ASAP Educational License;
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Simulation of optical phenomena in step-index fibers and fiber-bundles

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1. Motivation

In panel-displays which are based on a fiber bundle technique, each "pixel" is illuminated by a slim fiber bundle, consisting of several dozens of single fibers. These individual fibers bundles are tightly packed and sealed together a their input end to form a fiber cable harness with a compact common input face ("super-bundle"), illuminated by a particular programmable projector. In this tightly packed "super-bundle" the single fibers belonging to different bundles are no longer well separated but glued in close proximity to one another. Under these circumstances, cross-talk between fibers belonging to different bundles is becoming a critical effect. For that reason, modeling of optical phenomena in fibers and fiber-bundles should provide some insight to the origin of the cross-talk effects observed in experiments.

In the Lab for Engineering Optics of the Fachhochschule Wiesbaden, University of Applied Sciences, led by Dr. Uwe Langbein, core competence in fiber analysis has been based so far on wave-optical simulation techniques that are not appropriate to the highly multimode fibers used in fiber harnesses. For that reason, the application of a suitable ray-optical simulation tool was in order. Such a tool should not only provide some more insight into those specific cross-talk effects, which have been the subject of my final thesis, but should deepen our understanding of optical phenomena in optical fibers in general from the point of view of ray optics.

Our decision for ASAP was based on the good reputation of this software system but also by the fact, that the project was partly performed in cooperation with SCHOTT Glas, a major global supplier of optical glasses, who uses ASAP too.

2. Demonstration of basic optical phenomena in single multimode fibers

In a first step, ASAP was used to simulate basic optical phenomena in single optical fibers. This step should provide both improving the own capabilities in handling ASAP and to obtain graphical presentations of specific phenomena for educational purposes.

2.1 Setup of a single optical fiber

ASAP starts in defining optical objects by their geometric properties, i.e. bounding surfaces und interfaces.

Figure 1 shows a single step-index fiber, which is covered by a layer of glue. The surrounding medium is air.

![Figure 1 Basis geometry of the single fiber relevant for the subsequent simulations](image-url)
The following parameters and optical properties have been assigned to the involved media:

**Geometrical parameter**

- $d_{\text{Fiber}} = 53 \, \mu m$
- $d_{\text{Cladding}} = 1.6 \, \mu m$
- $d_{\text{Glue}} = 100 \, \mu m$
- $l_{\text{Fiber}} = 10 \, mm$

**Optical properties**

- **Core glass**
  - Refractive index $n_{LF5} = 1.5848$
  - Damping constant $D_{LF5} = 180 \, dB/km$

- **Cladding glass**
  - Refractive index $n_{T8250} = 1.4905$
  - Damping constant $D_{T8250} = 9000 \, dB/km$

- **Glue**
  - Refractive index $n_{\text{Kleber}} = 1.564$
  - Damping constant $D_{\text{Kleber}} = 256000 \, dB/km$

The operation wavelength is 550 nm.

Code-Segment 1 shows the implementation of the introduced parameters, which are valid for all simulations.

```plaintext
!! REFRACTIVE INDICES
N_LF5=1.5848     !! Fiber Core
N_T8250=1.4905   !! Fiber Cladding
N_GLUE=1.564     !! Glue

!! DAMPINGKOEFFICIENTS D
D_LF5=180*10^-6  !! dB/mm
D_T8250=9000*10^-6 !! dB/mm
D_GLUE=256000*10^-6 !! dB/mm

!! Zuweisen der optischen Eigenschaften zu benannten Medien
MEDIA
(N_T8250) ABSORB D_T8250*LOG(10)/10 'MANTEL' !! n-Cladding
(N_LF5) ABSORB D_LF5*LOG(10)/10 'KERN' !! n-Core
(N_GLUE) ABSORB D_GLUE*LOG(10)/10 'KLEBER' !! n-Glue

!! GEOMETRY
D_FIBER=0.053     !! Fiber diameter [mm]
D_CLADDING=0.0016 !! Thickness of cladding [mm]
D_GLUE=0.100      !! Diameter of glue “ferrule” in mm

!!
F_FRONT=0        !! Start of fiber along Z-Axis [mm]
F_BACK=10        !! End of fiber along Z-Axis [mm]
```

