Selected Application of Linear Composites Containing Side Emitting Optical Fibres

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Abstract. The main aim of this contribution is description of side emitting plastic optical fibres basic properties and their efficient embedding into fibrous structures for creation of textile structures with active visibility in shadows. For preparation of textile structures containing side emitting plastic optical fibres the special weaving technology is used. Illumination system with light emitting diode (LED) is used as light source. Light intensity of textile structures is compared with light intensity of fibres. Incorporation of side emitting plastic optical fibres into fibrous tube provides sufficient side emission especially for plastic optical fibres with larger diameters. The corresponding technology has been developed and the possible applications were proved in real conditions. The use of side emitting POF in textile tube are still in the first stage of industrial realization and it will be necessary to optimize their composition and functionality for various targeted applications including surface effects, doping and use of special dyestuffs.

Keywords: side emitting optical fibres, safety textiles, active illumination, light intensity model, embedded optical fibres.

1. Introduction

Standard polymer optical fibre (POF) is a dielectric waveguide transferring light or infrared radiation across its axis by the mechanism of total internal reflection on the interface of two materials with different refractive indices. The main requirement for classical POF is to prevent side emission causing loss of transferred light. Description of classical POF and their application especially as sensors are described in [1]. In the side emitting plastic optical fibres (SEPOF) the light leaks out from their surface. Side emission occurs if the light incidence angle is smaller than critical angle. This effect can be obtained by the increasing of cladding refractive index, decreasing of core refractive index or by the change of incident light angle. It is also possible to use multiple micro-bending of core or cladding; additives causing reflection or fluorescence into core/cladding or to create geometric asymmetry in the core/cladding system. There are various commercial types of patented SEPOF including methods of their preparation [2, 3].

The SEPOF can be used for creation of optically active textile structures providing opportunities to highlight people and objects without the need for external light exposure. Due to the transmission loss, the intensity of radiation emitted in any direction decays exponentially along the straight fibre axis with increasing distance from the light source [4, 5].
An optical fibre integrated in weaving patterns can be described by a sequence of locally bended and straight sections. For this case the transmission loss is based on the distance between threads, thickness of threads and weaves. Local bends should be suppressed in the cases of using SEPOF for achieving active visibility at higher distances from light source. It is therefore necessary to use special embedding of SEPOF into textile structures e.g. in the form of tubes wrapped by textile yarns.

The aim of this paper is to describe optical properties of SEPOF and effective covering by fibrous structures to create safety textiles with active visibility under dark conditions. Braiding technology was used to create textile structures containing SEPOF [6]. The optical fiber end was connected with light energy source after cutting with heated wire and then by polishing with diamond powder. Light emitting diode (LED) was used as light source having illumination intensity $43.9 \text{ Wm}^{-2}$. A device was developed for measurement of light intensity on surface and cross section at various distances from light source. The dependence of intensity on surface and cross section with regard to the distance from light source is expressed by the exponential type model with the rate parameter attenuation factor. Second parameter defining quality of illuminating system is light intensity at the input to the fibre. The influence of the optical fibre type and diameter on the attenuation factor at the surface and cross section is quantified. Light intensity is compared between textile structures and optical fibres.

2. Experimental methods

Light rays are transmitted through optical fiber causing attenuation [7-8]. It depends on wavelength, type of fiber, it’s structure (i.e. crystallinity and orientation), impurities and accompanying substances (dopants), the distance from the source, and also on outer geometry (micro-bends, macro-bends, surface damage). When bending the fibers, some part of the emitted light rays is dependent on the ratio between fiber diameters and bending radius [9-11]. Bends in end emitting optical fibers inside textile structures are actually needed to achieve their surface illumination [11]. The bending of side-emitting optical fiber leads to loss of uniformity in illumination.

