Optical Attenuation of Linear Composites Containing SEPOF

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Abstract. Optical fibers are one category of specialty fibers originally developed for light transmission (fiber optic) and information (optical cables). The fiber consists of a core surrounded by a cladding. Standard polymer optical fiber (POF) is transferring light across its axis by the mechanism of total internal reflection. In the side emitting plastic optical fibers (SEPOF) the light leaks out from their surface. The conditions for obtaining side illumination can be derived from POF geometrical model composed of two materials with different refractive indexes. The main aim of this contribution is description of SEPOF optical properties and their efficient embedding into fibrous structures for creation of line illumination hybrid structure useful for design purposes and creation of safety textile structures with active visibility in shadows. The special device for measurement of light intensity on surface and cross section at various distances from light source is described. Light intensity of textile structures is compared with light intensity of fibers.

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 [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.

Comprehensive information about properties and applications of POF in the textile field are presented in the book [1]. There are various commercial types of patented SEPOF including methods of their preparation [2, 3, 11]. 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 main aim of this contribution is description of SEPOF optical properties and their efficient embedding into fibrous structures for creation of line illumination hybrid structure useful for design purposes and safety textile structures with active visibility in shadows. For preparation of textile structures containing SEPOF the special weaving technology is used [6]. The special device for measurement of light intensity on surface and cross section at various distances from light source is described. Light intensity of textile structures is compared with light intensity of fibres.

2. Basic of Fiber Optics

Standard i.e. end emitting optical fiber is a special form of a relatively long distance (hundreds meters to some kilometers) optical wave guide and consists typically of a cylindrical core and a cladding (see. fig. 1), both made from highly transparent materials. The core refractive index $n_1$ should be slightly higher than that of the cladding $n_2$ to avoid loss of illumination power due to side emission. Depending on ultimate applications, on the surface there is additional protective layer called as jacket.

![Figure 1. Typical structure of optical fiber.](image)

For purposes of line lighting in short distances (few meters) the so called side emitting optical fibers are used. The simple way how to obtain side emission is to change magnitude of refractive indices i.e. using slightly smaller core refractive index $n_1$ than that of the cladding $n_2$. Still there are a limited number of companies only producing side emitting optical fibers based on this simple idea. Second possibility is to use the end emitting optical fiber with modification enabling side emission. There are in fact possibilities to promote scattering of core by adding particles or changing super molecular structure; creating imperfections (grooves) in cladding; using structures with sharp bends (as in woven fabrics). In fact all these modifications are a little bit against aims of producers to suppress attenuation i.e. side emission. The side emitting optical fibers will be probably in future produced according to their main goal, i.e. side emission, with more even and approximately constant decay of illumination power along their working length. The properties and functionality of optical fibers are dependent on the refractive indices of core and cladding.

When light passes from a medium with a lower refractive index to a medium with a higher index, it is bent towards the normal plane between media. Otherwise light bends in the opposite direction (away from the normal plane, see fig. 2).

If the angle of incidence in this case is greater than the critical angle $\theta_c$ all the light energy is reflected back into the medium with a higher refractive index. This phenomenon known as total internal reflection is used to guide the light in optical fibers (fig. 2).
In the standard end emitting optical fibers, refractive index of core $n_1$ is always higher than refractive index of cladding $n_2$, i.e. $n_1 > n_2$. Over a certain angle $N_c$ the total reflection then takes place at the boundary between the core and the cladding. If light enters under lower angle, the partial refraction (side emission) occurs and only part of the total light energy is reflected back to core. Fig. 2 shows that total internal reflection (generally electromagnetic wave) occurs in the optical fibers at the boundary between the core and the sheath. The maximum angle $\phi_m$ (see fig. 2) when there is total internal reflection of light is equal to

$$\phi_m = \arcsin \left( \frac{n_2}{n_1} \right)$$

According to Snell’s law, the upper critical angle $\phi = N_c$ at input into the optical fiber is equal to [12].