**Code-Segment 1: Definition of the optical and geometrical parameters implemented into ASAP**

Absorption has been modeled in ASAP by using the `ABSORB`-Property within the `MEDIA` definition. The scaling factor $\log(10)/10$ is necessary to switch between the technical and the physical damping constant. The technical damping constant $D$ is defined by:
\[ \tau_D(l) = 10^{\frac{D}{10}} \]  

(1)

In contrast, ASAP uses the natural exponential function:

\[ \tau_D(l) = e^{-\alpha l} \]  

(2)

Hence the scaling factor is:

\[ \alpha_D = D \cdot \frac{\ln(10)}{10} \]  

(3)

Code-Segment 2 shows the implementation of the relevant interfaces into ASAP. The front- and endfaces of the fiber 'FIBER.CORE.FRONT' and 'FIBER.CORE.BACK' are described by an ellipse perpendicular to the z-axis. The radii auf the ellipse are equal to form a circle with the dimensions of the fiber core \( (D_{\text{FIBER}} - 2 \times D_{\text{CLADDING}})/2 \). (F_FRONT) and (F_BACK) fix the positions of the fiber surfaces along the z-axis. INTERFACE COATING BARE AIR CORE denotes the optical surface at the front and back-endface of the fiber.

The interface core - cladding has been modeled as a tube defined as \[ \text{TUBE Z (F_FRONT)} \ 2@\left(\frac{D_{\text{FIBER}} - 2 \times D_{\text{CLADDING}}}{2}\right) \ (F_{\text{BACK}}) \ 2@\left(\frac{D_{\text{FIBER}} - 2 \times D_{\text{CLADDING}}}{2}\right) /2 \). The tube interface, core-cladding has been described by INTERFACE COATING BARE CORE CLADDING. The cladding tube and the glue tube have been defined in the same way.

Figure 2 shows the fiber implemented into ASAP. Red lines indicate the fiber core, blue lines the cladding and light brown lines the surrounding glue medium.
2.2 Simulation of basic optical effects in optical fibers

In order to get a feeling of how ASAP is operating, a series of fundamental optical phenomena have been studied in single fibers.

First of all, the total internal reflection was modeled by ASAP. To this end three single rays have been sent onto the front face of the optical fiber with:

a) red drawn – incoming angle is exactly the critical angle for total internal reflection $\alpha_G$
   $\rightarrow$ The ray is transmitted along the core-cladding-surface
b) black drawn – incoming angle is $\alpha_G + 1^\circ$
   $\rightarrow$ Ray leaves the fiber
c) blue drawn – incoming angle is $\alpha_G - 1^\circ$
   $\rightarrow$ Ray is guided in the fiber by multiple total internal reflections

In all three cases the plane of incidence intersects the optical axis of the fiber (meridional rays). A more general class of light rays does not intersect the optical axis at all, thus traveling on helix-like paths (helix-rays). The projection of the trajectory of helix-rays onto the fiber cross-section forms a polygon. This polygon is enclosed by a circular ring, see figure 4.

![Figure 3 Guided and unguided rays within a fiber](image)

![Figure 4 Representation of a helix-ray, (a) projection view, (b) isometric including front and back face of the fiber](image)
Using a small slightly divergent ray bundle instead of a single ray, all rays will travel on their helix-paths. After a certain length of the fiber these single rays will spread over the complete circumference of the fiber core.

Figure 5 Chiral-rays, (a) beam spreading down the fiber, (b) spot diagram at the endface of the fiber

In summary, ASAP provides a descriptive insight into the propagation characteristics of helix-rays, quite frequently ignored in ordinary textbooks.

Simulation of the exit light-cone formed by a fully excited fiber

In this numerical experiment, the fiber core has been illuminated homogeneously by a circular light disk placed in close proximity to the input face of the fiber core. The light disk diameter did not exceed the fiber core diameter and an isotropic illumination into the full half space has been assumed, see figs. 6 and 7a.

The corresponding code in ASAP is:

```plaintext
EMITTING DISK Z -0.001 2@((D_FIBER-3*D_CLADDING))/2 (N_RAYS) 2@(W_ABSTRAHL) ISO
```

With:

- 2@((D_FIBER-3*D_CLADDING))/2 → semi diameter of the disc
- (N_RAYS) → number of rays emitted by the disc
- 2@(W_ABSTRAHL) → aperture of the disk as shown in figure 6
- ISO → isotropic ray density for the complete aperture

Figure 6: Fiber illumination by an emitting disk
The light cone created by the fiber at its back face will be mainly determined by the optical properties of the fiber, especially by its critical angle of total internal reflection. For instance, this angle defines the aperture angle $\alpha_G$ of the exit light cone of the optical fiber:

$$\alpha_G = \arcsin\left(\sqrt{n_K^2 - n_M^2}\right) = \arcsin\left(\sqrt{1.5848^2 - 1.4905^2}\right) = 32.58^\circ \quad (4)$$

which is strictly relevant for meridional rays.

