ABSTRACT

The main aim of this work is evaluation of experimental illumination intensity of side emitting optical fibers in straight and bent state. Illumination intensity is dependent on fiber diameter, bending angle and distance from light source. It was found that for smoothing of experimental data of illumination intensity as function ratio between diameter of bending cylinder and diameter of fiber the linear piecewise function can used. Side emitting polymer optical fibers embedded to textile structures can be applied for creation of optically active textile structures providing opportunities to highlight people and objects without the need for external light exposure.

Key Words: side emitting polymer optical fibers, attenuation coefficient, mean attenuation rate

1. INTRODUCTION

Standard optical fiber is a light guide transmitting the light beam along its axis working in accordance with Snell's law of reflection. Typically, the optical fibers are used in telecommunication technologies [1]. Side-emitting optical fibers illuminate part of the rays through their surface. These fibers incorporated into textile structures may be used as the active visibility textiles in conditions of reduced visibility [2].

When light rays are transmitting through optical fiber, attenuation occurs [3-8]. It mainly depends on light wavelength, fiber type, fiber structure (i.e. crystallinity and orientation), impurities and accompanying substances (dopants), the distance from the source, and also on the outer geometric shape (micro-bends, macro-bends, surface damage). Bends caused by incorporation of end emitting optical fibers to textile structures are actually needed to achieve their surface illumination [9-12]. The bending of side-emitting optical fiber leads to loss of illumination uniformity.

It is possible to define attenuation coefficient, attenuation rate and working fiber length. Attenuation coefficient is defined as logarithm ratio between illumination power on the input and on the output [14-15]. The attenuation rate is defined as the ratio of attenuation coefficient and the distance between measuring powers. Working fiber length is the length of the side-emitting optical fiber, till which it can be really used. At the end of this length the illuminated power is still sufficient [16].

2. EXPERIMENTAL PART

Special devices for measurement of optical fiber illumination intensity in straight state and bent state were proposed. Illumination system with light emitting diode (LED) was created and used as light source for side emitting optical fibers. Polymeric side emitting optical fibers “Grace-standard” and “Hypoff” with different diameters were used for measurement of
illuminating intensity in straight and bent states. The optical fiber end connected with light energy source was prepared by cutting with heated wire and then by polishing with diamond powder. Illumination intensity as function of distance from source for optical fiber „Grace-standard“ having diameter 0,25 mm is shown in Fig.1.

Experimental illumination intensity data can be used for creation of regression model (see eq. (1)). Corresponding parameters can be obtained by the standard nonlinear or linearized regression using least squares criterion. Illumination intensity $P(L)$ at the distance from source $L$ can be described by equation

$$P(L) = P(0) 10^{-\alpha L / 10}$$  \hspace{1cm} (1)

where $P(0)$ is illumination intensity on the fiber input and $\alpha L$ is attenuation rate. By logarithmic transformation of eq. (1) the straight line $\log P(L) = -\alpha L / 10 + \log P(0)$ results. Slope of this straight line $k$ can be used for calculation of mean attenuation rate $\alpha L = -10 k$ and intercept $q$ can be used for calculation of illumination intensity on the fiber input $P(0) = 10^q$. The quality of fit is expressed by coefficient of determination $R^2$. Parameters $P(0)$ and $\alpha L$ are shown in table 1. On the end working length of optical fiber $L_p$ the sufficient value of illuminating power $P_{Lp}$ should be ensured.

Illuminating power $P_{Lp}$ can replace $P(L)$ in Eq. (1) and then working length of optical fiber $L_p$ can be calculated

$$L_p = \frac{10}{\alpha L} \log \left( \frac{P(0)}{P_{Lp}} \right)$$  \hspace{1cm} (2)

Working length of optical fiber $L_p$ calculated for attenuation rate $\alpha L$ is connected with attenuation coefficient $\alpha_{Lp} = \alpha L L_p$ [dB]. The $L_p$ for $\alpha_{Lp} = 10$ and 20 dB is shown in table 1 for optical fiber „Grace-standard“ with diameter 0,25 mm.

Figure 1. Illumination intensity of fiber „Grace-standard“ – fiber diameter 0,25 mm

It was found, that at short distances from light source is illumination intensity strongly decreasing especially for optical fibers with higher diameter (higher than 1 mm). Estimation of parameters $P(0)$ and $\alpha L$ is not accurate and model function (Eq.(1)) is not suitable for these purposes. Black piecewise solid line in Fig.1 is so called LLF2 model. This linear piecewise function consists from two different straight sections. This model is based on the assumption that in short distances from light source there are some no uniformity in side emission due to accommodation to aperture and critical angle. In second phase the illumination intensity is
slowly decreasing with distance from source $L$ (system is accommodated). Local slopes of LLF2 are in fact sensitivity coefficients $a_1$, $a_2$. Corrected illumination intensity on the fiber input is $P(0)_{cor}$. LLF2 model is described by equation (it is in fact linear regression spline with one knot)

$$LLF2 = P_{cor}(0) + a_1L + a_2(L - L_c),$$  

(4)

where function $(x)_+ = 0$ if $x$ is negative and $(x)_+ = x$ if $x$ is positive. The $L_c$ is distance of transition between first and second phase. By using of modified linear regression procedure [17] parameters of LLF2 for optical fiber „Grace-standard“ with diameter 0,25 mm were found, see table 1. By using of Eq.(3) working length of optical fiber $L_p$ for attenuation $\alpha_{lp}$ 10 and 20dB were calculated see table 1. Attenuation rate was calculated by Eq. (1) and smoothed by LLF2, too (see Fig.2).