$$N_c = \arcsin \left( \frac{\sqrt{n_2^2 - n_1^2}}{n_0} \right)$$

Here $n_o$ is refractive index of surroundings (for air $n_0 = 1$). The acceptance angle ($2N_c$) corresponds to the vertex angle of the largest cone of rays that can enter the core of the fiber. Assuming that there is a total internal reflection (i.e. input angle $\phi$ is below the critical angle $N_c$) the whole electromagnetic radiation is captured in core and propagates along the fiber axis. If the angle of incidence on the optical fiber is lower, the part of the light is refracted and there appears so-called leakage or partial side emission. Side emission occurs if the input angle of light incidence $\phi$ is higher than critical angle $N_c$. This effect can be obtained by the increase of $n_2$ or decrease of $n_1$ or by the change of input angle of incident light $\phi$.

The sine of the maximum incident angle $N_c$ is defined as the numerical aperture $NA = n_0 \sin(N_c)$. The angle $N_c$ is often denoted to as the acceptance angle, and twice the acceptance angle is denoted as the aperture angle. The $NA$ is defined by relation

$$NA = \left( n_1^2 - n_2^2 \right)^{1/2}$$

The $NA$ is a very important parameter of optical fibers, since it indicates their capacity for accepting and guiding light. The size of the $NA$ is solely dependent on the difference in the refractive indices of
the core and cladding material. For standard PMMA fiber is \( n_1 = 1.49 \) and \( n_2 = 1.40 \); thus \( NA = 0.50 \) and \( N_c = 30^\circ \).

Compared with other fiber types [8], POF has the largest numerical aperture and the largest core diameter. This is one of the most important advantages of POF, since the connection technology that can be used for POF fibers is more economical to apply than that used for glass fibers.

Due to the transmission loss, the power of radiation \( P \) [W] emitted in any direction decays exponentially along the fiber axis with increasing distance from the light source of the fiber as observed by Zajkowski [13, 14], while the percentage of light emitted per unit length is uniform over the entire fiber length.

The simple exponential model for prediction of this attenuation is proposed. Illumination power \( P(L) \) for straight optical fiber is decreasing with increasing distance from source \( L \) according to relation [15]

\[
P(L) = P(0) 10^{-\alpha L}
\]

where \( P(0) \) is illumination intensity of source and \( \alpha \) is attenuation coefficient of optical fiber. Coefficient \( \alpha \) describes attenuation dependent on fiber length

3. Measurement of Optical Attenuation

Illumination efficiency characterized by loss of light intensity generally depends on: light wavelength, fiber type, fiber structure, impurities, accompanying substances, outer geometric shape and mainly on distance from the source. For POF, the goal is to suppress attenuation because it is source of information loss. For SEPOF is side emission wanted and can be supported. The standard approach to characterize attenuation, dispersion and bandwidth of POF is described i.e. in book [1].

Special measurement and evaluation system was constructed for evaluation of LIHS attenuation in straight state and creation of the attenuation profile \( P(L) \) i.e. dependence of illumination intensity on distance from light source \( L \) till maximum length in the range of 1-20 meters [15]. Main principle is measurement of illumination intensity by using of integrating cylinder. The light emitted by the LIHS falls on the inner surface of the cylinder, which has a high reflectivity and is opaque, thus incident rays are scattered randomly in all directions (into the interior of the cylinder). For sufficiently big dimensions of this cylinder the random light scattering extends substantially to the statistically uniform illumination of its internal surface. Irradiation of inner surface \( E(A) \) [W m\(^{-2}\)] depends on the light power (illumination intensity) \( P(L) \) [W m\(^{-2}\)] escaping from measured surface area \( A \) of the LIHS to the inner surface of the cylinder at distance \( L \) from light source.

