Modelling of light propagation through aged and non-aged POFs

Lukasz Jankowski[1], Christian-Alexander Bunge[2], Joseba Zubia[3], Anilkumar Appajaiah[1]

[1]Federal Institute for Materials Research and Testing (BAM)
Unter den Eichen 87, D-12205, Berlin, Germany.
lukasz.jankowski@bam.de, *anilkumar.appajaiah@bam.de*

[2]POF-AC, Wassertorstr. 10, D-90489 Nuremberg, Germany.
christian-alexander.bunge@pofac.fh-nuernberg.de

[3]University of the Basque Country, Alda.
Urquijo s/n, E-48013 Bilbao, Spain.
jtpzuzaj@bi.ehu.es

Abstract: *In this paper we discuss aging influence on optical properties of POF. We propose a raytracing POF model capable of modelling fibre imperfections, attenuation and mode coupling. The model is validated for a non-aged and aged fibre sample by comparing measured and simulated far field profiles and optimising values of model parameters to get the best fit. Resulting sets of optimised parameters are compared and represent influence of specific aging conditions on fibre in terms of very basic optical properties.*

Introduction

Good understanding of aging processes is necessary to achieve POF durability and good resistance to climatic stress factors. While chemical investigations allow better understanding of physical aging mechanisms, the optical ones try to explain aging processes in terms of basic fibre optical properties, such as attenuation and scattering.

Most of thus far developed POF models rely on geometric optics [1] or Gloge diffusion model [2]; see [3] for a short review. The model proposed in this paper is a raytracing model, main differences to the model described in [1] lie in more realistic modelling of bulk scattering, attenuation parameters and in using also clad for tracing, besides core. There is no obvious literature on optical modelling of fibre aging, for a review on possible approaches see [4].

In the first part of the paper we describe raytracing model suitable for ideal POFs and make it more realistic by including imperfection parameters, necessary to model aging effects. Later we give a short overview of chemical investigations of POF aging. In the second part we verify validity of proposed model and show how it can be used to investigate aging influence on light propagation and basic POF optical properties. For this purpose we use two POF samples: one fresh and one aged one month at 100 °C with low humidity.

1 POF raytracing model

1.1 The ideal case

The general idea behind presented fibre raytracing model is as follows:

- The angular power distribution of a light source is used as a probability distribution to generate rays incident on the fibre input face.
- Generated rays are traced through the fibre (core only or core and clad, as in the described model) according to the Snell's and Fresnel laws through successive reflections on the core-clad and/or clad-air (jacket) interfaces. Fresnel law usually requires splitting the ray into the reflected and transmitted parts at reflection points. If traced rays were actually splitted, the total number of rays would increase exponentially and quickly become unmanageable. To avoid it, traced ray may be on the interface not splitted but rather either reflected or transmitted with probabilities equal to the power of the respective (reflected and transmitted) rays. For example, if, according to the Fresnel law, reflected ray takes 15 % and transmitted ray takes 85 % of the incident ray power, then this case is modelled by one ray, that has 15 % chances to be reflected and 85 % chances to be transmitted.
- At the fibre end face several characteristics (such as attenuation, far and near filed profiles) may be computed.

However, in order to model aging influence several aging-related imperfection parameters have to be introduced in the model. Most obvious of them are scattering and attenuation.

1.2 Scattering

Several types of scattering mechanisms occur in a real fibre. In the proposed model they are modelled by two:

- Bulk scattering to model the Rayleigh and Mie scatterings.
- Interface scattering to model the interface imperfections.

Bulk scattering is modelled by small bubbles of a slightly different refractive index immersed into the fibre core and clad material. The direction of the ray hitting a bubble is modified as if it hit a real bubble in a random point on its surface and was refracted/reflected according to the Snell's law. This kind of scattering is described by two parameters:

- *Mean free path* (or its reciprocal - scattering intensity) describes an average distance between successive bubbles encountered by the ray. As the probability of encountering a bubble is constant for unit length of ray path, the real distance is modelled by exponential random distribution.
- *Scattering scale* is the standard deviation of the relative index difference between bubble and surrounding material. The real difference at each scattering point is modelled by drawing from corresponding centred Gaussian distribution.

Axial and azimuthal imperfections of the core-clad and clad-air (jacket) interfaces are modelled as a deformation of the cylindrical shape to tiny random waves on the interface in both directions, along and across the fibre. The tilt of the tangent plane in the point where the ray hits the interface is described by two parameters: the standard deviations of axial and azimuthal tilt angles.

All used scattering parameters are listed in Table 1.

