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Wearable photonics based on integrative polymeric photonic fibres

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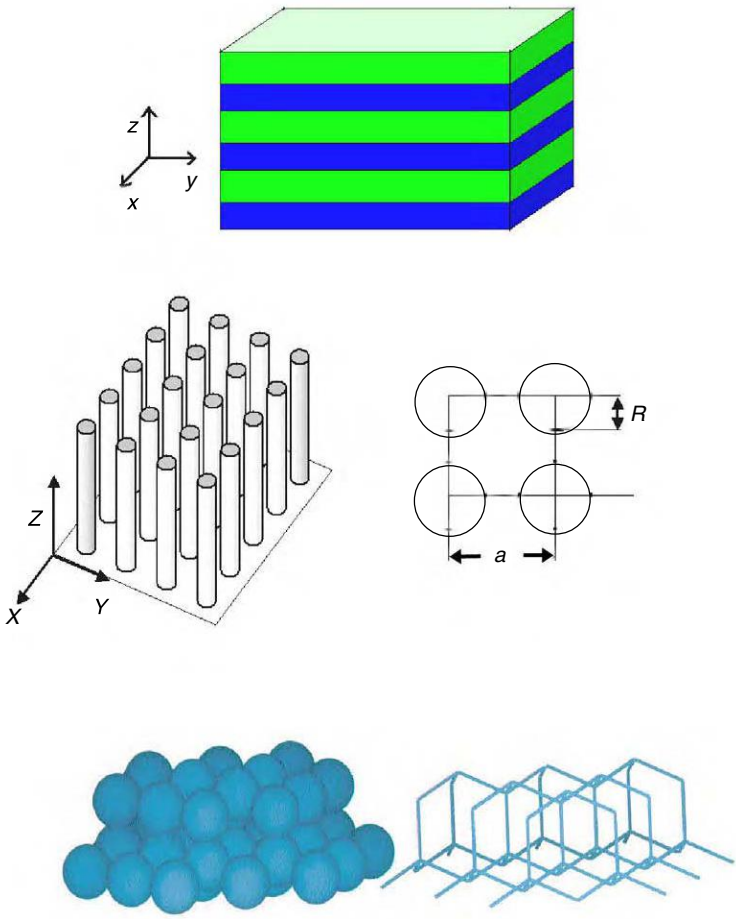
7.1 Introduction

This chapter is intended to provide a review and overview of the development of wearable photonics with integrated polymeric photonic fibre structures. Photonic fibres can be defined as fibres that generate, transmit, modulate and detect photons. These fibres may form a base for a range of sensors as well as displays of flexible fabric that are capable of controlling colour, the intensity of luminescence, scattering intensity and self-amplification. Sensing by photonic fibres has been reviewed by the present author earlier (Tao, 2002); hence this chapter will concentrate on their display applications.

The generation and modulation of light within the visible range (380–780 nm) are the cause of the colour (wavelength) and intensity of materials. The major sources of colour can be grouped into the following categories: emissive radiation, absorption, reflection, dispersion, scattering and interference. In textiles, the most widely used mechanism is the absorption of dye stuff or pigments of certain wavelengths from white light. This is a subtractive modulation process. This method of coloration does not allow colour and intensity to be controlled after the process is completed. In other words, such a method produces a lifeless colour. Because of the wet chemical processes used, there has been pressure for the method to become more environmentally friendly.

7.2 Photonic band-gap materials

Photonic band-gap (PBGs) materials or photonic crystals (PhCs) are materials with a periodic dielectric profile, which can prevent light of certain frequencies or wavelengths from propagating in one, two or any number of polarisation directions within the materials. This range of frequencies is similar to an electronic band-gap; thus, it is often called a photonic band-gap. As shown in Fig. 7.1, the PBG materials can be one (1D), two (2D) or three-dimensional (3D). The Bragg



7.1 One, two and three-dimensional photonic band-gap structures.

grating structure is the best known one-dimensional PBG. Like an electronic band-gap, the PBG is caused by a lattice or a crystal structure. The lattice scale of PBG is in the order of the wavelength of light (0.1–2 mm), rather than in the order of atoms.

The PBGs may be passive or active. The interaction of passive or active PBGs with light can be described fully by using the Maxwell equations. Various numeric schemes have been developed and used to deal with these problems. We have used a finite difference time domain analysis to study the reflection and amplification of light in passive and active PGBs.

Light interacts with and within a PBG by multiple scattering and diffraction that is similar to Bragg reflection and diffraction gratings. Defects in a PGB will strongly affect the local electromagnetic field. Hence, these PGBs have been

demonstrated to possess unique optical resonances and their properties can be tailor-made through the appropriate design of the band-gap and induced defects.

