the most effective and efficient preparation method at present, but it also has the problem of high cost and unsuitable for mass production, i.e., it has not been widely used at present.

3. Applications
The fully flexible OLED fabric display system tends to show fantastic application prospects in a wide range of scopes. In light of its nature of high flexibility and good durability, it is highly possible that it can be put into use in lots of fields e.g., the internet of things and human-computer interaction, such as intelligent communication, real-time positioning and medical assistance, etc. [17].

3.1. Communications
This system can be used for intelligent communication, which offers an alternative way of instant communication with greater convenience in terms of saving time. On this basis, one can enter some letters by means of pressing the keyboards on the display and sending the message via the Enter button [18]. Based on setting, one can also input digits on the display. The sending message could be revealed on other’s OLED fabric displays and also the mobile phones. Similarly, when a person sends a message via the phone, this message can be displayed on the clothes for people to read.
Indeed, this kind of communication which is based on OLED fabric display facilitates people’s daily lives to a huge extent. For daily travelling excluding some long journeys, with the help of the OLED fabric display system on clothes, sending messages, ringing up and even making electronic payments are feasible. Therefore, one could deservedly go out without carrying phones, which reduces the risks of losing phones. However, there are someone who have gotten used to using their mobile phones and may be reluctant to change their habits. In this situation, the flexible OLED fabric display system can also be helpful. If the phones are out of power, the display system will provide people with timely support and avoidance of some troubles.

3.2. Navigation
This system can also be used for navigation and real-time positioning. A map can be clearly shown on the clothes with the exact bearings and overview of routes, which explicitly informs people of their precise real-time positions and helps them find the destination more quickly. With the guidance of the navigation, people can accurately know where they are and which direction they should go, i.e., they are unlikely to lose their way.

Additionally, besides daily travelling, in some work scenarios such as polar scientific expeditions or geological exploration, people may visit some dangerous places like oceans or snow mountains. Some hazardous natural disasters are inevitable, e.g., hurricanes, tsunamis and avalanches. For example, if somebody gets in a mortal accident and loses his way, his real-time location information can be displayed with just a few taps on the clothing, GPS and the map navigation can guide the way by the clothing. Furthermore, the distress signal can be easily sent so he can find a relatively safe place according to the map and wait for the rescue team. This is compared to wearing a monitor on your body, which provides safer conditions and greater security for exploration, due to the smaller probability of occurrence of accidents.

3.3. Medical assistance
Moreover, this system can be used in medical assistance as well. Because flexible OLEDs are used for luminescent light, the product will have similar properties compared with it. The colour can be displayed with high brightness and contrast with a fast, timely response [19]. By using electric currents, people are able to come into access to information about their health conditions. When the heart beats faster, there are higher waves with greater frequency displayed on the screen, and the world which expresses people’s moods changes from ‘relaxed’ to ‘anxious’. If possible, an electrocardiogram can also be shown on the screen using this technology, which could inform people of the potential existence of disease such as hypertension, risks of diseases attack and the need for treatment [20].

Besides, with the combination of more advanced apparatus, human being’s brain waves could be collected and then decoded, finally displayed on the clothes in the form of words or colors. For example, via the process which is mentioned above, the desire of this man can be shown on the screen as a sentence of ‘I need some food’. Certainly it can be much simpler, just using one word like ‘hungry’ or ‘thirsty’ to achieve exact meaning with maximum simplification. Moreover, different colors can be used in an emergency due to the fact that each colour can be endowed with a special meaning. For example, a red colour shown may represent that the person is in a dangerous situation and needs some assistance. This function helps to determine what people require in an easier way, which greatly brings convenience.

4. Advantages and limitations

4.1. Advantages

4.1.1 Multi-color light
The system can meet people’s demands by combining light-emitting devices and silk fabric. With the
use of the rational selection of dielectric polymer matrices and the semi-conductive organic material OLED, this product can release both light and colour. With the changing of the luminous material, it can create a multi-colour light fusion [21]. Flexible OLED is able to make the display brighter. Thus, with the combination of the materials, the resolution requirements of many practical applications are preliminary met, people are able to change the color according to their own preferences and get a colorful display fabric. These functions can be easily used in the aspect of decoration or in an emergency, which greatly brings convenience.

4.1.2. Fast response speed
Compared with other technologies, the use of OLED can accomplish a much higher response speed. Microsecond level can even be reached by the respond time. The faster response is able to promote greater speed of the present of light and colour, which helps to avoid long pause time. The response speed of OLED is about 1000 times faster than the LCD’s response speed [22]. Therefore, the product becomes more efficient when people are using it.

4.1.3. Soft and comfortable
Displaying by OLED helps to achieve the property of soft and comfortable when wearing the display fabric (Fig.6). Firstly, OLED is produced on flexible substrates, i.e., it can achieve soft screens and exist external friction. Due to the fact that OLED is actively emitting light, it can accomplish a wider viewing angle. This means that the objects presented will not be distorted even in a large viewing angle. The vertical and horizontal viewing angle will reach more than 170 degrees. This property of long-term flexibility and toughness enables the display clothing to bend repeatedly and it is less easy to be damaged. When the human body moves and bends muscles and joints, the wearable display will also move with the body, acting like normal clothes people wear daily. Secondly, OLED has the property of ultra-thin and lightweight, people who wear it won’t feel heavy. This enables everybody in a different age group, different height, and different situations to wear. The wearable display is portable. Therefore, it can achieve the significant property of clothing. Therefore, people can wear it without any discomfort [23].