Attenuation is characterized by decrease of illumination intensity in optical fibers and it is undesirable when used in telecommunications technologies, due to loss of information. Due to the huge differences in the illumination intensity the attenuation is usually expressed in decibels. Attenuation coefficient $\alpha$ in decibel [dB] is defined as logarithm ratio between illumination power at input $P_i$ and at output $P_2$:

$$\alpha = 10 \log(P_i/P_2)$$

Eq. (1) implies that change in power ratio by one order is shown by change of attenuation by 10 dB. The attenuation rate $\alpha_L$ is defined as ratio of attenuation coefficient and distance between measuring powers $P_1$ a $P_2$.

$$\alpha_L = \alpha / L = \frac{10}{L} \log(P_i/P_2)$$

The unit of the attenuation rate is dB/m. The attenuation rate is ideally constant [14], but generally it is a nonlinear function of the length L. In the case when $\alpha_L = \text{constant}$, it follows equations (1) and (2), see [11]

$$P_2 = P_1 10^{-\alpha_L L/10}$$

Working fiber length $L_p$ is the length of the side-emitting optical fiber, which can be used realistically. At the end of this length illuminated power $P_{1p}$ is still sufficient. For this work attenuation $\alpha_p = 20$ and 30 dB were selected. The working length of the optical fiber can be calculated from Eq. (4).

$$L_p = \frac{10}{\alpha_L} \log(P_i/P_{1p})$$
Special device was developed for measurement of illumination intensity in straight condition. This on-line computer controlled device is composed of a light sensor, step driver, control unit, measuring channel and input/ output rollers. A schematic of this device is shown in Fig. 1.

![Figure 1. On-line device for measurement of illumination intensity in straight state, 1- light sensor, 2– step driver, 3– control unit, 4– measuring channel, 5– output rolls, 6– input rolls](image-url)

An illumination system with light emitting diode (LED) was developed and used as light source. The fiber end was connected with light energy source after cutting with heated wire and polishing with diamond powder. Optical fibers of type “Grace standard” and “Grace flexi” with different diameters were used (table 1).

Table 1. Optical fibres specification.

| Grace fibres specification | standard | flexi |
|---------------------------|----------|-------|
| Core/ Cladding material   | PMMA/ Polyvinylidene fluoride | PMMA Polytetrafluorethylene |
| Diameter                  | from 0.2 - 3 mm | 2 - 14 mm |
| Core refractive index     | 1.49     | 1.475 |
| Cladding refractive index | 1.41     | 1.34  |
| numeric aperture          | 0.48     | 0.48  |
| maximal input angle       | 57.4     | 75    |
| mass density              | 1190 kg m$^{-3}$ | 1190 kg m$^{-3}$ |
| wavelength                | 400 - 900 nm | 380 – 780 nm |
| temperature of use        | 20 – 70 °C | 15 – 80 °C |

3. Results and Discussion

Illumination intensity is measured as function of distance from source and is shown in Figure 2 and Figure 3. Experimental illumination intensity can be used for creation of regression model (see eq. (5)) and corresponding parameters can be obtained by nonlinear or linearized regression using least squares criterion. Eq. (3) can be written as

$$P(L) = P(0) 10^{-\alpha L/10}$$

(5)
where \( P(L) \) is illumination intensity at the distance from source \( L \), \( P(0) \) is illumination intensity at fiber input and \( \alpha_L \) is attenuation rate. By logarithmic transformation of eq. (5) the straight line \( \log P(L) = -\alpha_L L/10 + \log P(0) \) is obtained. Slope of this straight line \( k \) can be used for calculation of mean attenuation rate \( \alpha_L = -10 k/10 \) and intercept \( q \) can be used for calculation of illumination intensity on the fiber input \( P(0) = 10^q \). By use of regression, straight line parameters \( k \) and \( q \), coefficient of determination \( R^2 \) and parameters \( P(0) \) and \( \alpha_L \) were obtained, as shown in table 1.

