

Chapter 5

New Structures with Light Effects



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5.1 Introduction

Currently, several different fibers are available with properties that predetermine them for technical applications. In addition to traditional natural fibers (especially cotton) and standard synthetic fibers (polyamides, polyesters), special fibers are also used for many applications. These fibers have usually important properties (physicochemical, transport, surface, etc.), for the creation of textiles. On the other hand, there are some limitations to using fibers mainly for technical products (as is in the case of composites, e.g., low adhesion to the surface of some polymers or long-term creep). One category of special fibers is optical fibers, both conventional (glass) and polymeric. These fibers were originally developed for the transmission of light (light guides) and information (optical cables). Plastic optical fibers (POF) were developed by Du Pont only in 1964. They are very flexible waveguides made of almost transparent dielectric materials. The first commercialized POF was created by Japan company Mitsubishi Rayon. Standard POF is composed minimally of two layers, i.e., core and shell with different refractive indexes. The core with a high refractive index is surrounded by a shell (cladding) with a low refractive index. This layered structure is responsible for the spread of light inside of POF and minimal light escapes their surface (see Fig. 5.1) (Mishra et al., 2013; Křemenáková and Militký 2019a, 2019b). If the side emission is required (side-emitting POF), the refractive indexes of the core and shell are changed.

Design, characterization, and use of SEPOF in various branches of industry are presented in (Bunge et al., 2017). In this chapter, the characteristics of SEPOF and

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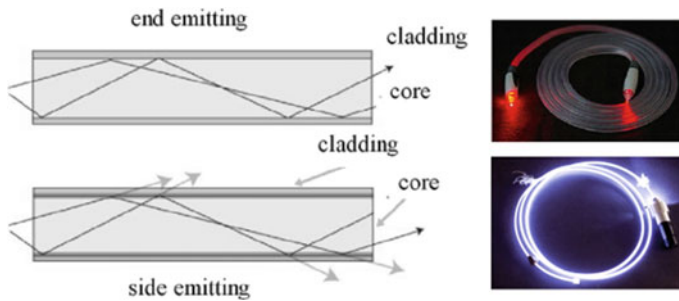


Fig. 5.1 Light spread in end-emitting (POF) and side-emitting POF (abbreviation SEPOF) (Mishra et al., 2013)

their use for illumination purposes are described. POF is often used for the design of different kinds of sensors (see, e.g., Militký & Křemenáková, 2013; Mishra et al., 2013), More recent is the application of POF for line illumination purposes which is typical for the design of special lighting elements in clothing textiles and special safety textiles. It is possible to use POF for direct lighting purposes in special applications such as bed illumination, safety illumination, lighting of advertising panels, etc. The autonomous line illumination systems (ALIS) are constructed for these purposes. ALIS is standardly designed as LED arrays connected by (metal) conductors (see Fig. 5.2).

This solution has several disadvantages such as local heating, higher energy consumption limiting the operating time and sensitivity to mechanical stress. This paper describes the construction of an ALIS based on side illuminating optical fibers covered by a special textile layer denoted as side-emitting linear composite (SELC), which eliminates or at least strongly reduces the disadvantages of the previous solutions (see Fig. 5.3).

The basic areas of the possible use of ALIS for actively lighting clothing components and local lighting in places where there is no access to electricity from the

Fig. 5.2 Examples of ALIS from LED arrays (Hardy, 2018)

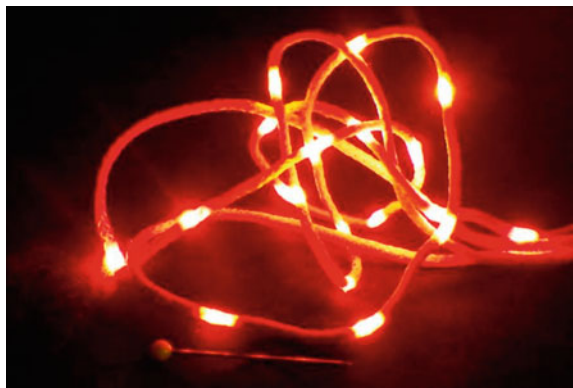




Fig. 5.3 Examples of ALIS from SELC



Fig. 5.4 Applications of ALIS from SELC for safety and design purposes

network are also specified. A special application of ALIS is as a design element (Friedman, 2016) or as part of safety textiles (see Fig. 5.4).

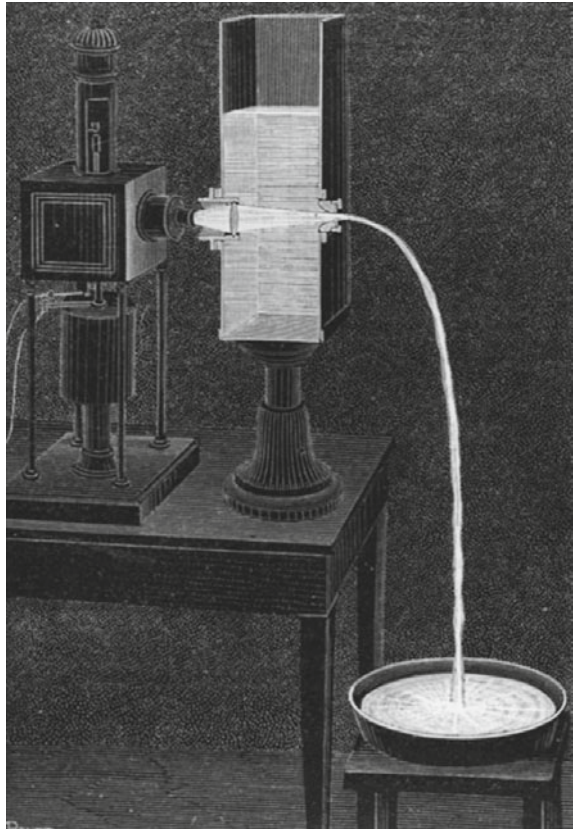
This chapter is mainly devoted to the construction and properties of SELC and ALIS based on them.

5.2 Optical Fibers

POF history and development are discussed, e.g., in (Šesták & Militký, 2013). In 1854, scientist John Tyndall showed to the British Royal Society transport of light by water stream escaped from vessel illuminated by the lamp (see Fig. 5.5).

In 1888, bend glass tubes were used for illumination of human body cavities (Roth and Reuss Austria). In 1920, John Logie Baird patented a bundle of glass tubes for

Fig. 5.5 Tyndall experiment with light-guided transport (Colladon Fountain) (image credit: Oxford University Press Hecht 1999)



the transfer of images, and in 1970, Corning Glass Works developed single-mode optical fiber with attenuation less than 20 dB/km. Charles Kuen Kao was awarded the Nobel Prize for physics for light transmission in optical fibers in 2009. Glass optical fibers are usually based on silica. The refractive index of these POF is about 1.5. As for the price of the raw material, the ideal material for production is pure quartz glass or pure silica SiO_2 . This material has a very low attenuation (loss of transmitted light intensity) in the infrared region. The attenuation of quartz glass decreases sharply at long wavelengths. SiO_2 has minimal attenuation around the 1400 nm wavelength. From 1500 nm, the attenuation begins to rise again. In the region of low attenuation, however, there are several maxima on the curve caused mainly by $-\text{OH}$ ions, i.e., dissociated water located inside the fiber. Therefore, the moisture content of the fiber must be minimized. This is also the reason why silicon optical fibers are extremely sensitive to wetting (moisture causes their so-called blindness) and must be carefully protected from moisture by protective jackets immediately after the drawing process.

In order for a fiber to work, its core must have a refractive index higher (about 1%) than the cladding. Unfortunately, quartz glass has a refractive index value of only around 1.544 and the admixtures can be increased, but almost never decreased.

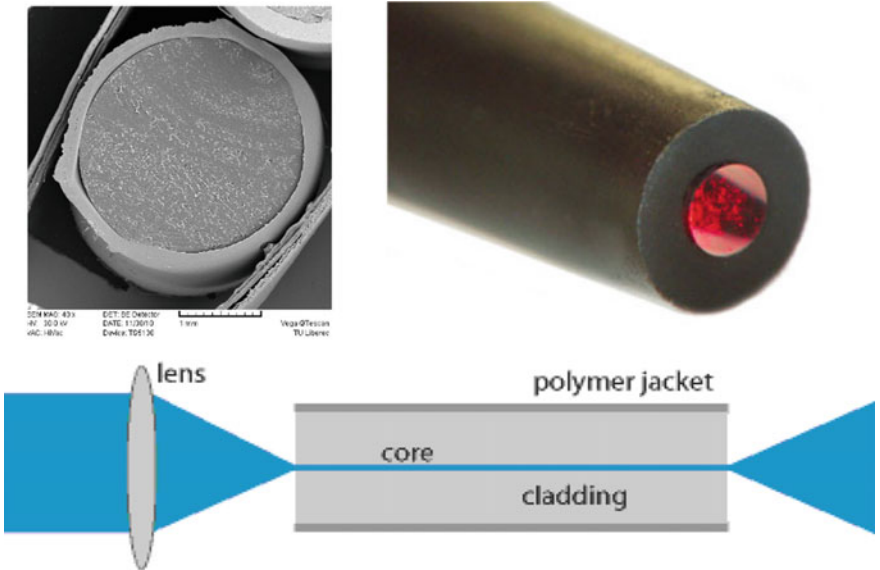
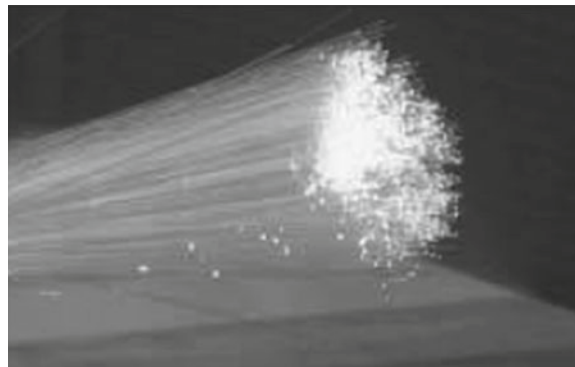


Fig. 5.7 POF is composed of a core and surrounded by cladding with a protective jacket

Fig. 5.8 Classical end-emitting POF



fiber material has the characteristic internal absorption and scattering of light, which are the main source of attenuation. Light losses also occur due to impurities, defects, and geometric imperfections of the fibers.

