

Flexible displays for smart clothing: Part I—Overview

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This overview describes different technologies and developments over the past few decades that have been used in the production of textile-based flexible displays and screens. The paper covers textile displays based on optical fibres for the use in communicative clothing, fashion or medical applications; large flexible screens based on flexible ribbons and LEDs to make or to create communicative clothing; and low cost, washable 'textronics' produced by combining SMD components with textile materials for the production of light-producing multilayered OLED flexible structures. For each technology covered in the review, the examples from the commercial products or from the products under research have been considered to illustrate the concept and its potential applications.

Keywords: LED display, Optical fibre display, OLED display, Textile flexible display

1 Introduction

In this article, the concept of 'intelligent apparel' as a class of apparel that has active functions, in addition to the traditional properties of clothing, is introduced. The building blocks of intelligent apparel, such as keyboards and displays, and several existing approaches for the creation of flexible display technologies as well as applications of such textile based displays, such as technical textiles, car interior and flags, are proposed. The intelligent function of the apparel is obtained by utilizing either a specially developed textile or by integrating an electronic device into conventional textile—a combination of the two. Thus, a sweater that changes color under the effect of heat could be regarded as intelligent clothing, as could a bracelet that records the heart rate of an athlete while he/she is exercising. Accordingly, three categories for these intelligent clothing are envisaged as follows¹:

- (i) Clothing assistants that have a 'memory' to store information and carry out complex calculations
- (ii) Clothing monitors that record the performance, behaviour or the health of the person
- (iii) Regulative clothing that adjusts certain parameters, such as temperature or ventilation

All intelligent clothing can function in manual or automatic mode. In the case of manual functioning, the wearer can act on the added intelligent function, while in the automatic mode, the clothing reacts

autonomously to external environmental parameters, such as temperature, humidity and light.

Communicative clothing can be perceived either as an extension or as the next generation of intelligent clothing, where the information recorded is coded and transmitted by means of electronic components in clothing. Communication clothing also differs from 'intelligent clothing', which reacts to exterior or physiological stimuli to regulate and control the users well-being. Communication can be achieved between clothing and the person who wears it, or alternatively between clothing and the external environment and others. In both cases, 'communicative' clothing refers to any clothing or textile accessory that receives or emits information out of the structure that it is composed of. The integration of portable telephones and miniature PCs are just two of many applications being studied and more are yet to be imagined. It is also important to note the distinction between 'communication clothing' and 'wearable computers', which are not incorporated into the clothing itself, but transported as objects.

In terms of usage of these intelligent and communicative clothing, the needs can be broadly classified into the following groups of people:

- Professionals^{2,3} (the need for 'hands free' functions, safety, data exchanges)
- Health care⁴ (monitoring, training, remote diagnosis)
- Everyday life⁵ (telephoning, wellness)
- Sports⁶⁻⁹ (training, performance measurement)
- Leisure (aesthetic personalization, network games)

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A study of the various technologies involved in the process of producing intelligent clothing can help to anticipate the new uses and new communication services that could be added to clothing. It is therefore advisable to have an overview of the various techniques or the building blocks used for conferring various form of intelligence on clothing. Some of these are described below. The challenges are also outlined.

Control Interfaces—positioned near the part of the body concerned (i.e. human interface) to control a device, e.g. the positioning of ear phones in a shirt collar or a hood, a microphone in a shirt collar or a keyboard applied to the sleeve of a jacket. Another emerging technology here is that of voice recognition¹⁰⁻¹³.

Sensors—used as a physical support within clothing to translate and interpret human activity, e.g. the recognition of movements of the textile, to facilitate certain commands that are intuitive, i.e. the automatic connection (or disconnection) of a phone call when one moves the collar of clothing to the ear^{14,15}; to initiate a analysis of an athlete's performance in an activity; and to conduct a patient's medical follow-up in real time.

Interfaces—used for communication of information generated by communicating systems, e.g. the integration of flexible displays, screens or loudspeakers within clothing as communication interface. Such devices will be subject to the same ergonomics and mechanical resistance criteria as those quoted by the textile they are applied to.