Figure 7: Angular light distribution, (a) of the light source, (b) at the back face of the fiber

Figure 7.a shows the angular light distribution of the emitting disk placed directly in front of the front face of the fiber. A homogeneous distribution within statistical noise is visible. Figure 7.b displays the angular light distribution at the back face of the fiber, formed by rays guided along the fiber. A very sharp slope at an angle of 32,6° (measured within the ASAP plot file) is the result of the simulation. This angle is similar to the analytical value (see equ. 4), which is quite satisfying.

Modeling of length-dependent fiber transmission

The main mechanisms which reduce optical fiber transmission are material absorption and Fresnel-losses. A rough analytical model predicts:

$$\tau(l) = \tau_{\text{Fresnel}}^2 \cdot \tau_{\text{Dämpfung}}(l)$$

$$\tau(l) = 1 - \left(\frac{n_{\text{Kern}} - n_{\text{Luft}}}{n_{\text{Kern}} + n_{\text{Luft}}}\right)^2 \cdot \frac{D_{\text{Kern}}}{10} \cdot 10^{-\frac{D_{\text{Luft}}}{10}}$$

$$\tau(l) = \left(1 - \frac{1.5848 - 1}{1.5848 + 1}\right)^2 \cdot \frac{180 \cdot 10^7 \cdot dB}{10}$$

By means of ASAP, a scan of the fiber length has been performed by applying an $\text{ITER}$ procedure. In Figs. 8 and 9 both analytical and numerical predictions have been compared,
where Figure 9 shows an enlarged part of both transmission graphs from figure 8. An almost perfect correspondence for both graphs can be stated.

Figure 8 Comparison of the simulated (a) and calculated (b) length depended transmission.

Figure 9: Zoomed plot of the transmission curves of Figure 8.
3. Cross-talk modeling at the common input face of a fiber harness

3.1 Setup of the fiber bundle

A bundle of fibers packed in a glue tube has been used as the simulation model. The fibers will be arranged in a hexagonal grid pattern to ensure a high package density. For both cases. For the following cross talk simulations only the hexagonal packing which is the closed possible packing has been used. For comparison a rectangular grid has been introduced too, see Fig. 10.

Figure 10: Cross section of two fiber bundles with (a) hexagonal and (b) rectangular packing grid

Now two new geometric parameters have been introduced. One parameter is the distance of two neighbouring fibers [A_FASER]. The distance is set to 53.5 µm which is a very close approximation of the fiber distance, with implies a minimal distance of 0.5 µm, which is a quite realistic value. The other new parameter is the overall diameter of the bundle [D_KLEBER].

3.2 Packing density

As a first check of the introduced bundle setup, its total transmission under complete illumination of the bundle cross-section has been simulated. Evidently, the total transmission is determined by the packing density $\eta_P$ which can be checked by calculating the relevant fluxes $\Phi_{IN}$ and $\Phi_{OUT}$, see equ. 6 and 7.

![Figure 11 Section of the fiber bundle with assigned fluxes](image)

The flux emitted at the back face of the fiber with ignored damping losses is calculated as:

$$\Phi_{OUT} = \Phi_{IN} \cdot (1 - \rho_{\text{Fresnel}})^2 \cdot \eta_P$$  \hspace{1cm} (6)

This formula gives the packing density as:

$$\eta_P = \frac{\Phi_{OUT}}{\Phi_{IN} \cdot (1 - \rho_{\text{Fresnel}})^2}$$  \hspace{1cm} (7)

where $\rho_{\text{Fresnel}}$ denotes the Fresnel reflection losses at both endfaces.
For calculating the packing density from the geometrical parameters the following formula holds:

\[
\eta_p = \frac{A_{\text{Faserkerne}}}{A_{\text{Bündel}}} = N_{\text{Fasern}} \cdot \frac{d_{\text{Faserkerne}}^2}{d_{\text{Kleber}}} \tag{8}
\]

In ASAP the light source was realized by an emitting disk place directly in front of the bundle, sized equally to the bundle diameter. The source emits its flux in an aperture angle of 1°. 10000000 rays and a bundle length of 10 mm have been chosen.