Standard POF is composed of polycarbonate, polymethyl methacrylate, or polystyrene. Advanced POF is composed of “perfluorinated” polymers. The standard radius of the core from 125 to 490 mm, the refractive index of the shell is 1.46, and the core has a refractive index of 1.48. In the case of a lower refractive index, the light spread in this medium is increased as is shown in Fig. 5.9.

Fig. 5.9 Changes in light speed due to changes of medium refractive index (adapted from Mishra et al., 2013)

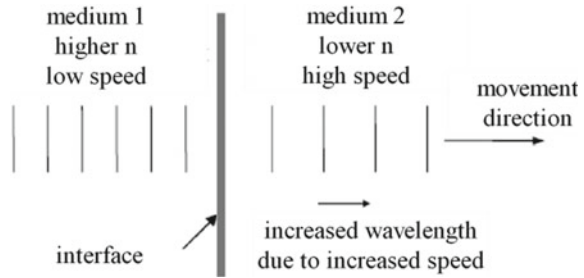
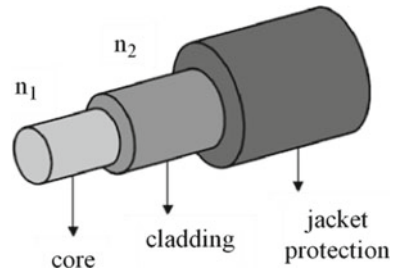


Fig. 5.10 Typical structure of end-emitting optical fiber (adapted from Mishra et al., 2013)



The most of POF is composed of three layers with the outer layer functioning as mechanical protection (designated as mantle or jacket) composed of polyethylene, polyvinyl chloride, and chlorinated polyethylene (see Fig. 5.10).

POF is usually composed of polymethyl methacrylate (PMMA) with a refractive index $n_D = 1492$. This value can be changed by using special dopants. Glass transition temperature of PMMA is nearly $105\text{ }^\circ\text{C}$. PMMA can be processed to temperatures about $220\text{ }^\circ\text{C}$. The long-term stability in the air is $85\text{ }^\circ\text{C}$. Above this temperature and in moist conditions, the PMMA undergoes rapid degradation. More mechanically resistant polycarbonate has lower sensitivity to moisture and much higher ductility (10.8% compared to only 6.3% for PMMA). POF from polycarbonates is applicable to temperatures up to $120\text{ }^\circ\text{C}$. Maximum temperature can be increased to up to $135\text{ }^\circ\text{C}$ by coating (using crosslinked polyethylene or polyolefine elastomers). Polycarbonate-based POF is mechanically much better than PMMA fibers but has a higher attenuation. Their industrial applications are mainly oriented to higher temperature conditions. Generally, the POF attenuation decreases with increasing core diameter. The attenuation of 570 nm light is for PMMA core with a diameter of 0.5 mm equal to 70 dB/km and a lower diameter of 0.25 mm. The process control is more complicated for smaller core diameters because the temperature gradient is higher, and the number of defects is increasing. Attenuation is also growing in the cases of POF macro-deformation as bending and twisting.

The low initial tensile modulus of POF from PMMA is about 2.1 GPa (Blyler, 1999) and for polycarbonate is 2.55 GPa (Guerrero et al., 1998) ensuring sufficient flexibility and bending ability. Cyclic bending also causes attenuation changes which are also a result of repeated bending. After 1000 bends at a bend radius of 50 mm is

attenuation of PMMA (diameter 1 mm) equal to 0.15 dB (38). Attenuation strongly depends on the surrounding air humidity. For example, the attenuation increases by 0.02 dB/km if the POF is kept 1000 h at 85 °C and 85% relative humidity. The attenuation increases by more than 0.03 dB/m in the increase of relative humidity to 90%. POF-based on fluorinated cores or polyethylene shells are strictly hydrophobic (no water absorption), and the attenuation is not affected by air humidity or by immersion into water. POF fibers decompose rapidly at an illumination intensity of 30–50 mW/mm². The use of wavelengths below 400 nm (UV radiation) is particularly dangerous.

5.3 Optical Fibers with Side Emission

There are some ways how to obtain sufficient side emission of standard end-emitting POF. Well known is to using multiple micro-bending (as in woven structures), and using additives responsible for scattering or creation of spatial asymmetry of the core/shell components. Various types of side-emitting optical fibers and waveguides and methods of their production are patented. The basic options are:

- During the production of fibers, suitable “micro”-beads are placed in the polymer,
- The surface of the fibers is chemically or mechanically damaged.
- Special polymers are used for the production of so-called mirror fibers (2D photonic crystals containing alternating layers of material with a high difference in refractive indices).

The simplest is local bending due to weaving of POF (see Fig. 5.11). POF and SEPOF can be a part of different textile structures such as labels, tapes, strips, cords, special patches, and fabrics. Their functionality must be ensured with suitable illumination and a power supply system. The final system must be easily attached to various fabrics and easily detachable. By the creation of woven structures, POF micro-bended and the angle of incident light rays on the interface between the core and the shell changes locally. Results are changes in local side emission intensity. In order to guarantee the conduction of light along with the optical fiber, it is necessary to ensure a match between the exposure angle and the critical angle for the total internal reflection in the fibers. The intensity of light transmission decreases with the increasing bending angle of optical fibers. Transmission losses increase exponentially with the increasing ratio between bending radius and fiber radius. The warps yarns in the woven fabric are usually less bent than the weft yarns and therefore fabrics with optical fibers in the warp are more convenient. Side emission can be enhanced by using a fluorescent material in the SEPOF cover (Gokarneshan, 2007). The weaving of POF is suitable, e.g., rapier looms. One model describing the influence of weaving parameters on the side emission intensity of POF is published in (Masuda et al., 2006).

The major limitation is here complicated connection with the light source and very quick decay of side emission due to frequent macroscopic bending (weaving

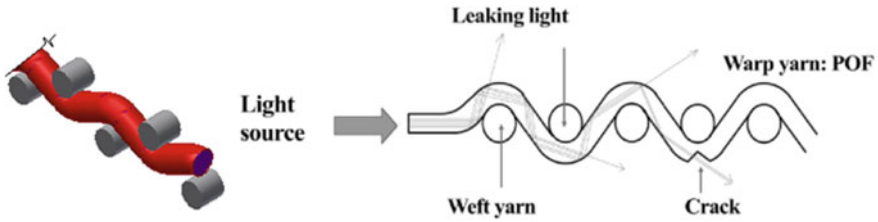


Fig. 5.11 Localized side emission in woven fabric (adapted from Masuda et al., 2006)

pattern). Much simpler is to design materials with local side-emitting effects to use surface and mechanical damage of standard POF. The changes in side emission due to pressing at elevated temperature are shown in Fig. 5.12.

The influence of different surface treatments (abrasion and surface etching) on the changes to side emission of POF (PMMA) is presented in Ho (2007). By local plastic deformation of the POF, surface is possible to create different light effects (see Fig. 5.13).

It is clearly demonstrated that for design purposes it can use relatively simple tools for the creation of local side-emitting effects.

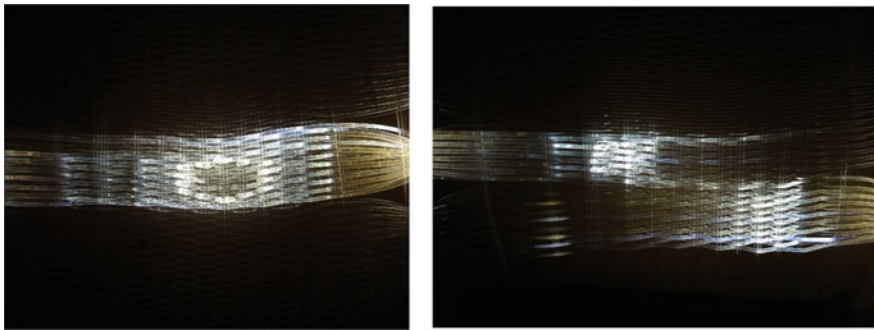
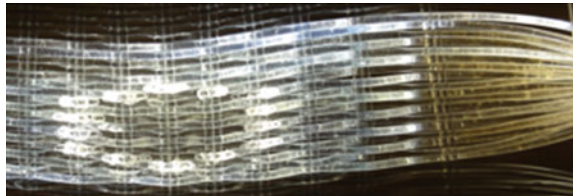


Fig. 5.12 Local side illumination of POF by mechanical pressing (adapted from Mishra et al., 2013)

Fig. 5.13 Light effects on end-emitting polymeric optical fibers induced by local plastic deformation (pressing by hot metallic stamp)



5.4 Side-Emitting Polymer Optical Fibers

When the incident angle of light is less than the critical angle, the side emission of SEPOF appears (see Fig. 5.14).

Among the most commonly used core polymers for SEPOF are polymethyl methacrylate (PMMA), which has a high transfer rate, low losses, and a refractive index that can be varied depending on the intended use. Perhaps the only drawback of PMMA material is the low UV resistance. The cladding should, among other things, protect the core and have a good thermal resistance. It is preferred to use fluoropolymers which are used in combination with PMMA materials because they are well resistant to external influences (1–2). The current market offers various commercial types of SEPOF fibers. Based on the comprehensive testing, the GSPOF-300R (Grace POF Co. Ltd, China) was selected. The structure of a typical Grace SEPOF is shown in Fig. 5.15.

Form analysis of IR spectra (see Fig. 5.16), it was found that the core of Grace is a copolymer of PMMA/PVA/vinylethylcarbonate and the jacket is from polytetrafluoroethylene.