Data Processing—the hardware required for memory storage, computation and data processing (RAM, hard disks and processors) will certainly not evolve much in the short term unless they do so in the direction of miniaturization. However, their integration has become entirely possible, as seen in the incorporation of a micro PC into the loop of a belt.

Connectors—used to transport information and energy among the various components of the electronic system with optimal efficiency, e.g. wireless transmission, such as infrared or radiowave takes place today using various standards (IEEE 802.11, Bluetooth, etc.) and freeing communicative clothing from the need for physical connections.

Energy autonomy continues to be a major handicap of the majority of mobile electronic devices. In the case of communication apparel, it's not only autonomy but also the weight and volume of the

energy source on which a compromise must be made. Battery technologies have evolved (e.g. lithium-polymer), but unfortunately the batteries are still often the heaviest part of portable devices. The advantage of communication apparel is that the weight distribution in clothing may make it possible to be partly free from this constraint.

This article shall focus on the development of flexible textile-based displays that are fully compatible with clothing for casual or professional use. Several approaches have been proposed dealing with flexible displays and screen development over the past decade with the objective of obtaining sufficiently bright or high contrast flexible displays in order to facilitate their integration into communicative clothing. Two of the approaches involving new textile materials described here are (i) using the optical fibres in textile structures and (ii) depositing SMD LEDs on flexible substrates or creating flexible OLEDs flexible structure. The original contribution of the GEMTEX laboratory with respect to optical fibre based displays integrated to fabrics is to enable (i) high contrast displays for clothing and (ii) high homogeneity for applications in medical field, and improve the connectivity (electrical and mechanical) between the electronic SMD component and the textiles.

2 Optical Fibre Displays

Optical fibres (OF) were developed primarily as a waveguide to transmit light between two ends of a fibre and typically consist of a transparent core covered by a cladding material that has a lower refractive index. Light is kept in the core by total internal reflection and can be transmitted over long distances without losses, hence their wide use in communication. They are also immune to electromagnetic fields. Due to their fine dimensions (0.125 - 2.0 mm) and their relatively good flexibility, OF can be easily shaped using textile processes (mainly by weaving). Therefore, the idea to create textile-based illuminated surfaces has naturally evolved. For applications related to lighting (backlight, display...), OF can be lit, not only at its ends, but at particular selected locations along the fibre as well. For the purpose, the cladding must be treated to allow light to leak on the side of the fibre. The treatment/damaging of the fibre can be done by mechanical (toothed roll, abrasion, sandblasting), chemical (solvent) or thermal (plasma, laser) treatments¹⁶.

The first mention of OF, included in textiles by weaving, appeared in the 70s-80s. Daniel *et al.*¹⁷

described a plain weave fabric made of OF, together with another textile fibre. The light traveling through the OF is emitted through scratches by mechanical indentations (toothed roll), that pierce the fibre. In the late 90s and early 21st century, mechanical indentation of textile based OF started making use of other processes. In particular, the projection of particles¹⁸⁻²⁰ or chemical treatment²⁰ (solvent action) on the cladding to form the indentations in the fibre, have been developed. These kinds of indentations have become commonly used because of the use of POF (PMMA) as an alternative to glass fibre. Glass OF are harder, not sensitive to solvent and do not lend themselves to weaving. The advantage these treatments (projection of sand and solvent action) have over mechanical indentation (by toothed roll) is that they can be selective. Therefore, it is possible to create light patterns and thus pixels. POF included in textile structure can also be treated by plasma to introduce defects on its surface²¹.