For expressing working length of optical fiber \( L_p \), an illuminating power \( P_{Lp} \) must be obtained on the end of this length with sufficient value of attenuation coefficient \( \alpha_{Lp} \).

\[
\alpha_{Lp} = 10^{-\frac{10}{P_{Lp}}} \quad (6)
\]

Illuminating power \( P_{Lp} \) can replace \( P(L) \) in Eq. (5) and the working length of optical fiber \( L_p \) can be calculated as

\[
L_p = \frac{10}{\alpha_L} \log(\frac{P(0)}{P_{Lp}}) \quad (7)
\]

Working length calculated for attenuation coefficient \( \alpha_{Lp} \) from 10 to 20 dB is given in table 2.

| Parameters |
|-----------|
| „Grace-standard“ 0,25 mm | „Grace-flexi“ 14 mm |
| Illumination intensity on the fibre input \( P(0) \) [Wm\(^{-2}\)] | 0.000007 | 0.01367 |
| Attenuation rate \( \alpha_L \) [dB mm\(^{-1}\)] | 0.0071 | 0.00254 |
| Working length of optical fibre \( L_p \) for attenuation \( \alpha_{Lp}=10 - 20 \text{ dB} \) [mm] | 1409 and 2817 | 3937 and 7874 |

Illumination intensity model curve as standard power function (Eq.(5)) derived from assumption of constant rate of attenuation is shown in Figure 2 and Figure 3 as grey curve [1]. It was found, that at short distances from light source illumination intensity is sharply decreasing especially for higher diameter optical fibres (higher than 1 mm). Estimation of parameters \( P(0) \) and \( \alpha_L \) is not accurate and standard power function (Eq.(5)) is not suitable for these purposes. Black piecewise solid line in Figure 2 and Figure 3 is so called LLF2 model, it is linear piecewise function consisting of two different linear sections. This model is based on the assumption that in small distances from light source there is no uniformity in side emission due to aperture and critical angle. In second part the illumination intensity is slowly decreasing with distance from source \( L \) (system is adjusted). Local slopes of LLF2 are sensitivity coefficients \( a_1, a_2 \). Corrected illumination intensity at the fibre input is \( P_{cor}(0) \). LLF2 model is described by equation (it is linear regression spline with one knot)

\[
LLF2 = P_{cor}(0) + a_1 L + a_2(L - L_c) \quad (8)
\]

where function \((x)_+ = 0\) when \( x \) is negative and function \((x)_- = x\) if \( x \) is positive. \( L_c \) is distance of transition between first and second phase. Parameters of LLF2 for optical fibre were found by use of modified linear regression [18] as given in table 3. Working length of optical fiber \( L_{pcor} \) for attenuation \( \alpha_{Lp,cor} \) from 10 to 20 dB was calculated by using Eq.(7) as given in table 3.
Figure 2. Illumination intensity of fiber “Grace-standard” – fiber diameter 0.25 mm.

Figure 3. Illumination intensity of fiber “Grace-flexi” – fiber diameter 14 mm.

Table 3. Parameters of smoothing curves of illumination intensity calculated by using of LLF2

| Parameters                          | „Grace-standard“ 0.25 mm | „Grace-flexi“ 14 mm 0.25 mm |
|-------------------------------------|--------------------------|-----------------------------|
| Minimal residual sum of squares     | 1.372 E-11               | 0.00037                     |
| Corrected illumination intensity on the fibre input | 0.000009                 | 0.02993                     |
| Slope of first straight line $a_1$  | -1.64 E-08               | -0.000121                   |
| Slope of second straight line $a_2$ | -1.96 E-09               | -2.72 E-06                  |
| Distance of transition between first and second phase $L_c$ | 359.9                    | 165.0                       |
| Working length of optical fibre $L_{pcor}$ for attenuation $a_{pcor}$ = 10 and 20dB | 1378 and 1791           | 2709 and 3699               |

3.1 Illumination Intensity of Woven Structures

Weaving technology was used for preparation of textile structures containing side emitting POF[6, 11]. The differences between side illumination of POF with or without textile cover are shown in Figure 4.
Illumination intensities as function of distance from source are shown in Figure 5 for POF and the same POF covered with textile. It is visible that POF in textile cover shows higher side emission intensity.

![Figure 5. Side illumination intensity of POF and POF with textile cover.](image)

The parameters of LLF2 for POF and POF in textile cover is calculated by modified regression and given in the tab. 4.