Fig. 5.14 Side-emitting POF with textile cover (Mishra et al., 2013)

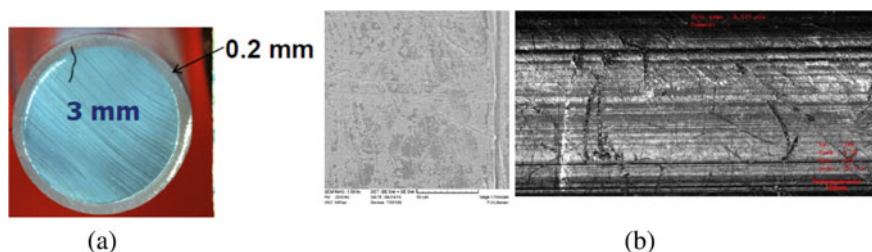


Fig. 5.15 SEPOF grace **a** cross-sectional structure **b** surface form confocal microscopy (Mishra et al., 2013)

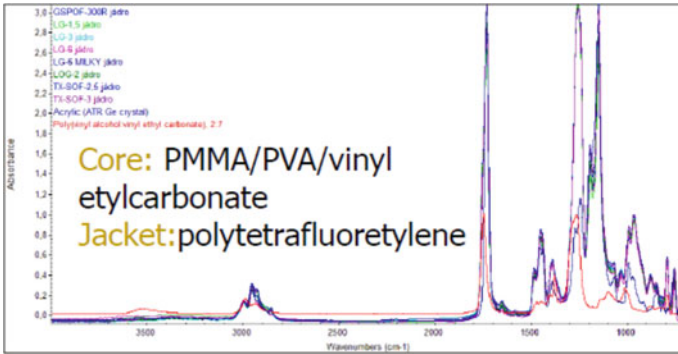
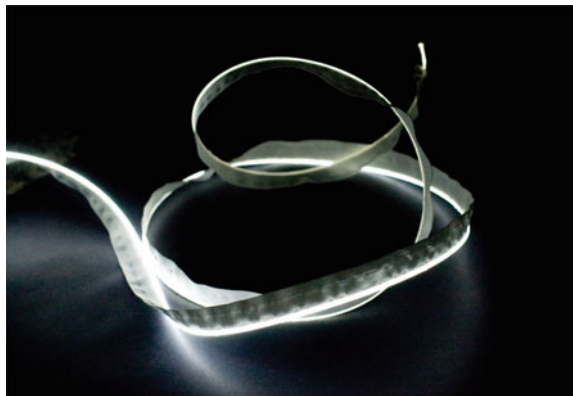


Fig. 5.16 IR spectra of SEPOF grace (Mishra et al., 2013)

Fig. 5.17 Strip covering SEPOF



SEPOF can be covered by a wide range of textile structures such as strips tubes, etc. (Fig. 5.17).

Appropriate lighting and power supply system stable under the conditions of use will need to be supplied with each structure. The resulting complex systems SELC can be designed to be easily attached to various classic textile structures and easily replaceable. The textile cover of SELC increases the illumination intensity especially by using reflective colors such as yellow or orange; furthermore, the emitted light is uniform and the SEPOF fiber is protected against mechanical and chemical damage. Thanks to the textile technique used for the creation of the cover, SEPOF can be structurally applied by sewing or other removable means on clothing or other textile components. The attachment and trajectory of SEPOF in products significantly influence the illumination intensity. When applying these structures to garments, it is recommended not to bend the SEPOF at a small angle, as this will cause light rays to emit at the bend and reduce the homogeneity of emission along the length. The polyester multifilament cover was selected as the most suitable material in terms of

illumination intensity, resistance to external damage and aging under maintenance and external climatic conditions.

5.5 Side-Emitting Linear Composite

Side-emitting linear composite (SELC) is composed of an active core created by side-emitting polymeric optical fibers (SEPOF) and cover layer enhancing light intensity and protecting SEPOF (see Fig. 5.18b). A comparison of illumination of SEPOF and LK is shown in Fig. 5.18.

The textile structure of the SELC cover can be prepared by weaving, knitting, or wrapping. The main advantages of SELC are:

- Increase the side illumination intensity by selecting the proper material, construction, and color of dopant or cover.
- Environmental protection includes UV radiation and temperature/humidity influences.
- Enabling to use standard maintenance by washing and dry cleaning.
- Suppression of mechanical damage due to abrasion and repeated multi-axis stress.
- Easy attachment to textile or other substrates, e.g., by sewing, gluing, thermal fusing.

The basic colors of the cover are shown in Fig. 5.19. The most used is yellow (in black background).

Light illumination decay of POF and SELC as a function of distance from the light source can be measured by the new device POFIN2 (Militký & Křemenáková, 2018). The integrating cylinder is the main part of the POFIN2 device. The emitted light contacts the high reflective and opaque inner surface of this cylinder. Light rays are then randomly scattered in all directions. For a sufficiently big cylinder, the random light scattering ensures the statistically uniform illumination of its inner surface. The irradiance of the inner surface is measured by a suitable light output sensor (spectrometer) The device POFIN2 is shown in Fig. 5.20.

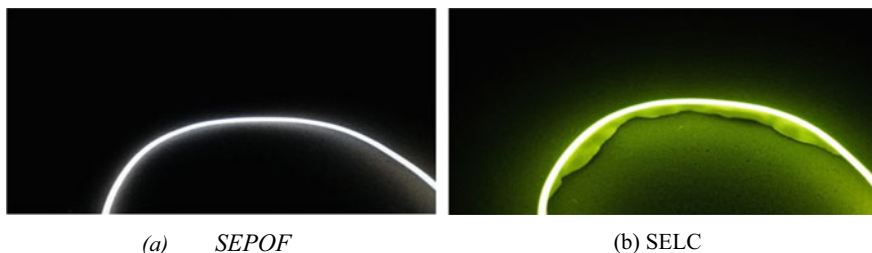


Fig. 5.18 Side emission of SEPOF and SELC (Mishra et al., 2013)

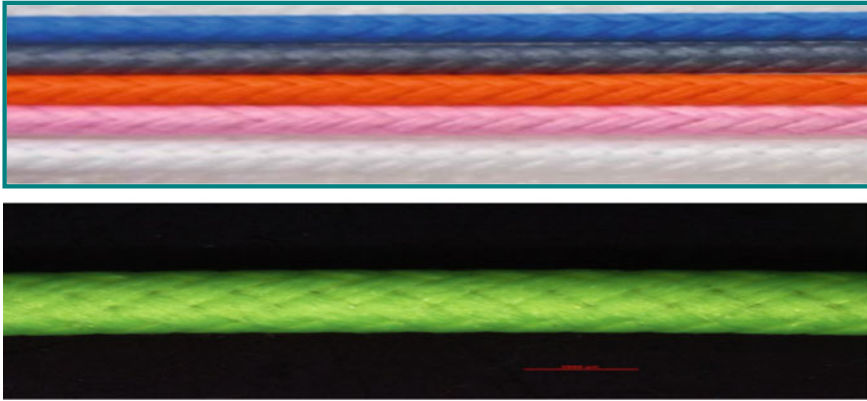


Fig. 5.19 Different colors of cover

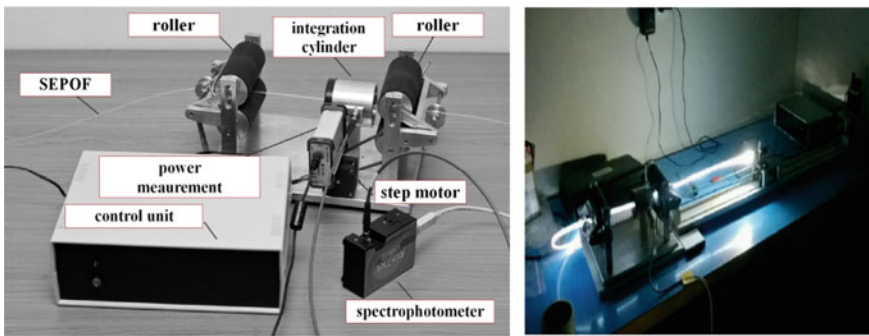


Fig. 5.20 System for measurement of illumination intensity decay

POFIN2 uses a radiant flux light sensor (THORLABS PM 1000 SB). Other components are a step driver, control unit, measuring channel, input/output rollers, and LED illumination unit connected with the power source. The electric power supply is 3 W (3 V voltage and current of 1A). For approximately 10% conversion is the light output power about 300 mW. Usually, about 30% radiates outward from the fiber, and therefore, the radiant flux at the input into the fiber is about 100 mW. POF and SELC are guided by the feed rollers driven by a step motor to the integrating cylinder. The measurements are controlled by a computer program in MATLAB language. The fiber end in contact with the illumination unit is firstly cut by heated wire or freeze knife and then polished by diamond powder (see Fig. 5.21).

The enhancement of illumination intensity of SELC in comparison with SEPOF is shown in Fig. 5.18 which is clearly visible in Fig. 5.22 (red curve is for SELC, and the black curve is for SEPOF).

The outputs, i.e., illumination intensity decay curves, are smoothed by the LLF2 linear regression model. This is a linear function, which consists of two linear sections

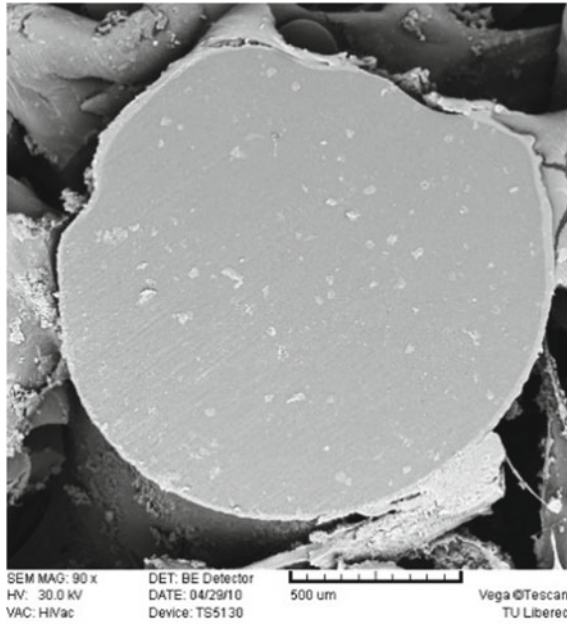


Fig. 5.21 Preparation of fiber end by heated wire and diamond powder polishing (Mishra et al., 2013)