The OF can also emit light without indentation of the surface fibre or cladding. Parker²² described a light emitting panel made from one or more layers of POF woven into a sheet (plain weave) and then coated with diffusive material. In this case, the bends of the woven OF allow light emission. This plain weave of POF, encapsulated into two rigid sheets, is provided by the Lumitex Company. Current studies undertaken by INSERM (French National Institute of Health and Medical Research) and ENSAIT show that a specific pattern based on a satin weave allows the production of a homogeneous (i.e. more homogenous than LED panel) light emitting fabric. In this case, the fabric remains soft (not encapsulated in a rigid sheet) and not polluted by solvents or sand. Moreover, the homogeneous distribution of light provides the possible medical application in the field of photodynamic therapy (PDT)²³. PDT is a treatment that uses photosensitizing agents, along with light, to eradicate premalignant and early-stage cancer cells. For this purpose, the nature and the wavelength of the light source are very important parameters. In the close future, it will be possible to develop a large textile light diffuser to be used as part of a clothing, to treat skin lesion or disease.

The weaving of optical fibres can sometimes be problematic due to their rigidity (POF breaks a lot during weaving). Depending on the number or density of POF, the final textile based POF may be rigid in form and structure. Some laboratories are working on

the concept of highly flexible OF, based on silicones²⁴. This method allows production, in the lab, of shorter fibre lengths with larger diameters. However, these fibres usually contain a high proportion of air bubbles and do not have a suitable optical transparency. Currently, this kind of OF are mainly used as sensors in the field of smart clothing²⁵.

Applications of rigid panels based on POF (Lumitex) are in the area of backlight LCDs, lighting or communicative clothing. The POF panel represents a visual medium which can be used for security, exchange of information, publicity, lighting up and showcasing particular items, communicative clothing, and car interiors. In May 2002, France Telecom R&D designed a prototype for a flexible display made of woven optical fibers capable of displaying static or animated graphics such as logos or texts^{19,20} (Fig. 1a). Independent pixels may be formed and therefore can be turned on and off to create a changeable image (Fig. 1b). With this innovation, clothes became a graphical communication interface.

Many of the current applications for illuminated POF fabric are concerned with fashion and design. Lumitex has already manufactured and displayed several decorative and functional items, such as table

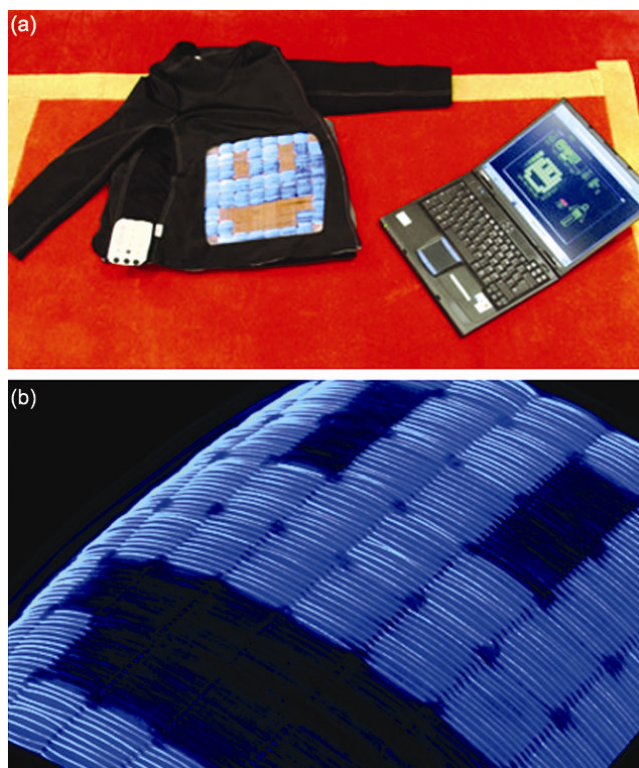


Fig. 1—France Telecom R&D prototype of communicative flexible display based on optical fibre¹⁹



Fig. 2—Illuminated bag from Luminex

cloths, cushions, umbrellas, shirts and bags (Fig. 2). However, these products are not able to broadcast messages or animation unlike France Telecom R&D prototype. Visually, the effect is purely aesthetic, that of a "starry sky". Additionally, the uniformity of the lighting is not a priority, as it is for the medical applications (PDT) discussed above.