There are one, two and three-dimensional photonic band-gap structures. One-dimensional PBGs consist of alternating layers with different values of refractive index. Methods of fabrication include molecular beam epitaxy, chemical vapour deposition (CVD) technology, metallo-organic CVDs, metallo-organic vapour phase epitaxy and the holographic exposure of ultraviolet (UV) beams to photo-sensitive materials. Two-dimensional PBGs have periodicity along their two coordinate axes and homogeneity along the third. They can be fabricated through dry etching by reactive ions or wet electrochemical etching. The first method allows accurate control over the size and arrangement of holes (with nanometre precision), but has a limited maximum depth of etching. Wet electrochemical etching can obtain very deep holes and is suitable for fabricating high aspect ratio structures, but the size of the etched holes is somewhat less predictable.

Although two-dimensional PBGs provide some degree of three-dimensional control of the propagation of electromagnetic (EM) waves, truly three-dimensional PBGs are needed for full control via the effects of PBGs. Despite all the flexibility and precision of modern semiconductor processing techniques, experimental success in producing 3D PhCs is still somewhat limited. Among the methods of fabrication are: (1) colloid self-assembly; (2) the Yabonovite hole-drilling procedure using reactive ion etching; (3) etching and wafer fusion; (4) anodic aluminium oxide films; and (5) laser microfabrication.

7.3 Fibre-harvesting ambient light-reflective displays

Interference has been used by nature to produce many biological colours without the use of dyes and pigments. The wing scales of tropical Morpho butterflies form gratings that produce a brilliant blue colour by the constructive or destructive interference of light (Lippert and Gentil, 1959). The *Serica sericae beetle* and the indigo or gopher snake are other such examples. Reflection is the predominant mechanism in the colour of metals, which are a low-pass filter with a plasma frequency. Colour can also be produced by dispersion, or by the variation of the refractive index with a wavelength of incident light. All of these processes are passive, that is, they harvest and modulate ambient light.

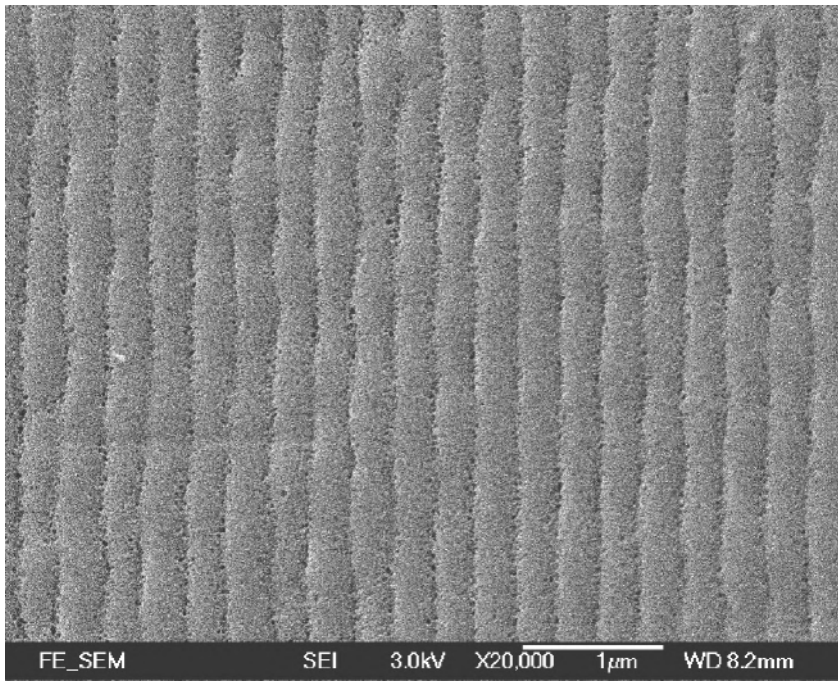
Iridescent films and fibres have been produced commercially without dyes or pigments. Multilayered iridescent film is a thin film composed of a plurality of generally parallel layers of transparent polymeric material, in which the adjacent layers are of diverse materials whose refractive index differs by at least 0.03. The individual layers of film range from about 30 to 500 nm. Distinct colour reflections are obtained with as few as 10 layers, but for maximum colour intensity, it is desirable to have 70 or even more layers (Englehard Corporation, 2001). High colour intensity is associated with a reflection band that is relatively narrow and has high reflectance at its peak.

Optical fibres have been used for transmitting light and rapid technological advances have made the modulation and amplification of light by all fibre-based devices a reality. Various permanent grating structures (one-dimensional PBGs) have been developed by the modulation of the refractive index of the photoensitive core of germanium-doped silica fibres or polymeric optical fibres. The gratings have been used for optical filters/reflectors, fibre amplifiers, fibre lasers, sensors, and so forth. In the past, the author's group has investigated various methods of fabrication and characterisation for thin films and gratings of glass and polymeric fibres. Photosensitive polymeric single-mode optical fibres have been fabricated and characterised (Yu *et al.*, 2004). The team has also developed various new hybrid fibre-grating structures. In order to guide the design and fabrication of optical fibres and gratings, theoretical tools have been developed to deal with the optical responses (transmission/reflection spectra and polarisation states) of the optical fibres under various physical perturbations.