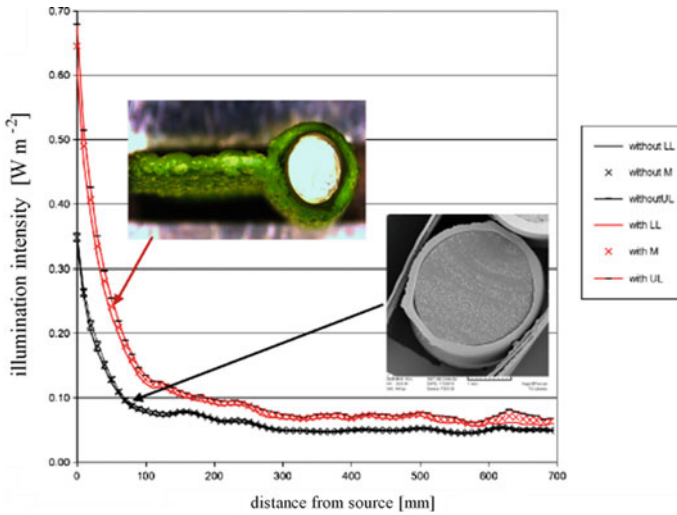


Fig. 5.22 POF and SELC illumination intensity decay curves (Mishra et al., 2013)

with slopes a_1 and a_2 and intercepts q_1 and q_2 . This model is based on the assumption that at short distances from the light source there are important imprecisions caused by the aperture and the critical angle of reflection. The radiation intensity thus decreases sharply. In the second section, the side illumination is uniform, and its intensity decreases very slowly. An example of smoothed decay curves for different POF fibers with different diameters is in Fig. 5.23.

Input illumination intensity depends on the light source output, the quality of the SEPOF-end, LED guidance, the POF diameter, composition, structure, material, and color of SEPOF or color of the LED. The higher source power and a larger SEPOF diameter result in a higher illumination intensity value. It is visible that the highest illumination intensity is achieved by wrapped round cover with reflexive dyestuffs (the best is yellow). In the case of luminescent pigment, probably there is probably some emission from LED consumed for activation of phosphorescence. SELC samples with a polyester textile covering layer in the form of a wrapped round cover (see Fig. 5.24) and a woven strip (see Fig. 5.25) of white color were compared as well.

The used SEPOF was with a diameter of 3 mm. On POFIN 2, the intensity of illumination was measured in dependence on the distance from the source at short

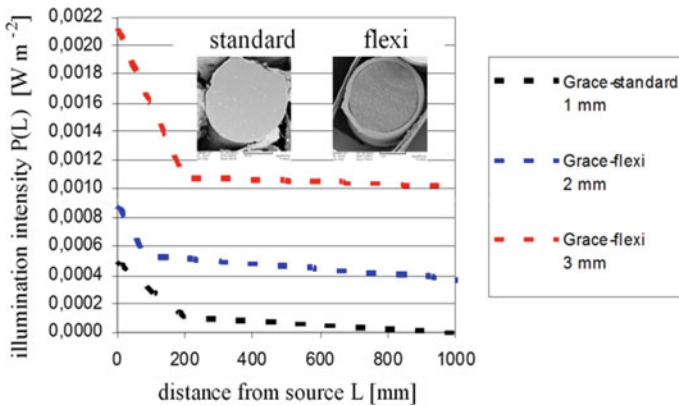


Fig. 5.23 Smoothed illumination intensity decay curves for different POF diameters (Mishra et al., 2013)

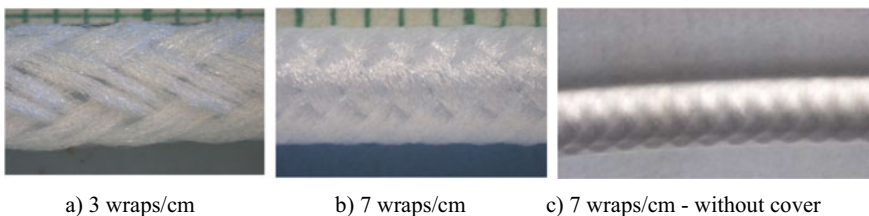


Fig. 5.24 Macroscopic images of the wrapped round cover of SELC

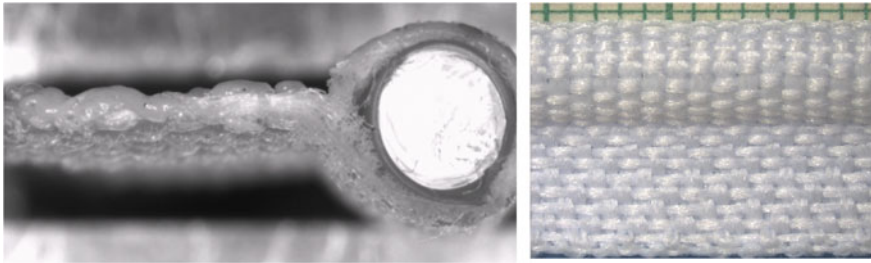


Fig. 5.25 Macroscopic images of SELC strip

lengths up to 80 cm. The illumination intensity of the original SEPOF Grace was also measured. It was visible that there is a statistically significant difference between the specific illumination intensity of the white strip, the SEPOF after removal of the sheath, and the original SEPOF. The wrapped around cover has the highest value, and the original SEPOF has the lowest specific illumination intensity value. During wrapping, the SEPOF surface is regularly deformed due to the multifilament tension, see Fig. 2.22c, which increases the illumination intensity. There is no deterioration of the surface during the formation of the strip cover, and the difference between the illumination intensity of the strip covered and SEPOF after the cover removal is statistically insignificant. The radiation intensity of the LK strip covered is lower than that of the SELC wrapped round covered. When measuring on long lengths (up to 20 m), due to attenuation, the differences between the specific illumination intensity values of SELC covered in a different manner and SEPOF after removal of cover are very small (statistically insignificant). This is because SELC with textile covers emits more at a distance from the source to 1 m than at longer lengths. This is suitable for SEPOF applications in clothing materials, where lengths of 1–2 m are being used.

These results confirm the importance of SELC textile cover in terms of increasing illumination intensity and its justification for use in safety clothing textiles.

The SELC structures are used for the following applications:

- Silhouette visualization in the dark is important for the identification of road users (pedestrians, cyclists), objects (cars, bikes, baby carriages, wheelchairs), animals (dogs, horses),
- Warning lighting (identification of open doors of cars in the dark, restrictions on roads),
- Demarcation of limits (parking areas, carpets edges, stairs steps, etc.),
- Emergency lighting (hospitals)—illumination of corridors, lifts, etc.,
- Highlighting of information,
- Aesthetical complements—different color effects related to the design, creation of emotional fabrics expressing the mental state or feelings.

5.6 Illumination System

The linear composite illumination system is based on a miniature LED source. The basic requirement is that the light source is firmly connected to the SEPOF fiber end. There are various colored LEDs that emit in the color corresponding to required wavelengths (see Fig. 5.26). This may affect the efficiency of the luminophore excitation in the case of hybrid illumination with a luminescent part.

The utilization of LED provides considerable savings in electrical power and lowers maintenance costs. LEDs life extends considerably beyond 15 years (Held, 2009). The LEDs are powered by a battery. The control unit is composed of the built-in microprocessor device that enables to react to external stimuli or to choose between individual light modes such as constant lighting or flashing at different time intervals. An example of a control circuit is shown in Fig. 5.27.

The control units are standardly equipped with rechargeable batteries. A typical illumination unit is shown in Fig. 5.28. The Cree, XPG-3, and XML-2 Cree LEDs were selected for color perception and optimal fit in functional patterns. It was found that for activating luminescence one of the best light source is a white LED. The very limiting factor is the generation of heat during illumination by LED.

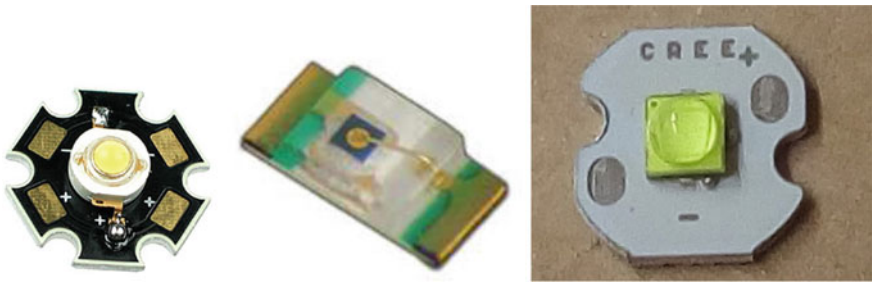


Fig. 5.26 Examples of LEDs (image credit: CREE LEDs)



Fig. 5.27 Control circuits for regulation of illumination intensity and creation of light effects (image credit: Scilif s.r.o. company)

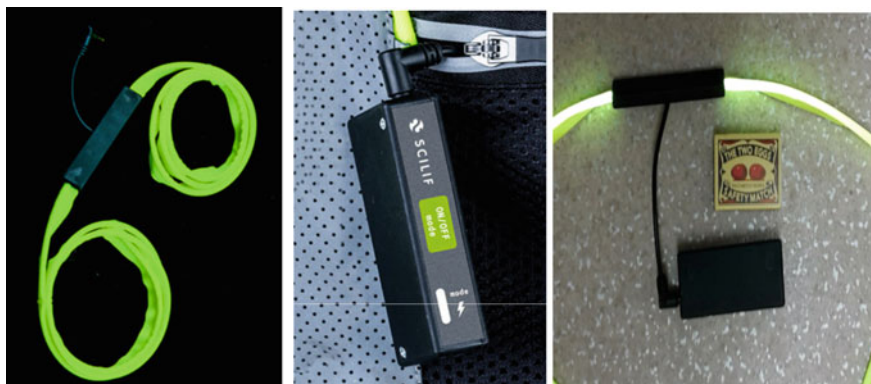


Fig. 5.28 Illumination unit composed of LED light source and control unit with the power source (rechargeable battery) (image credit: Scilif s.r.o. company)

The effectivity and temperature changes of the control unit containing LEDs simulating white light (white LEDs) with different chromaticity and power were tested. The testing device of LED effectivity E (lux/W) in combination with SEPOF illumination intensity I_0 (lux) composed of Luxmeter and the variable power source is shown in Fig. 5.29.