\[
E(A) = \eta P(L) \left( \frac{\pi d^2}{4} l \right)^{-1}
\]

where \( \eta [-] \) is efficiency coefficient, \( l \) is length and \( d \) is inner diameter of integrating cylinder. The sensor of light power has active area \( S_s \). Then the illumination intensity \( P(L) \) is calculated from measured radiant flux \( \Phi_s \) [W] by using of equation

\[
P(L) = \frac{\pi d^2 \Phi_s}{4 \eta S_s l}
\]

This principle was used for construction of on-line computer controlled measurement and evaluation system for creation of the attenuation profile (fig. 3). System is composed from radiant flux light sensor (THORLABS PM 1000 SB), step driver, control unit, measuring channel, input/ output rolls and illumination unit based on LED.
Illumination unit is composed from light emitting diode (LED) connected with power source. Electric power supply is 3W. At 10% conversion efficiency the light output power is of 300 mW. Moreover, about 30% radiates outward from the fiber, so that the radiant flux at the input is 100 mW. The LIHS is located between the feed rollers, which guide them to the integrating cylinder. The tow rollers are driven by step motor. The actual measurement is performed in predefined step lengths. Step lengths are processed by a step motor that drives the two rollers. The measurement process is controlled by a computer program created in MATLAB.

The computer unit is used also for calculation of attenuation profile including statistical analysis. Due to relative high variability of results, 20 attenuation profiles are usually measured. Robust estimator of mean illumination intensity and corresponding 95% confidence intervals are then calculated by robust Horn procedure suitable for small sample sizes [16].

It was found, that the model defined by eqn. (4) is not sufficient for mean intensity profile experimental course approximation. It was found that at short distances from light source, illumination intensity is strongly decreasing especially for POF with higher diameter (higher than 1 mm). For better expression of P(L) behavior, the so called LLF2 model was proposed. LLF2 is in fact linear spline i.e. linear piece-wise function composed from two different straight sections [16]. This model is based on the assumption that in short distances from light source there are some nonuniformities in side emission due to accommodation to aperture and critical angle. In second phase the illumination intensity is slowly decreasing with distance \( L \) from light source (system is accommodated). Local slopes of LLF2 are in fact sensitivity coefficients \( a_1, a_2 \). Corrected illumination intensity on the fiber input is \( P_{\text{cor}}(0) \). LLF2 model is described by equation (linear regression spline with one knot).

\[
LLF2 = P_{\text{cor}}(0) + a_1 L + a_2 (L - L_c), \tag{7}
\]

where function \( (x)_+ = 0 \) if \( x \) is negative and if \( x \) is positive, function \( (x)_- = x \cdot L_c \) is distance of transition between first and second phase. By using modified linear regression, [16] parameters of LLF2 for experimental mean attenuation profiles can be calculated.

As attenuation profiles characteristics of POF, the sensitivity coefficients \( a_1, a_2 \), corrected illumination intensity on the fiber input \( P_{\text{cor}}(0) \) and distance of transition between first and second phase \( L_c \) can be used. Based on comprehensive tests, it was found that the main factor influencing the intensity of the side emission of SEPOF is their diameter. For straight SEPOF, 20-40% of illumination intensity is lost.
at short distances from light source. The intensity of radiation is here falling sharply. After a certain length $L_c$, the illumination intensity decreases slowly.

As example the mean attenuation profile of SEPOF Grace-standard having diameter 0.25 mm was evaluated. Robust estimator of mean illumination intensity (points in fig. 4) and corresponding 95% confidence intervals (lines in fig. 39) were calculated.

![Figure 4. Mean attenuation profile for SEPOF Grace-standard with added line of $P(L)$ from eqn. (4) and line corresponding to LLF2 - eqn. (7).](image)

4. Line Illumination Textile Structure

Direct application of polymeric optical fiber - POF for embedding into textiles or creation of line lighting systems is not so easy. POFs are created from polymeric materials which are sensitive to surface damage, their mechanical properties are not as good as properties of synthetic fibers, durability in standard conditions of use are limited, they are degraded under UV radiation, sensitive to moisture, and their comfort properties including hand (touch) and drape are generally bad.