Holographic polymer dispersed liquid crystals (HPDLC) are a relatively new class of liquid crystal composites whose periodic structures are formed by holographic exposure to laser light. Phase separation occurs in the homogeneous mixture of liquid crystals and prepolymers during the laser irradiation induced polymerisation process, resulting in polymer-rich and liquid crystal-rich domains with predetermined periods. These structures are capable of reflecting or transmitting ambient light at controlled wavelengths. They are electrically controllable, self-adjusting in terms of reflected light intensity and have a high reflectivity of 70–100% (theoretical). Operating within the range of visibility, they produce tunable colours.

The interference of counter-propagating laser beams was first used in 1998 to create permanent switchable Bragg gratings consisting of a liquid crystal/polymer mixture sandwiched between two glass substrates. Electrically switchable Bragg grating (ESBG) generally refers to a multilayered HPDLC, whose transmission and reflection can be switched by applying electric voltage. The HPDLC is a variant of the conventional polymer dispersed liquid crystals that was developed for direct view, projection-display and switchable windows. The formation of the HPDLC Bragg gratings (a periodic structure with materials of an alternating refractive index) is based on the photopolymerisation of the photosensitive prepolymer under UV or visible light interferometric exposure. Figure 7.2 shows a SEM micrograph of an electrically switchable grating of HPDLC fabricated in the author's laboratory.

Compared with self-illuminating active displays, reflective or passive displays require relatively low operating voltage and are self-adjusting in reflective intensity. Reflective displays have many advantages over conventional liquid crystal displays. A higher reflectivity of between 70 and 100% can be achieved because no polarisers are used and thus the loss can be reduced (Crawford, 2003). The Bragg grating exhibits superior colour purity with narrow reflection peaks. This makes it possible to create red, green and blue reflectors without overlap of the



7.2 SEM micrograph of an electrically switchable grating of HPDLC fabricated in the author's laboratory.

reflection spectra, and to fabricate brighter full-colour displays with an extremely broad gamut of colour (Crawford, 2003; Bowley and Crawford, 2000). The optical properties of ESBG can be controlled by the action of an electric field. For example, the reflection peak can be tuned as a function of applied voltage. The reflective efficiency and peak wavelength of the HPDLC device can vary with those of other external fields such as shear-force. The ESBG or the HPDLC can be fabricated onto flexible substrates such as fabrics and films (Tomilin, 2003). The PDLC device can be easily manufactured over large areas and can achieve a fast rise time (~ 0.06 ms) and a high contrast ratio (~ 70:1) (for ferroelectric PDLC). The elimination of the backlight source may reduce power consumption and can make displays lighter and thinner.

7.4 Opto-amplification in active disordered media and photonic band-gap structures

One problem with current flexible displays based on side-emitting optic fibres is weak luminescence caused by the strong attenuation of light along the length of the fibres. Amplification along the length of the fibre is very desirable. One option is via opto-amplification.