The effectivities of different light sources are:

Bulb = $710 \text{ lm}/60\text{W} = 12 \text{ lm/W}$

ES bulb = $1155 \text{ lm}/20\text{W} = 58 \text{ lm/W}$

LED bulb = $600 \text{ lm}/8\text{W} = 75 \text{ lm/W}$



Fig. 5.29 Device for testing of LED effectivity

Table 5.1 Temperature parameters for some LEDs

Mode	Initial rate ($^{\circ}\text{C min}^{-1}$)			Equilibrium temperature increase ($^{\circ}\text{C}$)		
	Continuous light	Slow flashing	Quick flashing	Continuous light	Slow flashing	Quick flashing
6800 K 350 mA	0.52	0.28	0.73	5.35	3.36	3.37
5900 K 300 mA	1.08	0.66	0.77	10.83	7.13	6.66

To measure the heating of light sources under the influence of LEDs, a device for measuring the temperature by means of platinum temperature resistive sensors, controlled by LabVIEW software using the NI 9226 module, has been developed. The temperature was measured by a contactless thermometer from a height of 10 cm at 5 and 10 min after the power was turned on. The initial heating rate and equilibrium temperature increase relative to ambient temperature were evaluated. The initial heating rate (IHR) was defined as the slope of the regression line determined from the temperature/time curves in the interval from the start to 4 min. The equilibrium temperature increase (ETI) was defined as the steady-state regression line segment on the temperature/time curves (temperature after 30 min of measurement). Typical results are given in Table 5.1

It is visible that using the flashing mode both the IHR and the ETI are significantly lower than in the steady-state mode. Approximate values of the temperature of the light sources in the position of LEDs are given in Table 5.2.

Therefore, for designers, it is important to measure the heat effect and modify the proper placement of the control unit with LED out of direct contact with the human body (e.g., to use special pockets in places with good ventilation). Selected LEDs were subjected to simulated dry aging (105 $^{\circ}\text{C}$, 144 h) and wet aging (80 $^{\circ}\text{C}$, 65% humidity, 144 h, 288 h, 432 h). The LED panel has been developed with a panel of coolers and drivers with controllable power from 350 to 700 mA. It was found that the intensity of SELC illumination increases slightly with increasing chromaticity. After dry and wet aging, the SELC side emission intensity decreased, but the illumination intensity using both white and color LEDs is sufficient for selected functional samples (in terms of distance visibility). The wavelength distribution described by the spectral performance characteristics of SELC illuminated by selected LEDs subjected to simulated aging corresponds approximately to the relative spectral performance

Table 5.2 Surface temperatures of some lighting systems

Time of temperature measurements (min) /temperature ($^{\circ}\text{C}$)	Set 3 6800 K 350 mA	Set 4 5900 K 300 mA	Set 5 5900 K 350 mA	Set 6 5900 K 400 mA
5 min	40	30	40	40
10 min	45	40	45	55



Fig. 5.30 Examples of lithium-ion batteries (image credit: LiPol battery co. Ltd.)

characteristics of the LEDs reported by the manufacturers. An important part of illumination systems is powering. It is possible to use hard or flexible batteries. Other powering systems are (Spies et al., 2013):

- Standard portable sources (power bank, mobile phones, laptops)
- Energy harvesting systems based on mechanical vibrations, thermoelectric effect, and solar power)

For consumer electronics, lithium-ion batteries are used. They have high energy and power density and stable performance, but they are bulky and non-flexible (see Fig. 5.30).

Advantages of lithium-ion batteries are:

- High energy density is required for high capacities.
- One regular charge is sufficient.
- Relatively low self-discharge is less than half that of nickel-based batteries.
- Low maintenance—periodic discharge is not necessary.

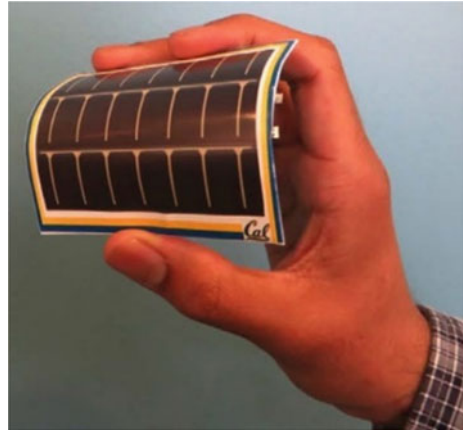
Limitations of these batteries are:

- A protection circuit to maintain voltage and current within safe limits is required.
- Sensitive to aging, even if not used. They must be stored in a cool place at a 40% charge reducing the aging effect.
- Expensive to manufacture—cost is about 40% over the cost of nickel–cadmium batteries
- Potential fire hazard—electrolyte is an organic solvent

LiPol batteries (see Fig. 2.30) have a higher energy density (20% more than classical LION batteries). The flexible cover of these batteries reduces their total mass. Flexible lithium-ion batteries are based on stainless steel ($12.5\ \mu\text{m}$) and nickel ($10\ \mu\text{m}$) foils. These foils are conductive and are working even after repeated flexing (see Fig. 5.31) (Ostfeld et al., 2016).

Lithium phosphorus oxynitride electrolyte (LiPON), as an amorphous thin ($2\ \mu\text{m}$) film is used in solid-state micro-batteries (Wang et al., 2018). Their capacity loss after 100 charge and discharge cycles is negligible.

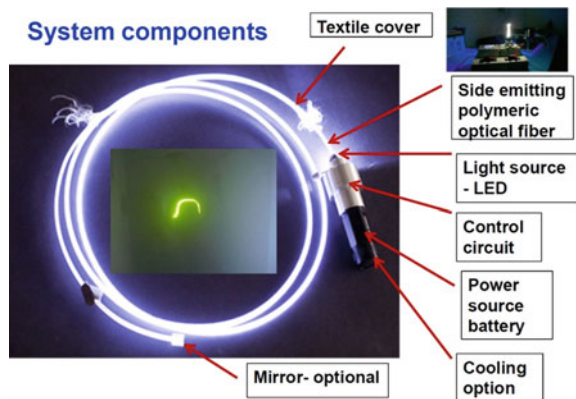
Fig. 5.31 Flexible lithium-ion batteries (Ostfeld et al., 2016)



5.7 Active Illumination Systems

Autonomous Line Lighting Systems (ALIS) are illumination systems enabling line lighting with a local portable power source as a battery or power bank. ALIS are commonly designed as LED fields connected by (metallic) conductors or as the end emitted polymeric optical fibers (POF) micro-bended due to their incorporation into woven or knitted fabrics, respectively (Bunge et al., 2017). Illumination intensity of micro-bended POF is not sufficiently high, there are problems with connection to LED, and there are limitations of durability due to low bending radius. LED fields have sufficient illumination intensity but have a number of disadvantages such as local heating, higher energy consumption limiting operating time, and sensitivity to mechanical stress. The challenge was to develop an ALIS based on side-emitting optical fibers which eliminate or at least severely restrict the disadvantages of the previous solutions. We developed ALIS which is shown in Fig. 5.32.

Fig. 5.32 Proposed ALIS (Mishra et al., 2013)



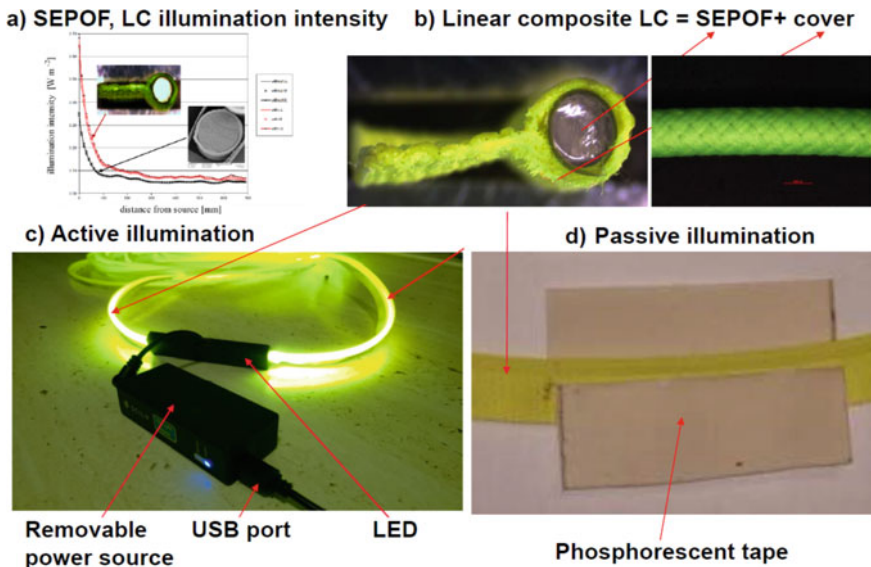


Fig. 5.33 Components of ALIS based on SEPOF

This ALIS system is composed of linear composite SELC (see Fig. 5.33b) as side-emitting optical fibers (SEPOF—see Fig. 5.33a) covered by a special textile layer enhancing illumination intensity (Fig. 5.33a), power source, and LED light sources (Fig. 5.33c).

These ALIS systems have a good homogeneity of emitted light, and they can alternatively convert a portion of the UV radiation into the visible area and provide high resistance to external influences, etc. All of the ALIS parts can be optimized for the needs of the area of use. A major limitation for long-term use is the capacity of the battery which can guarantee the active lighting for 6–8 h only. One simple possibility is to use flash with a suitable frequency which can extend the active lighting time by more than 50%. Application of ALIS for design purposes is facilitated by simple placement into seams especially when the cover is in the form of a strip (see Fig. 5.17). It is possible to use them as well for artistic lighting as is shown in Fig. 5.34.

This system was successfully used also for purposes of safety illumination of warning cloths and temporary line illumination in remote areas or hospitals (see Fig. 5.35) and for hospital bed illumination (see Fig. 5.36).

The system can be used also for rescue uniforms (see Fig. 5.37) or a warning triangle (see Fig. 5.38).

A special application is for the indication of carpet edges (see Fig. 5.39).