For side emitting optical fiber - SEPOF it is possible to have sufficient side illumination in straight state. One solution how to avoid the problems with POF and SEPOF is to use so-called line illumination hybrid structure - LIHS composed from SEPOF in core and cover (textile tube) from textile material. LIHS, have the following benefits:

- Enhancing illumination intensity by selection of textile layer composition and surface dopants.
- Protection of LIHS against weather including UV and combination of temperature/moisture.
- Enabling LIHS standard maintenance during use as washing.
- Suppression of mechanical damage as abrasion and sensitivity to repeated multiaxial deformation.
- Simplification of attachment of LIHS into textiles by standard techniques as sewing.

Each structure containing LIHS needs to have lighting system and power supply. Components of side illumination system containing LIHS are shown in fig. 5.
The SEPOF end connected with light energy source is prepared by cutting with heated wire and then by polishing with diamond powder. Illumination system with light emitting diode (LED) is used as light source (illumination intensity of source is 43.9 Wm⁻²).

For quantitative comparison of SEPOF and LIHS side illumination the attenuation profiles P(L) were created. Illumination intensity as function of distance from source for SEPOF and the same SEPOF embedded into textile tube are shown in fig. 6.

It is visible that LIHS (SEPOF in textile cover) is producing higher side emission intensity in comparison with SEPOF only.

5. Discussion
LIHS can be used for creation of safety textiles, fashion purposes and line lighting. Safety textiles containing LIHS have these main advantages:

- The object shape is highlighted directly which significantly reduce the risk of incorrect interpretation of their size.
- Side emission is not dependent on the conditions of external exposure (typically vehicle headlights), these active lighting systems operate well in darkness.
- There is no glare disturbing e.g. road users.
Due to full integration into the fabric SEPOF are protected against environmental influences (moisture, UV radiation). It is simple to use reflective or fluorescence colors for dyeing or coating outer textile layer enhancing diffusion scattering. The simple removal of power/ light source enable treatment of textiles according to standard procedures. Based on the practical testing the following care rules were specified:

- gentle machine wash, moderate mechanical treatment, rinses and spin drying,
- do not bleach with chlorine,
- do not iron,
- can be cleaned with perchlorethylene,
- do not tumble dry.

The examples of application of systems containing LIHS for clothing and accessories are shown in fig. 7, fig. 8 and fig. 9.

Figure 7. Systems using LIHS for safety purposes.

Figure 8. Systems using LIHS for fashion.
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Figure 9. Systems using LIHS for accessories.

Line lighting systems based on LIHS have the following advantages:

- can be used for line illumination of complicated ways and significantly reduce the local variation of light intensity,
- low cost of lighting on the level of illumination standards,
- not local over lighting,
- intensity of light is controlled by voltage,
- simple connections to permanent or portable electricity sources
- simple branching of line lighting
- maintenance according to standard procedures

Line lighting systems based on LIHS can be used for:

- setting of limits (parking barriers, end of carpets, stairs, etc.).
- emergency lighting (hospitals, hotel, dormitories, supermarkets)
- lighting in corridors, lifts, edge visualization, etc.

The example of line lighting are in fig. 10.

Figure 10. Systems using LIHS for line illumination.

6. Conclusion
Plastic optical fibers applied in illumination and decorations are as follows [86]:

- End emitting optical fiber POF are mainly using the lighting effect of the end face of fibers to achieve decorative lighting.
- Side emitting optical fiber SEPOFs are easy to be used to set off the outline of patterns of objects and produce a variety of artistic design.
Flash point optical fiber are used to make special effect. These fibers can be made into fiber-optic curtains, fiber-optic waterfall and other fiber-optic craft products.

Recently, the POF and SEPOF technology has been developing quickly, the applications has been recognized in many branches. The LIHS 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 dye stuffs. The system of creation of illumination intensity profiles (see fig. 3) will be simple tool for evaluation of new effects and optimization of LIHS based systems. Probably the most important element for efficient low cost active illumination system creation is now the cost of control unit with battery.

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