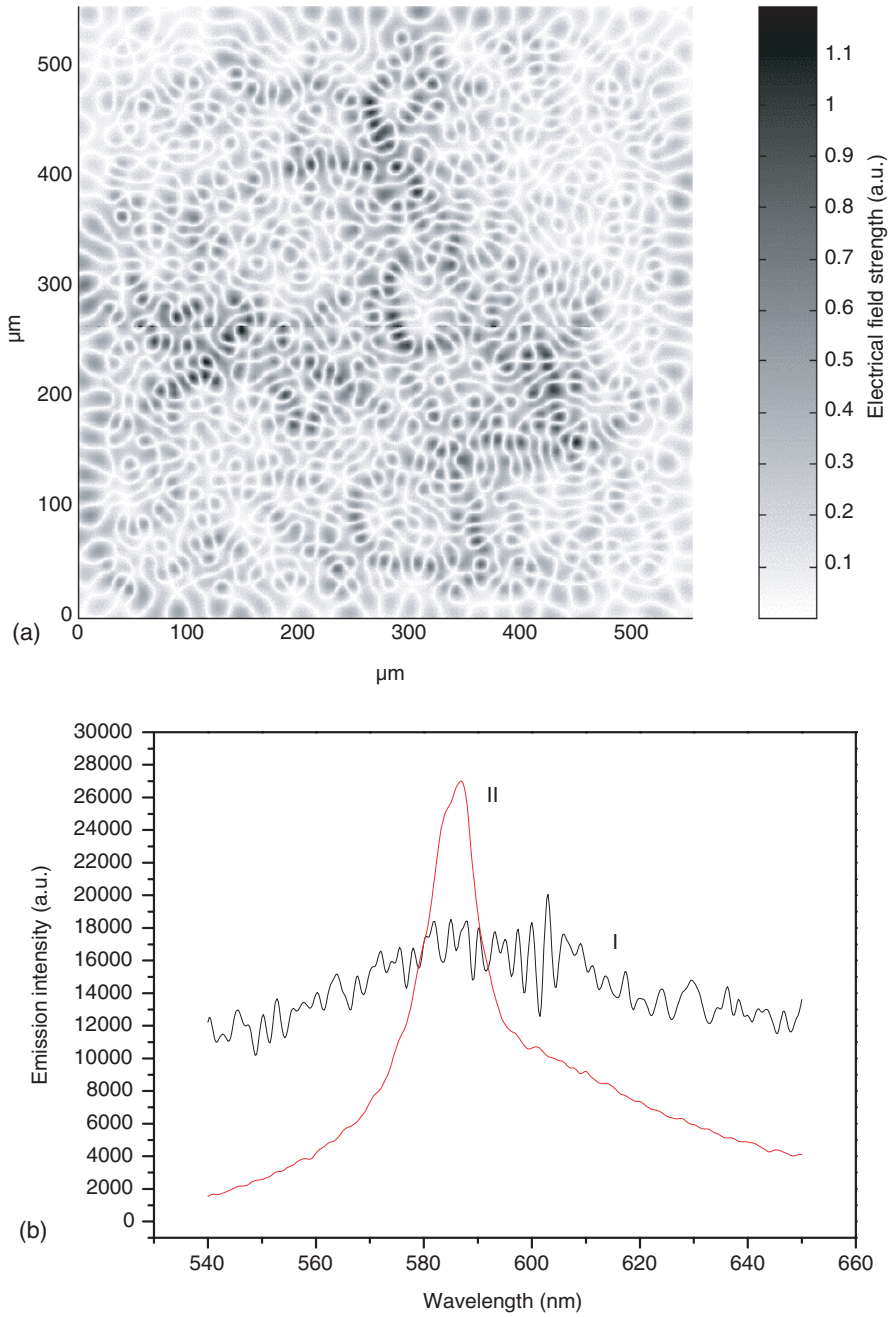
The conjunction of the laser and the disorder medium has been of interest since shortly after the advent of the laser (Letokhov, 1967; Ambartsumyan *et al*., 1970). In recent years various interesting interference effects have been recognised in light that is multiply scattered from disordered structures. There are several reference books on this topic: *Scattering and Localization of Classical Waves in Random Media* (Sheng, 1990), *Analogies in Optics and Micro Electronics* (Hareringgen and Lenstra, 1990) and *Introduction to Wave Scattering* (Sheng, 1995). For instance, it was found that the interference between counter propagating waves in disordered structures gives rise to enhanced backscattering. The phenomenon is known as coherent backscattering or weak localisation (Kuga and Ishimaru, 1984; van Albada and Lagendijk, 1985; Wolf and Maret, 1985). Later, more interference effects were recognised, such as the spatial correlations in the intensity transmitted through random media (Feng *et al*., 1988). These experiments were performed on both active and passive random media. The action of amplification is explained by the Anderson location theory.

The multiple scattering of light is a common phenomenon in daily life, occurring, for example, in sugar, fog, white paint and clouds. The propagation of light in these media can in general be described by a normal process of diffusion. For the diffusion of light through a disordered material, the same Ohm's law holds as for the diffusion of electrons through any common resistor: the transmission or conductance decreases linearly with the length (thickness) of the system.

Anderson localisation brings classical diffusion to a complete halt. That is, on increasing the amount of scattering beyond a critical value, the material makes the transition into a localised state. Figure 7.3 shows the results of a simulation where localised rings appear with the lasing effect. This transition can best be observed in the transmission properties of the system. In the localised state, the transmission coefficient decreases exponentially instead of linearly with the thickness of a sample. (At the transition, the transmission coefficient is expected to have a power-law dependence on the inverse thickness, which is probably quadratic.) This will make backscattered light interfere and amplify in a passive medium.

Consider a light source in a disordered medium at position 'A'. A random light path that returns to the light source can be followed in two opposite directions. The two waves that propagate in opposite directions along this loop will acquire the same phase and, therefore, interfere constructively in 'A'. This leads to a higher probability that the wave will return to 'A' and, consequently, a lower probability that it will propagate away from 'A'. When the mean free path is reduced, the probability for such looped paths increases and at a sufficiently strong scattering, the system makes a phase transition from the normal conducting state into a localised state, owing to interference. In the localised regime, the system behaves as a non-absorbing insulator. Light that is incident on, for example, a slab or solution would be almost completely reflected and the remaining transmission would decrease exponentially with the thickness of the slab.

In this disordered medium, a dramatic narrowing of the spectrum, shortening of



7.3 (a) Simulated E-field distribution where the localised rings appear with the lasing effect. (b) Emission spectrum of polymethyl methacrylate (PMMA) and TiO_2 nanocomposites (emission spectrum below (I) and above (II) the lasing threshold).

the emission time and abrupt buildup of peak intensity are observed above a threshold in pump energy. These results have raised the prospects of utilising the phenomenon for a variety of display, sensing and switching applications, particularly if the corresponding threshold can be significantly reduced. On the other hand, the non-saturable output and the narrow linewidth of the laser also open the door to a number of applications in medicine, identification and marking.