Fig. 5.34 Artistic lighting



Fig. 5.35 Emergency lighting in hospital

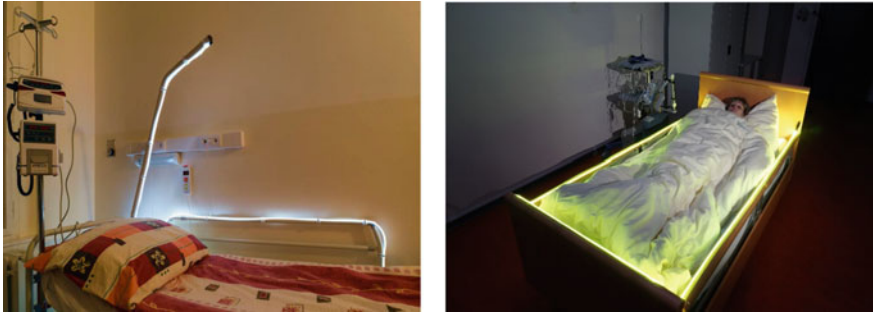


Fig. 5.36 Illumination of the hospital bed



Fig. 5.37 Vest for rescue people

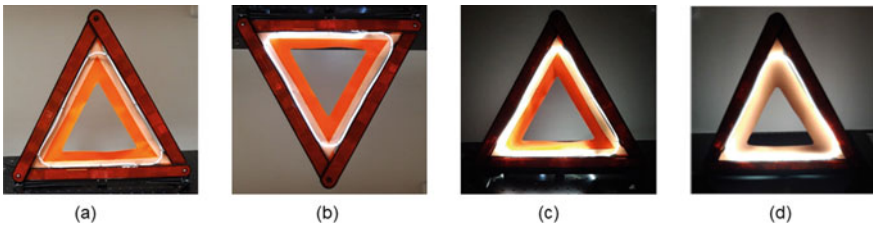
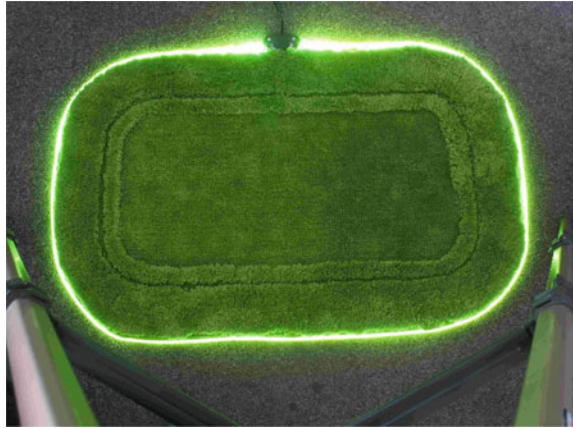


Fig. 5.38 Warning triangle **a** external illumination by a fluorescent lamp, **b** external illumination by a fluorescent lamp and switching on the ALIS (optical fiber), **c** no external light but switching on the ALIS (optical fiber), **d** no external light but switching on the ALIS (optical fiber) and presence of phosphorescent tape

Fig. 5.39 Visualization of carpet edges (Mishra et al., 2013)



5.8 Hybrid Illumination System

The motivation for the construction of hybrid ALIS is partial utilization of side emitted light from SELC for activation of passive luminescent lighting tape. This system is composed of textile tape coated with fluorescent pigments which emit light even after the active lighting is temporarily switched off. The selection of proper fluorescent pigments is based on the measurement of time to decay of illumination intensity to the limited value of sufficient visibility in the dark. Based on the comprehensive testing, it was found that for ensuring the activation of the phosphorescent active layer, which is typically placed under SELC, it is necessary to select a suitable LED (typically white) and a suitable color (usually white) for the SEPOF cover providing emission in the low wavelength region. For testing purposes, three types of hybrid structures were prepared. Type HS1 and type HS2 are composed of luminescent tape-woven fabric (polyester twill, sett 50×30 yarns/cm) of white color treated by luminophore “Glow Star.” Type HS1 is only luminescent tape. Type HS2 is composed of a combination of luminescent tape and SELC with different colors (optical brightening, reflexive yellow, and reflexive orange). Type HS3 is the round cover of SEPOF wrapped by luminescent filament *Paracord 550* (polyamide, cover intensity 32 filaments /cm). These hybrid structures are shown in Fig. 5.40.

The methodology of measuring the light output of samples with phosphorescent coating activated by SELC is based on the utilization of device POFIN 2. SELC is guided into the measuring cylinder of the POFIN 2, and a tape with a phosphorescent coating is placed on it (see Fig. 5.41). The tape is illuminated by SELC, and illumination is after the prescribed activation time is switched off. Using a Thorlab light sensor coupled to an integration cylinder, the light output at a given time is scanned and recalculated according to the sensor area for illumination intensity.

Specific illumination intensity of hybrid structures HS2 and corresponding SELC with different colors are given in Fig. 5.42.

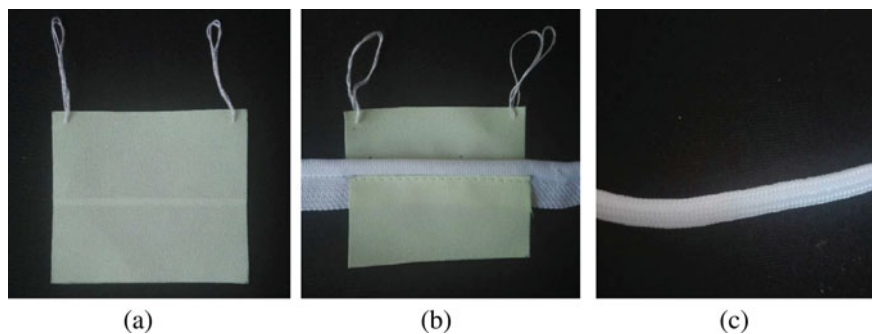


Fig. 5.40 Hybrid structures **a** HS1, **b** HS2, and **c** HS3

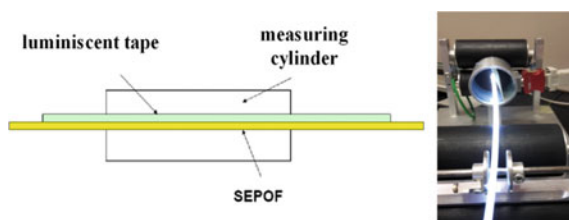


Fig. 5.41 Measurement of illumination intensity and phosphorescence decay during the time

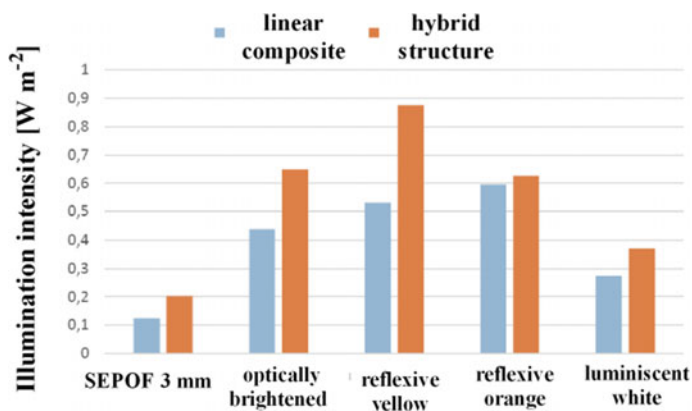


Fig. 5.42 Specific illumination intensity for hybrid structure HK2 and corresponding SELC

It is visible that luminescent tape enhances illumination intensity in the mode of lighting. The highest improvement is for reflective yellow. In the mode of phosphorescence after switch-off active lighting is the situation more complex. For measurement of phosphorescence decay on HS1, a 3 mm diameter SEPOF Grace was guided into the integration cylinder and a sample tape with a phosphorescent coating and a

Table 5.3 Parameters of luminescence decay model of hybrid structures

Hybrid type	HS1	HS2	HS3
I_0 (W/m ²)	0.00158	0.00505	0.000264
τ (s)	76.190	42.488	8.609
β (-)	0.481	0.4641	0.248
Correlation coefficient R	0.988	0.992	0.591

hydrophobic treatment was also stored there. In the case of HS2, active light exposure with SELC of different colors with SEPOF Grace 3 mm in diameter was used. The same sample with a phosphorescent coating fabric tape was illuminated.

Chen et al. (1993) examined the decay of luminescence in porous silicon and found that the decay curve is significantly slower than the exponential and can be described by the following function

$$I = I_0 \exp[-(t/\tau)^\beta] \tag{5.1}$$

where I_0 is the initial luminescence intensity after excitation and t is the luminescence decay time. The adaptation parameters β and τ are dependent on excitatory conditions such as excitation duration, intensity, and photon energy. The luminescence decay model (5.1) was used as a model of the measured data. The model parameters calculated by nonlinear least squares are given in Table 5.3.