**Table 4. Parameters of smoothing curves of illumination intensity calculated by using of LLF2.**

| Type               | 3mm-diameter POF | 3mm-diameter POF in fabric | 2mm-diameter POF | 2mm-diameter POF in fabric |
|--------------------|------------------|----------------------------|------------------|----------------------------|
| Critical point [Wm⁻²] | 0.123            | 0.203                      | 0.115            | 0.202                      |
| slope1 [Wm⁻²mm⁻¹]  | -0.0043          | -0.0071                    | -0.0012          | -0.0033                    |
| slope2 [Wm⁻²mm⁻¹]  | -5.40 E-05       | -0.00011                   | -9.96 E-05       | -0.00022                   |
| intercept1 [Wm⁻²]  | 0.826            | 1.439                      | 0.340            | 0.793                      |
| intercept2 [Wm⁻²]  | 0.097            | 0.152                      | 0.120            | 0.200                      |
| Lc [mm]            | 172.9            | 182.9                      | 192.8            | 192.77                     |

### 3.2 Applications of Line Light System

Side emitting POF in textile cover is useful for active safety applications which provide sufficient side emission especially with larger diameters. These structures can be used for many types of applications as silhouette visualization in the dark conditions: useful for active visibility of road users, persons (jackets, school bags, handbags, backpacks), objects (cars, bikes, baby carriages, wheelchairs), animals (straps for dog, bridle for horses), security lighting systems (cars outline, identifying open doors of cars in the dark, restrictions on roads), setting of limits (parking barriers, end of carpets, stairs, etc.), emergency lighting (hospitals) - lighting in corridors, lifts, edge visualization, etc., highlight information, aesthetically complement - separate application area may be a different color effects related to the design, creation of so-called emotional fabrics characterize the
mental state respectively feelings - information system. Some applications of POF with textile cover are given in Fig. 6.

![Applications of POF with textile cover.](image)

Figure 6. Applications of POF with textile cover.

Optimized POF in textile tube can be also used in the emergency lighting facilities (LIHS) marking of escape routes, etc. Illumination lighting with application of POF in textile tube (SEPOF Grace, diameter 6 mm, polyester textile cover of white color) in Na Plesi hospital (CZ) for lighting of irradiation room (Figure 6 (b)) and bed (Figure 6 (c)) were successfully realized.

The energy consumption and total cost of lighting were evaluated for hospital corridor of 16 m length. For sufficient illumination the LIHS (totally 6 W) or 4 light bulbs (each 40 W, i.e. totally 160 W) or alternatively 3 fluorescent tubes (each 15 W, i.e. totally 45 W) were installed and compared. The luminosity was measured by luxmeter (see Figure 7).

![Comparing of luminosity of different lighting systems.](image)

Figure 7. Comparing of luminosity of different lighting systems.

Line illumination by LIHS is evenly covered in the space (ratio between maximum and minimum luminosity is 1.5) and has minimal consumption of energy. Illumination by light bulbs and fluorescent tubes is uneven with over glare and low shine regions. Ratio between maximum and minimum luminosity is for light 2.3 and for fluorescent tubes even 4.6.

| Illumination system | Daily voltage | Daily consumption | Year consumption |
|---------------------|---------------|-------------------|------------------|
| Light bulb          | 12.8 kWh      | 33 CZK            | 12 147 CZK       |
| Fluorescent tube    | 3.6 kWh       | 9 CZK             | 3 416 CZK        |
| LIHS                | 1.4 kWh       | 4 CZK             | 1 329 CZK        |
For light illumination of 100 m hospital corridor of 8 hours daily during one year (price level 2.6 CZK per kWh) is price for different system given in table 5. It is visible that the lowest total cost is for LIHS illumination system i.e. 1329 CZK.

4. Conclusions
Lighting system [11] with (LED) was developed. Prototypes for measurement of illumination intensity in side emitting optical fibre was developed. Data treatment and evaluation was carried out. Quality of illumination system was determined as illumination intensity at fibre output. Parameters characterizing quality of optical fibres are attenuation rate and working length. Illumination intensity and mean attenuation rate are described as function of distance from the light source. There is considerable variation in the mean attenuation rate (upto 240 mm from light source for optical fibre). It was found that the inclusion of optical fibres into active safety systems will provide adequate visibility with larger fibre diameters. The adequate working length of fibres was obtained as about 2 m. Optical fibers can be used in straight form or with macro-bends for active visibility textiles. Textile covers improve the durability of the fibers.

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