Over the past several years, there has been a great deal of renewed interest in multiple scattering systems with gain. In the case of gain, laser action has been demonstrated in these systems (Lawandy *et al*., 1994; Diederik *et al*., 1997) and has resulted in a number of technological applications. More recently, the effect of amplification on the coherent backscattering signal has been observed in a weakly amplifying sample of Ti_2O_3 doped Ti:sapphire powders and in a system with high-gain laser dyes and passive scatters. The amplification and temporal laser behaviour of light propagating in various types of disordered gain materials have been studied theoretically. But up to now, the exact mechanism of these observations is unknown and further experimental and theoretical investigations are required.

In a laser crystal powder medium, the amplification was ascribed to the diffusion process. Assuming a diffusion process, one can describe the time and position-dependent energy densities of pump, probe and amplified spontaneous emissions (ASE) by a diffusion equation with appropriate absorption and/or gain terms that depend on the local excitation of the system. The (also time-dependent) local excitation of the system is described by the set of rate equations of the laser material. The total set of coupled differential equations describing the system is formed by three diffusion equations for, respectively, pump light, probe light and amplified spontaneous emissions, and the rate equation for the concentration of laser particles in the metastable state.

In a nanoparticle doping dye medium, the physical picture of the system is as follows. The dye molecules absorb energy from the pumping beam and are excited to higher states. Then, through spontaneous emissions, some excited molecules randomly emit photons with frequencies different from that of the pumping beam. These photons travel in the medium, being scattered by the TiO_2 particles and amplified by the dye molecules through the stimulated-emission process. They finally leave the medium and reach the detector.

A laser model proposed by Lawandy and his colleagues sees the scatters providing feedback on the emitted light into the gain medium required to achieve laser action. This system has been modelled as a diffusive ring laser in a gain medium with distributed scatters. In this model the probability of a photon making a closed path in the gain medium by way of a random walk in the diffusive limit has been calculated and used to estimate the threshold gain. This model predicts the observed input–output characteristics and the emission linewidth as a function of pump energy.

The model is based on transient two-level laser equations and includes the detailed spectral properties of the dye gain system. The feedback mechanism in the

laser model was quantified by a Monte Carlo simulation of this multiple scattering problem, which can be completely characterised by the scattering cross section and the Henyey–Greenstein phase function. The peak intensity theoretically calculated is in excellent agreement with the experimentally measured curves, whereas the linewidth data do not completely follow the experimental data at low energies, but collapse at the right energy for the densities of all scattering particles.

The disordered medium used can be classified into four categories. The first kind is a suspension of sub-micron polystyrene spheres. This is a kind of passive medium without gain. A high concentration is necessary to reduce the mean free path of light as much as possible, preferably down to its wavelength, which is necessary to induce the effects of location. The most effective scattering occurs if the size of the particle is of the order of the wavelength of light. The second is to use powder semi-conductor laser materials or to introduce scattering in laser materials, such as Ti:sapphire powders doped with Ti_2O_3 nanometre particles. These powders are fabricated by grinding laser crystals into powders or doping with scattering microparticles. The third is methanol solution doped with laser dyes and TiO_2 nanoparticles. The fourth is polymer sheets doped with laser dyes and TiO_2 nanoparticles. The latter three are active samples with a gain medium.

In general, the optical spectral properties of the above-mentioned disordered medium, including transmitting or backscattering light, are measured first to determine spectral narrowing above a certain threshold. Secondly, the peak input–output characteristics are given with a multichannel analyser and there is an obvious threshold, above which there is a linear increase. Thirdly, the influence of scattering particle density on the emission spectrum is also measured. Furthermore, the angular dependence and polarising properties of backscattering light in a passive medium are also involved in observations of good orientation emissions.

Photonic band-gap structures can suppress spontaneous emissions and control the lifetimes of chemical species in catalytic processes. If dye has infiltrated the PBGs, laser-like emissions may emerge in the mixture regime. It has been predicted that the lasing threshold can be reduced by introducing a defect into an otherwise periodic photonic band-gap structure. Since spontaneous emissions are suppressed in the band-gap, excitations will not then be drained by modes other than the lasing mode. In addition, the long dwell time of such localised defect modes reduces the gain required to reach the lasing threshold. Lasing has recently been observed in 2D photonic crystals, and promising 3D photonic crystals have been fabricated. The threshold for lasing may even be suppressed at defect modes in periodic structures that do not possess a full 3D photonic band-gap, such as in 1D periodic samples, including vertical cavity surface emitting lasers. Recently, lasing at the band edge has been demonstrated in dye-doped cholesteric liquid crystals (CLCs). In these chiral structures, a stop band exists for circularly polarised light that has the same sign of rotation as the CLC structure. Since the dwell time within the sample for emitted photons is enhanced near the edge of the band, the lasing threshold is also substantially reduced. There have been reports of

other lasing dye-infiltrated PBGs. But almost all of these studies focus on how to prepare the PBG and characterise its structure and properties. In order to design and fabricate colloid self-assembled PBGs and their applications, it is necessary to investigate the relationship between the size and shape of the particle, lattice constants, material constants and the band-gap, the laser properties (intensity, wavelength) and dye concentration.