Optical Fibre display technologies require a strong source of light. Traditionally, these sources have been bulky, heavy and electrically inefficient. The miniaturization of LED type sources solves this problem in part, as LEDs consume less energy and their electrical efficiency is higher, thus keeping the costs low. The next generation of OF display will perhaps use laser diodes as the light source. These sources are still expensive but have an even better performance than LEDs. To compare, incandescent bulbs have an electrical efficiency of nearly 5 %, LEDs ~ 17-20 %, and laser diodes up to 40 % (depending of the wavelength, temperature, etc). But the interesting thing is that OF display technology is independent of the light source of the display. The display will work whatever the light source (LED, Laser, etc), power (be careful with temperature as it could alter the PMMA OF) and color (except absorption by the material at some wavelengths). OF displays are therefore versatile technologies.

3 LED and Electro-luminescent based Display

3.1 Assembling Electronic Textile

Light-emitting diodes (LED) are low in cost, small in size and are available in an array of different

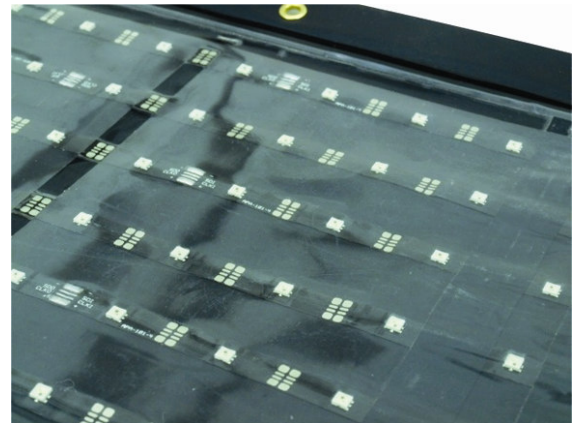


Fig. 3—Close view to flexible LED display²⁷

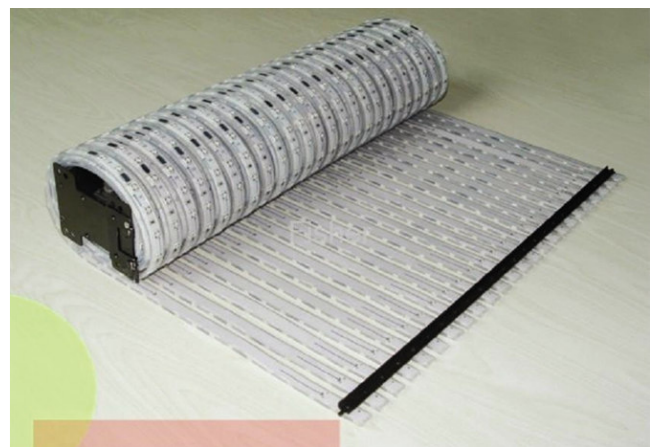


Fig. 4—Ribbon connector for LED

colors. This makes it possible for such electronic components to be used to make textile-based flexible displays with the ability to display animated graphics or pictures.

In the first prototype, each LED was glued (or fixed) on a flexible substrate (textile) and electrically connected to an electronic device which is able to index each LED and adjust its brightness and picture (animated or not). Much time was required to achieve this prototype as each LED was hand connected separately (Fig. 3). The spatial resolution was also not very good because large LEDs were used²⁷.

More recently, a company has developed flexible connectors such as ribbon cable (Fig. 4) for connecting electronic card on which LEDs can be fixed in 3 colors. The company sells this kind of specially designed product for large displays^{26,27}. The maximum pixel density of the display is 2500 /m² (20 mm pitch) with a power consumption of 80 W/m². The maximum resolution is 1280 × 1024 for a maximum dimension of 3.2 m × 3.2 m (pitch 100 mm). Due to the use of LED



Fig. 5—Flexible LED based display²⁷

technology, the lifetime of such products is good (~100 000 h). The number of colors used can be up to 16.7 million (Fig. 5). In such products, the quantity of textile is often very low as it is only used as a support.