The table shows the comparison of calculated (Equ.8) and simulated (Equ.7) packing densities.

**Table 1 Comparison of calculated an simulated packing density for two fiber grids**

<table>
<thead>
<tr>
<th># of fibers</th>
<th>calculated density [%]</th>
<th>simulated density [%]</th>
<th>(\Phi_{\text{OUT}})</th>
<th>(\Phi_{\text{IN}})</th>
<th>(\rho_{\text{Fresnel}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>rectangular packing</td>
<td>25</td>
<td>38,8%</td>
<td>38,9%</td>
<td>35</td>
<td>100</td>
</tr>
<tr>
<td>hexagonal packing</td>
<td>37</td>
<td>57,4%</td>
<td>57,5%</td>
<td>51,8</td>
<td>100</td>
</tr>
</tbody>
</table>

The simulation results are very close to the theoretical values, so a correct implementation is very likely.

Figure 12 shows the bundle geometry and the spot positions at the back face of the fiber bundles. Evidently rays are present at the core areas of the bundle only. All other rays have been attenuated within the glue and the cladding areas of the bundle cross section.
3.2 Potential cross talk mechanisms

3.2.1 Stray light mechanisms and their implementation
At the common endface of a fiber harness (“super bundle”), most of the stray light is produced in general. This is due to those light rays that impinge onto the entrance face areas outside the fiber cores. In addition, all bundle components contain imperfections which give rise to light scattering and hence to stray light.

At first we can assume volume scattering process, depending on the density of scattering particles inside the glass and glue. Furthermore a very thin wax layer which is applied during the production process of the single fibers will be an additional scattering source. This scattering mechanism will be implemented as a surface scattering process.

Volume scattering of Henyey-Greenstein type

The Henyey-Greenstein scattering model is a simple model based on three parameters.

These parameters are defined as:
- \( g \) directional factor of scattering, 0 for isotropic scattering, +1 for perfect forward scattering and -1 for perfect backscattering.
- \( p \) Scattering efficiency per particle; 1=every scatter particle will scatter the ray.
- \( q \) Overall fractional area obscuration per unit length in the scattering media, the product of \( q \) and \( p \) is the standard extinction coefficient.

Code-Segment 4 shows the modified media definition in ASAP with the introduced parameters.
For no information about the scattering behavior was available I have put the directional factor $g$ to 0 (zero), i.e. isotropic scattering.

The scattering efficiency $p$ is set to 1 that means every ray hitting a scattering particle will be scattered by this particle. This results in an overall fractional area obscuration $q$ which is equal to the standard absorption coefficient.

**Random surface scattering**

For scattering due to interface imperfections, the ASAP code SCATTER RANDOM $r'$ ($\text{N\_RAYSSCAT}$) ABS $r$ $t$ has been used. This code plays the role of an object modifier. The parameters denote: $r'$ = diffuse scattered reflectivity; $\text{N\_RAYSSCAT}$ = number of resulting scattered rays, $r$ = reflection coefficient and $t$ = transmission coefficient of the surface. The surface itself is no longer defined as a BARE interface, but described by code segment 5:

```
SURFACE
  PLANE Z 0 ELLIPSE 10 10
  OBJECT 1 'FRONT'
  INTERFACE 0 1E-12 AIR N_GLAS
  SCATTER RANDOM 1 20 ABS 0 1
```

**Code-Segment 5 Sample code for a random scattering surface**

Figure 14 displays the resulting scattered ray-pattern where one ray hits the surface and splits into 20 diffuse rays.

In a first step, only the central fiber core of the bundle has been illuminated by an emitting disk source.

Figure 15 shows the spots positions at the end face of the fiber bundle. All rays remain inside the fiber core. No cross talk is detectable. Parameters of the simulation: Bundle length: 100mm; 100,000 Rays.

**Figure 14** Simulated random surface scattering as implemented in Code-Segment 5

**Figure 15**: Simulation of a fiber bundle including scattering processes; illumination of the central fiber core only
In a second step, the light source has been enlarged to illuminate fiber core, fiber cladding and a glue ring circumventing the fiber simultaneously. Figure 16 shows the resulting spot positions at the end face of the bundle. Several spots appear now outside the illuminated area. Apparently they belong to scattered rays which have been captured by surrounding fibers. However, the flux guided by those fibers is just $10^{-5}$-th of the total flux emitted by the light source. Therefore this scatter mechanism does not explain the cross talk observed in experiments.