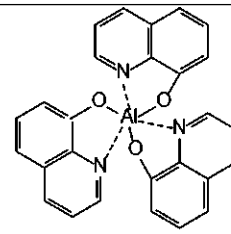
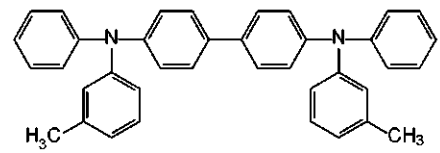
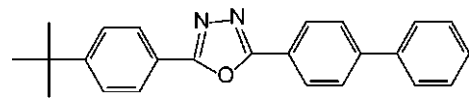
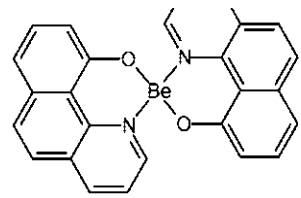
7.5 Electroluminescent fibres and fabrics

Emissive radiation, in which photons of specific energy and thus light with specific wavelengths are produced, may have many forms: black body radiation, fluorescence, photoluminescence, recombination of electrons and holes. All emissive radiations are additive. This kind of coloration has been widely used for lights with controlled colour and intensity of light, with television as a typical example. However, it has not been applied to flexible fibrous materials because of technical difficulties.

Recently, organic and polymeric electroluminescent displays have become an alternative to currently well-established display technologies such as cathode-ray tubes, liquid crystal displays (LCD) or inorganic materials. This is because such displays offer several advantages, such as self-light-emission, large viewing angles, low-driving voltages, high switching speeds, lightness of weight and solution processability. Conjugated polymers achieve semi-conducting properties owing to the existence of delocalised π-electrons along the polymer chain. Delocalised valence and conduction wavefunctions are formed containing π (bonding) and π^* (antibonding) orbitals, which facilitate the movement of mobile charges. Tables 7.1 and 7.2 show some semi-conductive materials being used in light-emitting diodes (LEDs). These organic/polymeric luminescent materials in a thin-film form are sandwiched between two electrodes. Injections of charge carriers, electrons and holes are then carried out in the emitting layer. They are consequently recombined and excited molecules are then formed. The molecules emit light once they decay. Therefore, the polymeric materials used in the device should possess high purity, be stable and easy to process, have good charge mobility with high quantum efficiency, and produce a band-gap corresponding to light emissions in a visible region.

Organic light-emitting devices (OLED) have been intensively investigated for use in flat panel displays since the first efficient OLED was discovered. OLEDs have been shown to have advantages over other display technologies, such as high brightness, low power consumption, low operating voltage, full viewing angle, high contrast ratios, fast response times and a wide temperature range. Compared to traditional OLEDs fabricated on glass substrates, flexible OLEDs (FOLED) are very lightweight, extremely rugged and more conformable, which makes them suitable for more user-friendly applications than can be managed by using flat panel displays, such as smart cards, wearable electronics, and so on.

Table 7.1 Molecular structures of typical semi-conductors

Commonly used acronym and chemical name	Chemical structure
Alq or Alq_3 *Tris*-(8-hydroxyquinoline)aluminium	
TPD *N,N*'-diphenyl-*N,N*'-bis-(3-methylphenyl)-(1,*N*')-biphenyl-4,4'-diamine	
PBD 2-(4-biphenyl)-5-(4-*t*-butylphenyl)-(1,1)-biphenyl-4,4'-diamine	
$Bebq_2$ *Bis*-(10-oxybenzo[h]quinolato)-beryllium	

Source: Friend, 1999.

7.5.1 Emitting species

To make highly flexible displays, the molecular bonds responsible for the mechanical properties of the thin films in the OLEDs must be tolerant of stress while the device is bent. The intermolecular bonding of organic molecules is a van der Waals force, the weak nature of which makes organic light-emitting materials suitable for fabricating FOLEDs. The structure of the OLED is given in Fig. 7.4. A layer of tris-(8-hydroxyquinoline) aluminium (Alq_3) was deposited onto an indium-tin oxide (ITO)-covered polyester sheet by vacuum-evaporation as the

Table 7.2 Conductive polymers used in polymer light-emitting diodes (PLEDs)

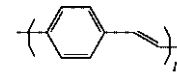
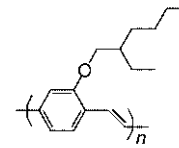
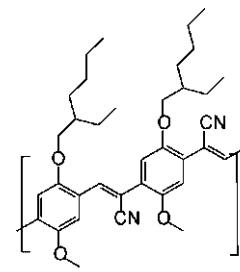
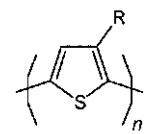
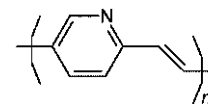
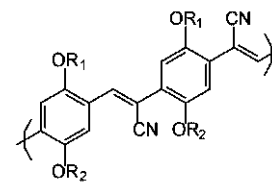
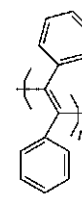
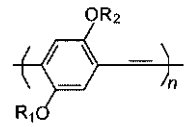
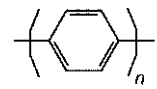
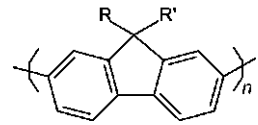
Commonly used acronym and chemical name	Chemical structure
PPV Poly(*p*-phenylene vinylene)	
MEH-PPV Poly[2-methoxy-5-(2'-ethylheoxy)-1,4-phenylene vinylene]	
MEH-CN-PPV	
PAT or P3AT Poly(3-alkylthiophene)	
PPyV Poly(*p*-pyridine)	
CN-PPV Poly[2,5-bis(hexylocy)-1,4-phenylene-(1-cyanovinylene)] ($R_1 = R_2 = C_6H_{13}$)	
PDPA Poly(diphenylacetylene)	