Experimental data and model courses with 95% confidence curves are shown in Fig. 5.43

As is shown in Fig. 5.43, hybrid structure HS2 with white strip reached the highest values, which is corresponding to parameter I_0 . On the other hand, hybrid structure HS3 with a wrapped round cover from white luminescent fibers is the worst. The

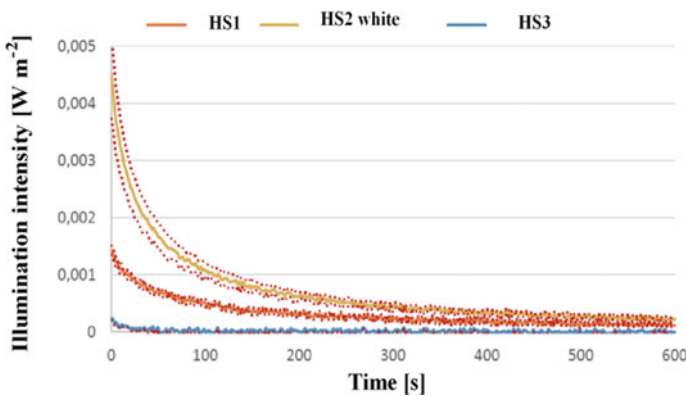


Fig. 5.43 Time dependence of illumination intensity caused by the phosphorescence of different hybrid structures

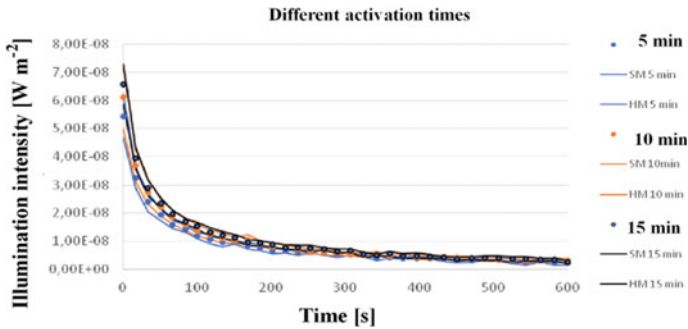


Fig. 5.44 Illumination intensity in phosphorescence mode as a function of activation time (SN lower bound, HM upper bound of 95% confidence band)

parameters τ and β influence the half-life time, i.e., how quickly the intensity of illumination decreases over time. According to these parameters, it is the half-life time highest for the HS2. Based on these and other experiments, it can be concluded that luminescent tape-woven material should be hydrophobic (e.g., polyester fabric). The aqueous coating based on butadiene-styrene containing a phosphorescent pigment, acrylic components increasing abrasion resistance, and polyurethane enhancing the flexibility of the system is ensuring sufficient phosphorescence intensity for at least 10 min. It was found that the time of re-activation of phosphorescence in the range of 5–15 min is not very important for passive illumination intensity decay (Fig. 5.44).

The SELC lighting (phosphorescence activation time) 10 and 10 min of passive lighting (phosphorescence) save 30 min per hour when compared with the active ALIS system. Therefore, with a standard 7-h power supply function, the hybrid ALIS containing a phosphorescent layer will increase active time to 14 h. The combination of active and passive illumination leads to enhance of illumination power by about 20% as well. The passive lighting element is composed of textile tape coated with fluorescent pigments which emit light even after the active lighting is temporarily switched off. The selection of proper fluorescent pigments is based on the measurement of time to decay of illumination intensity to the limited value of sufficient visibility in the dark. Fluorescent pigments can be used as cover for SELC as well (see Fig. 5.45).

The combination of active and passive illumination leads to the extension of total illumination time. The analysis of a hybrid illumination system is realized by the special testing system enabling the measurement of the time course of illumination intensity in the phase of active and passive lighting. Based on the analysis, the final hybrid system is designed and used as a part of special clothing.

Optical fibers for visibility and safety

Passive and active visibility of subjects (especially pedestrians) is one of the key issues of road safety. The majority of solutions are based on the utilization of retro-reflective materials functioning under direct illumination from external light sources

Fig. 5.45 Different types of wrapped round cover in SELC



only. These solutions indicate only the presence, but not the real size and shape of subjects, which may be a source of problems and the cause of road accidents. Passive safety features also respond only to direct illumination, and the subject is not able to accurately assess whether it is truly visible. In general, the visibility of workers or pedestrians can be increased by using colors with a higher overall reflection. If the clothing is fitted with accessories made of fluorescent materials, which increase the light contrast to the background, this increases the distance that the driver can record a pedestrian or cyclist. Fluorescent materials increase visibility in daylight and at dusk, but lose their function in the dark, because the principle of their functionality is to re-emit incident radiation, so in a certain part of the spectrum it appears as if their reflectance is higher than 100%. For this reason, high-visibility clothing today is complemented by retro-reflective materials, most often in the form of various tapes, which increase the wearer's visibility up to 200 m. Considering that at a speed of 75 km/h, the driver needs at least 31 m (1.5 s) to be aware of the danger and react accordingly. It is obvious that only with reflective materials do pedestrians and cyclists give the driver enough time to solve the traffic situation. Simply put, clothing with retro-reflective elements can be seen at night at a distance 3 times greater than white clothing and more than 10 times greater distance than blue clothing (www.cyklistikakrnov.com). Testing of products with high visibility is described in several international standards, of which the most important standard in the textile field is EN ISO 20471: 2013 (EN ISO 20471). This International Standard contains requirements for risk assessment and risk analysis of high-visibility clothing components. It defines the concept of conspicuousness, which is understood as a property that easily attracts visual attention to the object. The conspicuousness is determined by the contrasting brightness of the object, the color contrast, the pattern and appearance, and the movement characteristics with respect to the surrounding background against which it is seen. It contains quality requirements for both color and retro-reflection, as well as for minimal areas and placement of materials on protective clothing. According to the representation of the elements increase visibility, the standard defines three classes, each of which provides a different level of conspicuousness, class 3 is the

Fig. 5.46 Use of our AFIS for traffic safety



class that provides the highest degree of conspicuousness against the background most common in urban and rural situations in daylight and at night. Active light-emitting diodes (LED) are working without direct illumination but do not indicate the size of the subject's silhouette and are also sensitive to mechanical stress (especially repeated bending). It is possible to use active and passive lighting elements (SELCE) as parts of the hybrid illumination system. This system is constructed for clothing purposes mainly. As an active lighting element, the linear composite consists of side-emitting optical fiber covered by a woven textile layer, power supply, and LED light sources were developed (Militký & Křemenáková, 2018). An example showing the active lighting in traffic conditions by our ALIS system is shown in Fig. 5.46.

The passive lighting element is composed of textile tape coated with fluorescent pigments which emit light even after the active lighting is temporarily switched off. The selection of proper fluorescent pigments is based on the measurement of time to decay of illumination intensity to the limited value of sufficient visibility in the dark.

5.9 Safety Textiles

Current safety elements that are applied to clothing for easier identification in reduced visibility are divided into three categories (Křemenáková et al., 2012a, 2012b, 2012c):

- a. Safety elements that do not emit light but can reflect or re-emit light, i.e., passive elements.
- b. Safety elements are composed of active elements that emit light. They use their light source, so they need their power supply—an energy source.
- c. Hybrid structures that combine elements from the previous two classes. The resulting structure exploits the advantages of passive elements that are not

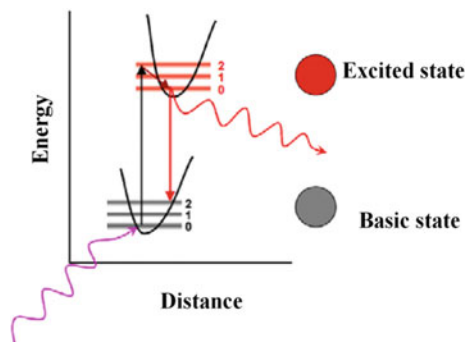
dependent on their energy source, and the functional advantages of the active illuminating elements.

5.9.1 Luminescent Materials

In the field of passive safety, it is still a novelty to use light-emitting (phosphorescent) materials (Vik & Vikova, 2013). Phosphorescence together with fluorescence belongs to the class of so-called photoluminescence phenomena (Schulman, 1977). Luminescence is defined as the spontaneous non-equilibrium light emitted by a solid or liquid, representing an excess of radiation from a body beyond its thermal radiation at a given temperature. When a substance absorbs certain energy, its electrons jump from a lower energy level to a higher energy level, thereby exciting the atom. The excited state is not stable, and then the de-excitation occurs; i.e., the electron jumps back to the original level. Excess energy is released in the form of light energy, heat, or other forms (see Fig. 5.47) (Schulman, 1977). According to Stokes law, the excited light radiation always has a higher wavelength (less energy) than the exciting radiation. Light may emit through the matter, even if it is not heated. Luminescence processes can generally be divided according to the method of excitation, according to the extinction time, and according to the composition of the luminophore.

Phosphorescence is characterized by the slow emission of radiation because the electrons are in a metastable state; i.e., they are reaching energy levels from which they cannot easily return to baseline. Therefore, in the case of phosphorescence, radiation emission persists for some time after the removal of the radiation source. Post-phosphorescence post-discharge time is longer than 10^{-8} s. In most cases, radiation can take several minutes to hours. Fluorescent pigments can generally be divided into a class of optically brightening agents that are used to increase the perception of the whiteness of materials, or into a class of fluorescent dyes that operate in the visual region of the spectrum (Vik & Vikova, 2013). In the textile area, the luminescence induced by light radiation in the visible light area or by UV radiation is most often divided into fluorescent and phosphorescent pigments. Either they are organic

Fig. 5.47 Excitation and emission of luminophore (Vik & Vikova, 2013)



luminophores or inorganic luminophores. In both cases, the luminescence is excited by ultraviolet rays, or rays in the visible region of the spectrum, such that the free electron is picked up from the ground state band to the excited state band. Organic crystals have a considerably shorter afterglow than inorganic luminescent crystals. In contrast, the temperature has a negligible influence on the luminescence effect of organic substances.

Most of the production of photo luminescent substances is in the form of inorganic powder materials—pigments that are harmless to health, contain no radioactive substances, are neither toxic nor toxic, and do not decompose. There are different types of fluorescent materials from yellow through green, orange, and even pink has fluorescent shades. Yellow color has proven to be most visible (Kwan & Mapstone, 2006), which is why it is the most widely used of all fluorescent dyes in the safety clothing and accessories segment. Not only the color but also the size of the surface can significantly increase the contrast of the garment to the background and thus the visibility of the wearer. The disadvantage is that fluorescent materials fade in shade much faster than other colors. However, these materials are widely used for clothing, helmets, bags, and other equipment. An important point of the luminescent radiation evaluation is the measurement of time decay. In the last decade, a large number of articles have been published describing the decay of luminescence in different materials and at different time scales (Chen, 1993).

5.9.2 *Retro-Reflexive Materials*

Retro-reflection is a special optical phenomenon related to the reflection of light rays. In retro-reflection, most of the incident rays return to the source. It is opposed to iso ideal diffuse reflection, where the reflected rays propagate in all directions in an imaginary hemisphere. In specular reflection on smooth surfaces, most rays are reflected at a mirror angle, and, therefore, the law on maintaining the angle of reflection relative to the angle of impact applies. Retro-reflective materials are widely used for safety reasons. There are produced various types of reflective elements (reflective threads, retro-reflective sewn strip, iron-on transfers, zip fastener, logos, etc.), accessories (reflective self-winding tapes, reflective stickers, pendants and reflectors vests, covers, and accessories such as hats, caps, etc.) or finished products such as reflective clothing (jackets), shoes, backpacks, and raincoats. Optical elements based on the relatively simple geometric principle of retro-reflection are corner reflectors—consisting of three mirrored mutually perpendicular surfaces, which together form a corner of the cube (prism). Reflective spheres are reflecting the incident beam always in the original direction (Vik & Vikova, 2013). Retro-reflective foils are divided according to the internal structure into three basic groups: foil with embedded microspheres, foil with encapsulated microspheres, or foil with corner reflectors (see Fig. 5.48).