Figure 16: Simulation of a fiber bundle including scattering processes; central fiber core and cladding illuminated

3.2.2 Simulation of broken fibers inside the bundle

Experimental data indicate much stronger cross talk effects than predicted by the simulations so far. For that reason fiber cracks within the “super bundle” have been considered next.

Single broken fiber

In the first approach, a fiber bundle of 100 mm length is used where the central fiber ends after 30 mm inside the glue medium. This means the light guided by this fiber is coupled into the glue and scattered randomly there. Those scattered rays have the potential to couple into the surrounding fibers.

Figure 17 shows a cut of the introduced bundle geometry. The light source is placed in front of the broken fiber core.

Figure 17: Cross sectional view of the considered bundle geometry

Figure 18: Spots positions at the back face of the bundle with the central fiber broken
Only 1 % of the emitted light has been coupled into the surrounding fibers. This low rate is not surprising, since there are at least two scattering acts necessary in order to get light captured by another fiber core.

**Two broken fibers**

Now the remaining end of the broken fiber has been added slightly displaced from its original position. Figure 19 shows the location of both broken fiber ends within the bundle. The flux coupled into the glue from the central fiber is 100 lm.

![Figure 19: Cut of the used bundle geometry with two broken fibers. The central fiber was illuminated.](image)

**Figure 20:** Resulting spot positions at the back face of the fiber bundle, the underlying geometry is shown in Fig. 19

Figure 20 displays the spot positions at the end face of the fiber bundle. Now a remarkable number of rays have been captured by the open fiber end in the glue material. The graph in figure 21 shows that the flux coupled into the fiber is 15% of the light emitted from the central fiber. It also shows that the rays fill a very small angular range, which is due to the specific positions of both fiber ends.

![Figure 21: Angular light distribution at the back face of the fiber bundle](image)
For a closer investigation of the light transfer mechanism between two displaced fiber ends, the fiber bundle has been reduced to a two-fiber-model.

Figure 22 shows the implemented fiber geometry. Light is coupled from a light source into fiber $1$. It leaves fiber at $1$ its broken end and is partially recollected by fiber $2$ after its intermediate migration through the glue material. The distance between the fibers $DZ$ has been varied from 0 und 3 mm. The fiber core of fiber $1$ is illuminated by a light source with an aperture of $5^\circ$.

The distance $DZ$ has been varied from 0 und 3 mm. The fiber core of fiber $1$ is illuminated by a light source with an aperture of $5^\circ$.

The simulation was performed with 1000 rays providing a flux of 100 lm. Figure 23 shows the guided flux in fiber $2$ depending on the distance $DZ$ between the two fibers ends.

The flux drops sharply with increasing fiber distance. At a distance of about 1 mm between both fiber ends the guided flux becomes less than 5%, beyond 2,5mm the guidable flux becomes less than 1%. In comparison to experimental results one can conclude that the faces of the broken fiber have to be closer than 2,5 mm to transfer enough flux between both fiber ends.

In a next step a transverse displacement of the open fiber ends have been studied. In Fig. 24 the flux captured by fiber $2$ has been monitored as a function of the lateral fiber displacement, where the displacement $DZ$ along the axis is the parameter.
Figure 24: Guided flux in fiber 2 depending on vertical and horizontal shifts

Figure 26 shows that a re-coupling of the light is only possible for small distances perpendicular to the optical axis of fiber 1. Fiber 2 has been shifted in a range of \(-0.3\) mm < \(DY\) < \(0.3\) mm. A comparison between our simulation results and the experimental crosstalk data suggests that fiber cracks within the "super bundle", as illustrated in Fig 25, are most likely responsible for the observed cross talk phenomena.

Figure 25 Principal arrangement of broken fibers within the "super bundle"
3. Resume of our simulations with ASAP

Our simulation results obtained by ASAP gave us a deeper insight into light propagation phenomena in highly multimode optical fibers. In particular, we could identify fiber cracks being presumably the main source for cross talk between different fibers in specific fiber bundles.

I experienced ASAP a powerful simulation tool full of potential for a large variety of practical applications. Learning program handling, in particular the syntax code of ASAP is time consuming, but I found the simulation results justified my efforts. The tutorial provided an essential starting help.