Table 7.2 Cont'd

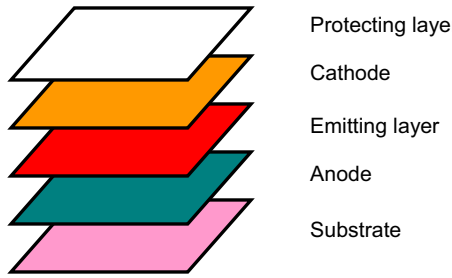
Commonly used acronym and chemical name	Chemical structure
DHO-PPE Poly[1,4-(2,5-dihexoxy)-phenylene ethynylene] ($R_1 = R_2 =$ hexyl)	
PPP Poly(*p*-phenylene)	
PDAF Poly(9,9-dialkylfluorene)	

Source: Nalwa, 2001.

emissive layer. Some other small molecules were also applied. The performance of these devices can be improved by addition of hole and electron-transporting materials, and can be compared with conventional OLEDs deposited on ITO-covered glass. The drop in light-emitting properties after repeated bending is miniscule. Thus far, Alq_3 has been intensively investigated in small-molecule flexible displays (Burrows *et al*., 2001; Krasnov, 2002).

Although small-molecule organic light-emitting materials show potential in FOLEDs, their deposition on the substrate through vacuum-evaporation is rather complicated. Besides their high light-emitting efficiency, conjugated polymers have good flexibility and mechanical properties, which makes them suitable for FOLEDs. Moreover, the excellent film-forming property of the polymers makes it easy to fabricate the emitting films by spin coating. Derivatives of PPV were used to fabricate FOLEDs only two years after the electroluminescence of PPV was first achieved.

Gustafsson *et al*. (1992, 1993) described a flexible light-emitting device with poly(2-methoxy-5-(2'-ethyl-hexoxy)-1,4-phenylene vinylene) (MEH-PPV) as the emissive layer and poly(ethylene terephthalate) (PET) as the substrate. The device had a turn-on voltage of 2–3 V and an external quantum efficiency of about 1%. Its performance was almost the same as that of devices based on ITO-covered glass. Some other light-emitting polymers, such as polyfluorene and copolymers, were also used to fabricate FOLEDs for emissions of different wavelengths and high performance light-emissions (He and Kanicki, 2000; Paetzold *et al*., 2003; Chang *et al*., 2003). In these cases, the emitting polymers were all fabricated by spin-coating; however, the fabrication of film by spin coating has certain disadvantages,



7.4 Structure of a typical LED.

such as the inefficient use of polymer solution and poor uniformity over large areas. Ouyang *et al*. (2002) developed a novel polymer thin film coating process, bar coating, to fabricate FOLEDs. Large area polymer thin films with a high uniformity were obtained, and high performance FOLEDs have also been produced with a performance comparable to devices produced by the spin-coating process. Although coating processes are convenient, they are still not ideal for the mass production of flexible displays. Bell Laboratory and some other groups are working on ink jet printing to produce polymer films or electronic circuits. The techniques show enormous promise – much lower cost production facilities, roll-to-roll rather than batch processing and opportunities to produce novel solutions such as flexible backplanes.

One of the challenges in FOLED displays is to achieve higher efficiency and minimise the consumption of power. Two types of excitons, singlet and triplet, are formed in a ratio of 1:3 in a working OLED. In a conventional fluorescent OLED, emission occurs only from the radiative decay of the singlet excitons; the radiative decay of the triplet excitons is forbidden, and the internal quantum efficiency is less than 25%. It was reported that phosphorescent emissions could be obtained from the radiative decay of the excited triplet states of phosphorescent organometallic materials, which are capable of producing an internal quantum efficiency of close to 100% (Adachi *et al*., 2001). Weaver *et al*. (2002) fabricated flexible OLEDs with fac tris(2-phenylpyridine) iridium (Ir(ppY)3) as the phosphorescent dopant and 4, 4'-*N*, *N'*-dicarbazolebiphenyl (CBP) as the host; the doping concentration is 6%. This device emits green electroluminescence with a peak wavelength of 514 nm, an external quantum efficiency of 6.4% and a luminance efficiency of 22.7 cd A^{-1} at a current density of 2.5 mN cm^{-2}. Their lifetime can reach 3800 h from an initial luminance of 425 cd m^{-2}. Chwang *et al*. (2003) achieved phosphorescent FOLEDs with a lifetime of 2500 h for a 5 mm^2 FOLED pixel test. The encapsulated devices are flexed 1000 times around a cylinder 1 inch (2.54 cm) in diameter and exhibit minimal damage, showing potential for use in flexible displays.