The same technology is also used in Lumalive prototype fabrics²⁸, but alternatively for clothing and interior design. The standard Lumalive display panel is based on a 14 × 14 RGB LED (20 × 20 cm) mounted on a thin and flexible substrate (Fig. 6). Each pixel contains closely spaced red, green and blue LEDs. The display panel is covered with a waterproof protection cover. Layers of translucent textile covering the LEDs diffuse the light such that the adjacent pixels merge into one another. The weight of the system is around 100 g. This display can easily be introduced under a shirt for instance, without loss of comfort.

To improve the comfort and integration of an electronic component, electro-conductive glue is usually used. Epoxy-based resins filled with conductive filler offer good possibilities in terms of electrical conduction and mechanical behavior. In a previous study²⁹, textile-electronic glue was developed based on 2 epoxy resins (DER 332 and DER 732 from Dow Chemical), one cross-linking agent (aliphatic tetraethylenepentamine from Sigma Aldrich) and a conductive filler (carbon black, CB, Printex L6 From Degussa or carbon nanotube, CNT, NC7000 from Nanocyl). The glue successfully binds electronic devices onto textiles and optimises the properties of adhesion, flexibility and conduction. Demonstrations (Fig. 7) show the feasibility of the integration of a surface mounting device (SMD) component onto a conductive textile. Washing tests at

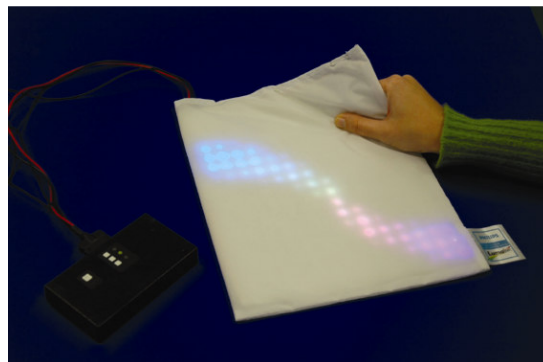


Fig. 6—Philips lumalive panel²⁸

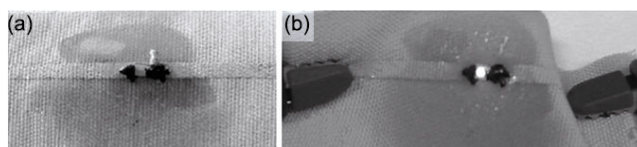


Fig. 7—LED SMC glued on the surface of a conductive textile (a) without energy input (before cleansing cycle) and (b) with energy input (after one cleansing cycle)

40°C with detergent were performed in order to prove the mechanical resistance of the conductive glue, in the case of the application of electronics components within clothing. Textile compatible conductive glue offers a lot of possibilities in terms of processability.

3.2 OLED Fibre or Textile

OLEDs are solid-state devices composed of thin films of organic molecules (Small Molecule OLED, SM-OLED or Polymer OLED, P-OLED) that create light when electricity is applied. Polymer OLEDs were invented in 1989 (ref. 30). In comparison to conventional light-emitting diodes (LED), polymer OLEDs are solvent processable and have a lower power consumption. Typically a P-OLEDs consists of the following parts: substrate (the mechanical support of the OLED), cathode (injector of electrons into the device), organic conducting polymer layer (to transport "holes" from the anode), an emissive layer (made of organic plastic molecules), and a transparent anode (to add electron 'holes' in the device). Because organic layers of an OLED are thinner, lighter and more flexible than the crystalline layers in an LED or LCD, OLEDs displays are potentially flexible.

Although OLEDs seem to be the perfect technology for flexible displays, some problems do exist in their use. The lifetimes of the emissive polymer layers are very different for different color. Green, red and blue OLED films have lifetimes of up to 200,000, 350,000 and 26,000 h respectively and

have a luminous efficiency of 50, 31 and 8 cd/A respectively³¹.