![Fig. 6 Soft and comfortable bendable display](image)

4.1.4. Energy efficient
The use of OLED for the displayed fabric achieves sustainability of resources and energy efficiency. Due to the fact that OLED is mainly organic material and glass, it contains less toxic materials, which makes it easier for recycling. The fact that OLED does not require back-light reduces the consumption of power and fuel for energy, which then leads to lowering the emission of greenhouse gas. OLED provides design freedom in order to enhance the operating of the wearable display for the consumption of energy and greenhouse gas emission [25].
4.1.5. Wide temperature range
The system is able to work in a wide temperature range, which enables the wearable display to operate in almost any conditions. On this basis, it helps to reduce geographical restriction and the system can also be used in extremely cold regions.

4.2. Limitations

4.2.1. The challenge of packaging technology
The electronic components inside the OLED could be oxidized by contacting with air and water[26]. This would cause electronics short circuits. Therefore, flexible packaging is very important for the uses of flexible display fabrics. Now there are two primary encapsulation technologies, including cover plate packaging and Thin Film Encapsulation. Although the cover plate packaging is simple and effective, the biggest problem is that it cannot meet the needs of flexible display. Thus, the biggest advantage of OLED will not come true. The studies show that TFE provides good water and oxygen isolation for flexible OLED display[24]. However, the barrier layer of TFE is usually damaged due to large stress changes during repeated bending.

4.2.2. Complicated and costly production process
The flexible color tunable electroluminescent device composed of double-stacked emissive layers of ZnS phosphors dielectric polymer composite is developed by an all-solution processable method[26]. The conductive fiber and luminous point are arrayed respectively and interweave them into form Electroluminescent units. Integrity of multilayer structures. In the subsequent solution deposition of semiconductor, insulating and/or conductive layers, the underlying layer may be dissolved away or expanded by the solvent used to deposit the subsequent layers. If the solvent binds to the layer below, it expands, which results in a decrease in the performance of the layer[27].

4.2.3. Potential uncomfortableness
The flexible display fabrics are made from ZnS. The intrinsic stiffness of Zns might cause people to feel discomfort. Additionally, light emitting devices remain difficult to be used as wearable displays due to their low luminance and low efficiency. The first-generation OLED luminescence materials are fluorescent materials, mainly singlet exciton luminescence, because its maximum quantum efficiency is 25%, the luminescence efficiency is low, which is four times lower than the luminescence device made of phosphorescent materials. Phosphorescent materials can make use of singlet excitons and triplet excitons at the same time, and their external quantum efficiency (EQE) can reach 20%, which is higher than that of fluorescent materials[28].

4.2.4. Poor color purity and short life circle
Flexible OLED has the problem of insufficient color purity, which makes it difficult to display bright and rich colors. In the case of red, the COLOR presented by LCD can be pure red, but the same red on OLED is orange[29]. This may cause some display errors and lead to miscommunication. The organic polymer material in OLED has some defects in the life of blue light display, and will appear color difference after a long time of use. The data indicates that the average life of OLED is only 5000 hours under normal temperature and pressure, which is lower than that of LCD, which is at least 10,000 hours. Moreover, organic materials with low glass transfer temperature are susceptible to the temperature of the operating environment or the Joule Heating generated inside the OLED components.

4.2.5. The problem of Using in extreme environments
The high temperature caused screen damage, resulting in information communication barriers[30]. When the working temperature of LED display exceeds the bearing temperature of the chip, the luminous efficiency of LED display decreases rapidly, resulting in obvious light decay and damage.
LED display is mostly packaged with transparent epoxy resin. If the temperature exceeds the solid phase transition temperature (usually 125°C), the packaging material will turn into rubber and the thermal expansion coefficient will rise dramatically, leading to open circuit and failure of LED display [31].

5. Conclusion

In summary, starting from the development trend of display technology in the future, this paper introduces the flexible OLED fiber display and its working principle and development status. This functional, large-area display textile can form electroluminescence direct units with cotton yarn by weaving conductive and luminous fibers, so as to form a multifunctional integrated textile system for various applications. It is highly expected that it will soon cover varied fields, e.g., intelligent communication, real-time positioning and medical assistance, etc. With the improvement of flexible OLED and conductive fiber technology, the future display screen will be softer, lower cost and clearer. Although there are some problems remained unsolved (e.g., unwished poor luminescence and colour purity, short life span, temperature limitations etc.), flexible display is still the general trend of the development of display technology in the future. Obviously, it will occupy the most important market share of display technology in the future. In the wake of the integration of more functions, we expect these "smart textiles" to form future communication tools. These results offer a guideline for the great importance of flexible OLED based on its versatility of wide ranges of scope.

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