7.5.2 Flexible substrates

The use of flexible substrates will significantly reduce the weight of flat panel displays and provide the ability to conform, bend or roll a display into any shape. Moreover, it will open up the possibility of fabricating displays by continuous roll processing, thus providing the basis for cost-effective mass production.

As a good barrier and transparent material, glass has been widely used in light-emitting devices. However it is brittle and can only sustain small strains, which limits its application in flexible OLEDs. Recently, Auch *et al.* (2002) reported their work on FOLEDs with ultrathin glass as the substrate and the encapsulating cover. The results show that when ultrathin glass is used and the OLED is kept at the neutral axis of the device, the flexibility can be considerable.

Metal foil has the excellent ability to prevent water and gas permeation. An efficient FOLED on a thin steel foil has been developed. Since light could not pass through the foil, light-emitting devices with such substrates have to be top-emitting. The device was constructed on the steel substrate with an organic stack of Alq_3 sandwiched by a highly reflective Ag anode and a semi-transparent cathode. It showed a peak efficiency of 4.4 cd A^{-1}, higher than the 3.7 cd A^{-1} of a conventional NPB/Alq_3 based OLED.

Polymers have excellent flexibility, are lightweight and low in cost, which makes them suitable for application in FOLEDs. So far, the most popular substrate used in FOLEDs is PET; however, it is permeable to water and oxygen, which will dramatically decrease the performance of the device. Polycarbonate and polypropylene adipate can also be severely damaged at high temperatures. Polyethersulfone is yellowish and absorbs moisture readily. Polyimide can bear high temperatures; however, it is also yellowish owing to intra- and/or intermolecular charge transfer complex formation.

To be effective in OLED applications, flexible films must demonstrate the following characteristics: low permeation rates from oxygen and moisture; a very smooth and uniform surface morphology; resistance to temperature and chemical use in conventional processing; optical clarity and transparency; and low cost.

7.5.3 Lifetime

The key challenge to developing FOLEDs is to achieve long-life operations. The failure mechanisms include fracturing of the ITO while bending and the permeation of oxygen and water. ITO is widely used as a transparent anode of OLED and other displays because it has high conductivity, high transparency and excellent workability. However, ITO has poor flexibility because of oxide ceramics. Chen *et al.* (2002) investigated the behaviour of these films under flexed conditions. The results show that a channelling crack is formed under tension, while under compression the film delaminates, buckles and cracks. Reducing the film or the thickness of the device will increase the allowable strain in the film. It is always

possible to maximise the flexibility of the film by placing the most critical component near the neutral axis of the lamination.

It is now well known that the electronic properties of organic and polymeric materials used in FOLEDs or FPLEDs (flexible PLEDs) degrade rapidly in the presence of moisture and oxygen, and that encapsulation is necessary to achieve high performance flexible displays. A good barrier should combine good transparency, flexibility of the plastics and the excellent water/oxygen-preventing properties of an inorganic oxide. A device lifetime of 10,000 h requires a maximum leak rate of 5×10^{-6} g m^{-2}/day. The BARIXTM barrier was reported to reach this level. Chwang *et al*. fabricated high performance encapsulated FOLEDs with such barriers, and the lifetime of the device improved dramatically to as long as 2500 h.

7.6 Textile-based flexible displays

Wall tapestries and carpets are flexible displays that tell intricate stories of the universe, war, human life, etc. But they are lifeless and not interactive. The long-term targets of current endeavours are to make fabrics that can display pictures like a television screen, yet can be worn on the human body, folded and deformed. The fibre structures discussed in the previous sections are potential candidates for making such display devices, that is, light-harvesting fibres, light-emitting fibres and optical fibres.

So far, very few such display devices are known. Photo-adaptive fibres that can undergo photo-induced reversible optical and heat reflectivity changes have been developed. A US patent has described interweaving optical fibres to make side-emitting fabrics. Deflin *et al*. (2001) developed a way to perforate optical fibres with tiny holes that allow some of the light to escape sideways. There are prototypes for a flexible woven screen made of optical fibres capable of downloading and displaying static or animated graphics (such as logos, texts, patterns, scanned images, etc.) directly on to garments. The jacket can contain a very low resolution grid of eight by eight pixels, which displays crude yet readable symbols such as numbers. The author's team at The Hong Kong Polytechnic University has developed a number of flexible displays via various routes, as shown in Fig. 7.5.

Despite the technological advances and efforts of many teams around the world, truly flexible displays remain a dream at this moment.

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(a) (b)

7.5 (a) Flexible displays of the logo of The Hong Kong Polytechnic University. (b) Mannequin wearing fabric displays.

7.8 References

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