The emergency vests with retro-reflective strips are shown in Fig. 5.49.

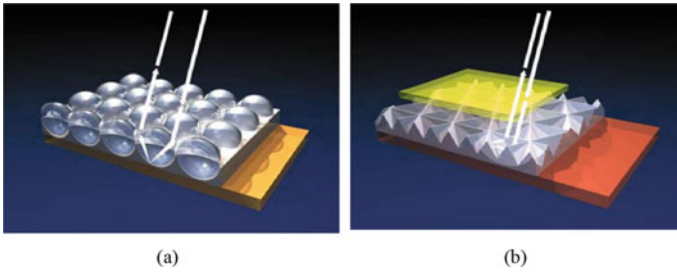


Fig. 5.48 Composition of retro-reflective sheets, **a** reflexive spheres, **b** corner reflector (Vik & Vikova, 2013)



Fig. 5.49 Emergency vests with retro-reflective strips (Vik & Vikova, 2013)

Aging is a natural feature of retro-reflective elements because retro-reflective materials are a common part of workwear that is subjected to frequent maintenance. Generally, it depends on the type of material, its conditions of use, the environment, and maintenance procedures. Retro-reflective properties of all reflective materials are affected by soiling. Each type of dirt, including liquid chemicals, fats, and similar substances, will reduce the brightness of the contaminated area and usually can damage the silver retro-reflective center strip. The retro-reflectometer measures the reflection of the light beam by means of a detector rotating around the light source. The measurement is carried out according to several normative regulations based on the CIE International Standard. The resulting brightness value L (cd m^{-2}) is influenced by the location of the object in space. The measurement assumes that the object being assessed (traffic sign, wearer of high-visibility clothing) can be viewed at different angles to the light source. From the observer's point of view, an important section is the so-called critical detail, which places the eye in the center of the viewing angle. The direct vicinity of the critical detail is decisive for the direct distinction of the critical detail (Vik & Vikova, 2013).

5.9.3 Active Light-Emitting Materials

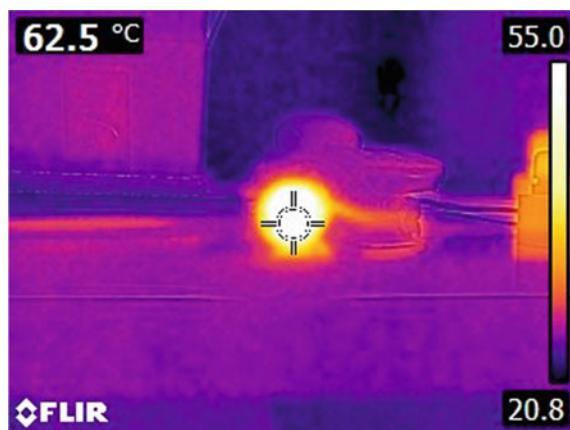
This is a kind of safety material that uses its light source. To ensure the function of active illumination, it is necessary to power and charge it. Clothing with built-in active safety features is not dependent on external exposure conditions. By applying electronics and lighting elements, either point LEDs or line illumination sources, it is possible not only to improve visibility but also to point out a change in driving direction or braking. This is the task of intelligent clothing, where the developments of active safety features are directed.

Point light sources

The main representative of point light sources is the light-emitting diodes LED—an electronic semiconductor device that works with relatively small values of input voltage and current. In the textile segment, these LEDs are used in combination with retro-reflective textiles that, thanks to their source, work in the dark, regardless of external light conditions. One of the basic disadvantages of LEDs is that they do not display direct contour and as point sources increasing the risk of misinterpretation of object dimensions. Arrays composed of LED radiation sources connected by conductive (metal) wires can eliminate this disadvantage. The problem is the substantial deterioration of clothing fabrics properties and increases in fabrics temperature due to heating produced by LED arrays (see Fig. 5.50).

It is, therefore, necessary to ensure its optimal cooling. Heating is generally a significant problem because the higher the current flowing through the LED, the higher amount of light is produced but also the higher amount of heat is emitted. As a direct point source of lights can the LED also cause dazzling to other road users. Textile reflective strips, removable magnetic LEDs, or cycling light reflective jackets (prepared at the Department of Clothing, TU Liberec) are LEDs in clothing

Fig. 5.50 Temperature of LED in use (62.5 °C)



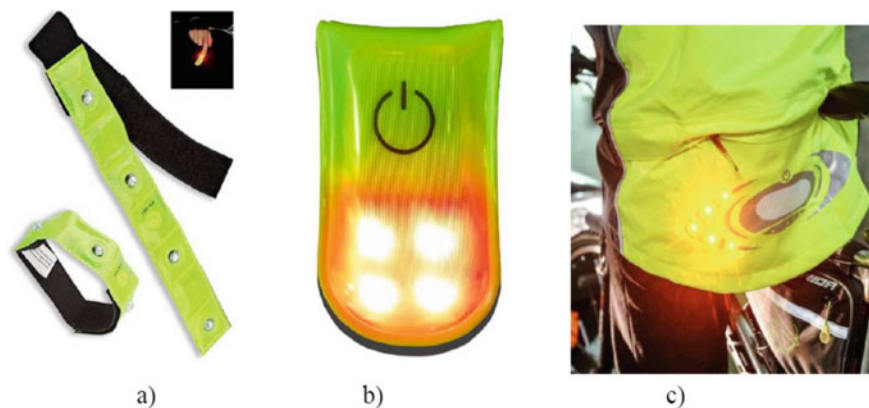


Fig. 5.51 Examples of safety elements with point sources of illumination, **a** textile reflexive strip with four LED, **b** removable magnetic LED, **c** reflexive jacket for cyclists

as an active safety feature or as illustrative examples of using a signaling element for communication with other road users (see Fig. 5.51).

In terms of durability, point illumination sources in textile structures are highly sensitive to mechanical stress and environmental influences. The intensity of the LEDs declines rapidly with the square of the distance from the source and depends on the chip type (Křemenáková, 2012a, 2012b).

Line light sources

In this active safety structure, the basic element is also an LED whose light is guided and continuously produced by the surface of the side-emitting polymer optical fiber (SEPOF) (1, 4–6). Side emission is enabled by modification of standard end-illuminated polymer optical fibers (POF) or by preparation of core-jacketed fibers (SEPOF). In order to ensure an active function, it is necessary to secure the fiber ends to the light source—LED and to a suitable power supply—the battery. Battery operation is time limited and usually lasts more than 7 h under continuous illumination (Křemenáková et al. 2012a, 2012b). For the selection of SEPOF, an important parameter is the attenuation of illumination as a function of distance from the light source, which critically depends on the diameter of the fibers. As a tradeoff between maximum illumination intensity and flexibility, the optimal diameters are 2–3 mm (Křemenáková et al. 2012a, 2012b, 2012c). It was evaluated (3, 6) that the working length of the fiber, which is effective to apply to clothing, is 2–4 m, and for line lighting, it is 10 m. Examples of utilization of structures (see Sect. 2.5) for safety textiles and active lighting are shown in Fig. 5.52.

Hybrid light sources

The only drawback of the active safety elements operation is the time constraint, which depends on the power source (battery) capacity. For this reason, there is a solution that would benefit from passive elements, in particular, those luminescent



Fig. 5.52 Example of safety textiles using line lighting systems, **a** textile safety strip, **b** illuminated school backpack, **c** functional reflective vest (image credit: SCILIF s.r.o co. Ltd.)

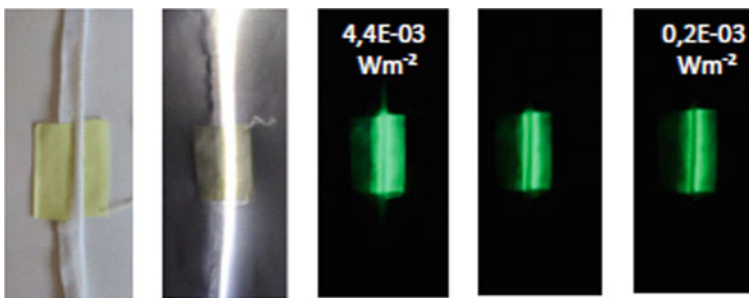


Fig. 5.53 Luminescence mode of hybrid ALIS

with phosphorescent pigments, when applying side-emitting optical fibers to textiles. These luminescent elements have a sufficiently intense secondary light emission capability (up to several **tens** of minutes). By combining them, a hybrid structure containing luminescent elements in combination with line lighting sources can be obtained, which could theoretically significantly extend the duration of operation of the entire active illumination system. Proper activation of the luminescence is a key point to ensuring the functioning of the whole system. The luminescence mode of hybrid ALIS is shown in Fig. 5.53 (Křemenáková & Militký, 2019a, 2019b).

5.10 Summary

The ALIS adaptive side illumination systems and their components were comprehensively analyzed. This system was already used for design purposes (see Fig. 5.54).

Fig. 5.54 Design with ALIS

It was found that illumination spectra of active and passive emission are in interaction. The use of reflective colors (yellow and orange) of the SELC textile cover increases the light output but does not sufficiently activate the luminescent tape with a phosphorescent coating. When using a white textile wrap or other non-reflective colors, the tape with a phosphorescent coating is sufficiently activated for intense emission after switching off of SELC illumination. For real use of the hybrid effect, it is necessary to find the proper frequency of SELC lighting (activation) and switch-off the exposure to extend the total time until the battery is discharged. Positive results were obtained by exposure to SELC color of white sample with woven-type tape phosphorescent coating, where the effect was measurable and visible within 30 min after exposure.

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