The short lifetime is linked to the fact that water can easily damage OLEDs. However, thin film encapsulation of the OLED, to protect the emissive layer has been achieved³². The use of such a thin, flexible and waterproof substrate and an encapsulating coating would allow for the successful production of flexible displays. For instance, a 6.5 inch flexible OLED (0.05 mm thin) was realized by Samsung in 2009³³ (Fig. 8). OLEDs, flexible and light, are easily integrated in/on textiles. Mechanical links can be achieved by glue, a thermo fuse layer or by ultrasonic soldering. The electrical connection can be achieved by several processes, such as embroidering³⁴, soldering and bonding.

The current research focuses on the development of textile based electro-luminescent or OLED displays or on developing OLED fibres themselves. In the first case, the classical polymer film substrate is substituted by a textile substrate. The advantage of this is that the woven substrate is more flexible and robust than the film itself. On the other hand, textile substrates are generally porous, thicker and rougher. However, porosity and roughness can be modified by coating the textile.

One of the most important technological challenges is to have a conductive, transparent and flexible layer. Presently, PET / ITO film is the most commonly used. Electro-conductive and transparent coatings could be prepared using intrinsic conductive polymers (ICP) or conductive polymer composites (CPC) based on transparent matrix (latex for instance) and transparent filler (ICP, ITO or ATO for instance)³⁵.

In the second case, the multilayer OLED structure is grown concentrically around a conductive fibre^{36,37} (Fig. 9). Manufacturing of this kind of fibre is based on bath coating of the electro-conductive core, firstly with an emissive, electro-luminescent polymer, then a transparent electro-conductive electrode and finally a protective coating. The main problems encountered in coating layer upon layer, are controlling of the thickness of each coating and sufficient adhesion between them.

As with OLED displays, the electro-luminescent light (EL) emitting textiles are also composed of a conductive substrate, an electro-luminescent compound and a conductive transparent electrode. The most commonly used electro-luminescent compound is based on ZnS doped with metal to produce different colours. EL powder dispersed in binder can be applied on textile by printing or screen printing. The main problem lies with the transparent flexible electrode.



Fig. 8—Flexible OLED display (0.05 mm) by Samsung

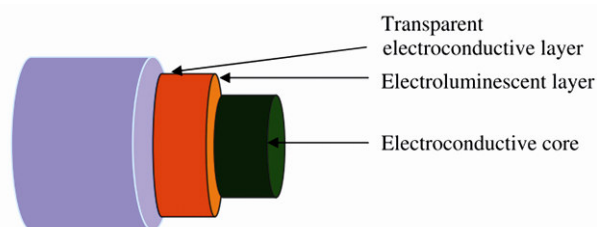


Fig. 9—Main structure of OLED multilayer fibre

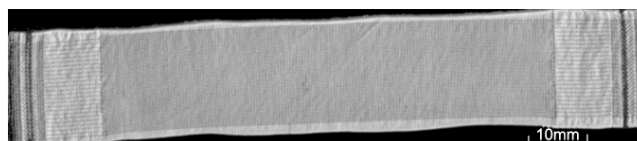


Fig. 10—Woven electro-luminescent display structure³⁸

However, EL compound being more stable to oxygen and water than OLED compound, total encapsulation is not necessary and light textile electrode can also be used. Silver coated comb structures are able to produce woven EL display structures³⁸ (Fig. 10).

4 Conclusion

This article has focused on the development of some flexible textile-based displays that are fully compatible with clothing for casual or professional use. The main objective of these projects has been to develop flexible displays with sufficiently bright or high contrast in order to display a visible message (text, icon, pattern...). Over the past decades, two different approaches have been used for developing new textile materials i.e. using the optical fibres in textile structures, and depositing SMD LEDs on flexible substrates or creating flexible OLEDs structure. Future developments will aim to produce structures that are more flexible (increased compatibility with textile behavior), more reliable towards general conditions of

use of clothing (wash ability) and less expensive. Cost reduction will result from use of alternative raw material (conductive glue, electro-conductive ink, optical fibre...) as also the use of printing technologies.

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