**Table 1.** Parameters of regression model and smoothing curves of illumination intensity for side emitting fiber „Grace-standard“ with diameter 25 mm

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Parameteres of regression model</th>
<th>Parameteres of smoothing curve LLF2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal residual sum of squares $S$ [Wm$^{-2}$]$^2$</td>
<td>-</td>
<td>1,372E-11</td>
</tr>
<tr>
<td>Illumination intensity on the fiber input $P(0)$ / $P_{cor}(0)$ [Wm$^{-2}$]</td>
<td>$P(0) = 0,000007$</td>
<td>$P_{cor}(0) = 0,000009$</td>
</tr>
<tr>
<td>Slope of first straight line $a_1$ [Wm$^{-2}$ mm$^{-1}$]</td>
<td>-</td>
<td>-1,64E-08</td>
</tr>
<tr>
<td>Slope of second straight line $a_2$ [Wm$^{-2}$ mm$^{-1}$]</td>
<td>-</td>
<td>-1,96E-09</td>
</tr>
<tr>
<td>Distance of transition between first and second phase $L_c$ [mm]</td>
<td>-</td>
<td>359,9</td>
</tr>
<tr>
<td>Attenuation rate $\alpha_L$ [dBmm$^{-1}$]</td>
<td>0,0071</td>
<td>-</td>
</tr>
<tr>
<td>Working length of optical fiber $L_p$ for attenuation $\alpha_{lp}$ =10 and 20dB [mm]</td>
<td>1409 and 2817</td>
<td>1378 and 1791</td>
</tr>
</tbody>
</table>

![Figure 2. Attenuation rate for fiber “Grace-standard” – fiber diameter 0,25 mm](image-url)

Technique for measurement of changes in light intensity along bent fiber was proposed. Principle of light intensity measurement along bent fiber is shown in Fig.3. First prototype of measurement device was created. The illumination intensity of side emitting optical fibers with different diameter $d$ was measured at various bending angles (from 0° to 180°) around cylinder with diameters $D$ from 30 mm to 350 mm. Illumination intensity can be imaged as function of ratio $D/d$ ( $D$ - diameter of bending cylinder, $d$ - fiber diameter) see Fig.4.
Illumination intensity in Fig. 4 was measured for fiber Hypoff having diameter 1 mm, 1.2 mm and 1.4 mm. For smoothing of experimental data of illumination intensity model LLF2 see eq.(4) was used, too. Local slopes $a_1$, $a_2$ of LLF2 representing sensitivity of illumination intensity on the ratio $D/d$ as function of bending angle are shown in Fig. 5.

**Figure 3.** Measurement of illumination intensity at bending of optical fiber
1 – light source, 2 – optical fiber, 3 – cylinder, 4 – sensor, 5 – clamp jaw

**Figure 4.** Illumination intensity of optical fibers as function of ratio between cylinder diameter and fiber diameter

**Figure 5.** Illumination intensity of optical fibers as function of ratio $D/d$ 
($D$ - cylinder diameter, $d$ - fiber diameter)
3. RESULTS AND DISCUSSION

Two methods for smoothing of experimental values of illumination intensity i.e. exponential regression function and LLF2 model (linear regression spline with one knot) were used. It was found that LLF2 model is much better for description of experimental illumination intensity, see Fig.1. It was found that illumination intensity can be divided to two phases. First phase represents no uniformity in side emission due to accommodation to aperture and critical angle and illumination intensity is strongly decreasing. In the second phase system is accommodated and illumination intensity has low level and it is slowly decreasing. The LLF2 model leads to better estimate of illumination intensity on the fiber input $P_{cor}(0)$ which represents quality of illumination system and it is necessary for calculation of other parameters. Quality of illumination system is dependent on its construction and on the quality of fiber cross-section. The LLF2 provides other parameters as distance of transition between first and second phase and slopes of straight lines, which express sensitivity of mean illumination intensity on the distance from source. Working length $L_p$ calculated by LLF2 is shorter than working length calculated by exponential function (Fig.1). By using of LLF2 it is possible to calculate mean attenuation rate of optical fiber (Fig.2).

According to these results, illumination intensity is decreasing function of ratio $D/d$ and can be divided to two phases described by LLF2 function, too. By using bent fibers, the illumination intensity is significantly increased (bending angle 90° - 100°). This phenomenon is used for illumination of end emitting optical fibers and should be used for side emitting optical fibers embedded in fabric. For embedding of optical fibers into woven or knitted fabrics it is necessary to investigate micro-bending of fibers with ratio $D/d$ about 1 also. In this case illumination intensity is strongly increasing and it can be applied for design or for construction of textiles with application in medicine [12]. For higher values of ratio $D/d$ macro-bending of fibers were studied because it is typical in application of side emitting polymer optical fibers for high visibility protection textiles [16].

4. CONCLUSION

Illumination system [17] with light emitting diode (LED) was created and used as light source. Prototypes for evaluation of side emitting optical fiber illumination intensity was developed and tested. The system of data treatment and evaluation of result was proposed and checked. Parameter for evaluation of quality of illumination system as illumination intensity on the fiber input was proposed. Parameters characterizing quality of optical fibers as mean attenuation rate and working length were defined. It was found that illumination intensity and mean attenuation rate are function of distance from light source. Method for calculation of their sensitivity was proposed. Despite of considerable variation in the mean attenuation rate (till 240 mm from light source for fiber "Grace-standard") it is clear that the incorporation of these fibers into active safety textiles will provide sufficient emissivity especially in larger diameter fibers. Results of this work should be used for incorporation of optical fibers into woven and knitted textiles. According to results of this work, it is suitable to use POF in straight state or with macro-bends for active visibility textiles. It is better to create fibers with textile cover from durability point of view [2]. Higher fiber diameter leads generally to higher bending rigidity and lower flexibility. The mechanical and thermal behavior of the optical fiber and their durability are important as well [17].
5. REFERENCES