Table 1. Scattering parameters.

bulk scattering	interface scattering
core, mean free path	*core-clad interface axial scattering*
core, scale	*core-clad interface azimuthal scattering*
clad, mean free path	*clad-air interface axial scattering*
clad, scale	*core-air interface azimuthal scattering*

1.3 Attenuation

The most obvious attenuation parameters are attenuations of bulk core and clad material, both proportional to the ray path length. Further ones are core-clad reflection, core-clad transmission and clad-air (jacket) reflection attenuation coefficients (mdB / reflection or transmission), see Table 2.

Table 2. Attenuation parameters.

bulk attenuation	interface attenuation
core attenuation	*core-clad reflection*
clad attenuation	*core-clad refraction*
	clad-air (jacket) reflection

As an average number of bubbles encountered by the ray is proportional to the ray path length, there is no need for a separate bulk scattering attenuation coefficient. This effect may be included in bulk material attenuation together with attenuation due to molecule vibrations.

2 Chemical processes involved in POF aging

Chemical investigations using chemiluminescence technique show that the thermo-oxidative degradation of the POF involves both its core and clad. No significant thermo-oxidative degradation of the fibre was found at the early stage of the aging, where the significant drop in optical transmission occurred. This early drop is assumed to be mainly due to physical changes in the POF (core-clad boundary imperfection, bulk scattering due to refractive index changes, etc.). The subsequently aged samples showed degradation occurred in the POFs causing more transmission loss [5].

3 Measurements

In order to verify the validity of the proposed model and describe the aging influence several measurements of far field profiles (FFPs) of a non-aged and aged sample fibre have been made and compared with simulation results to optimise values of model parameters.

Mitsubishi ESKA CK40 fibre (1 mm PMMA-POF, refractive indices $n_{core} = 1.492$, $n_{clad} = 1.402$) has been used as a non-aged test fibre. To obtain aged samples the same fibre was kept approx. 1 month (676 h) at 100 °C with low humidity. For both, aged and non-aged fibres three different lengths (0.8 m, 3.2 m, 10 m) and two light input angles (12 deg, 24 deg) have been used, resulting in six different measurement conditions. Fibre bend radius was kept not less than 150 mm.

As a light source a red laser (653 nm) with wide enough beam to cover whole input face of fibre has been used. Far field profiles (angular power distributions of output light) were measured with Hamamatsu's A3267-12 FFP optics and a calibrated 12 bit digital camera. On Fig. 1 measured far field profiles of 3.2 m non-aged and aged fibres are compared.

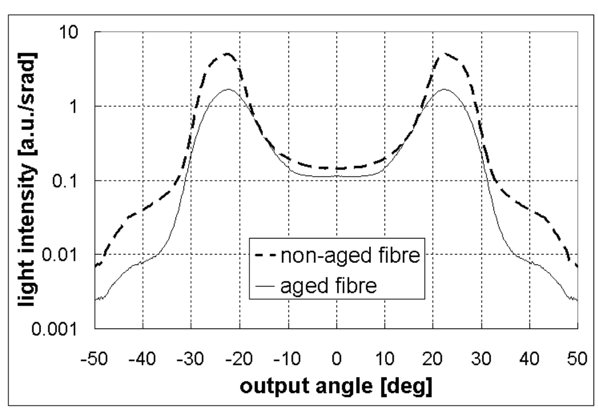

Fig. 1. Measured far field profiles of 3.2 m aged and non-aged POFs.

4 Optimisation procedure

As the next step, far field profiles at the same fibre lengths and input angles have been computed several times with software implementing the described model. A semiautomatic optimization procedure based on Powell's Direction Set Method [6] has been implemented and used to find the best values of the model's parameters and obtain the best fit between six computed and measured FFPs. This minimisation procedure was repeated two times, once for the non-aged fibre and once for the aged sample. As a target function (to be minimized) for a single pair of simulated far field profile p_{sim} and measured far field profile p_{meas} the following normalized square distance function was used:

$$d(p_{sim}, p_{meas}) = \frac{\int_{\Omega} (p_{sim} - p_{meas})^2 \, ds}{\left(\int_{\Omega} p_{meas} \, ds \right)^2}, \qquad (1)$$

where Ω is a part of a unit sphere with its origin in the middle of the fibre output face and extending up to 45 deg (i.e. FFP optics measurement range) out of the fibre axis. The overall target function was the square root of the average value of (1) over six compared far field profiles.

To decrease necessary computation time from thousands to hundreds of hours (on 1000 MHz PC), several assumptions about the number and values of optimised parameters have been made. Table 3 lists all optimised parameters and shows which of them were assumed to be equal. The meaning of the parameters was explained earlier in paragraph 1.2 and 1.3.

Table 3. Optimised model parameters.

attenuation parameters	
1.	*core bulk attenuation*
2.	*core-clad interface reflection attenuation = core-clad interface transmission attenuation = clad-air interface reflection attenuation*
scattering parameters	
3.	*core bulk scattering free mean path = clad bulk scattering free mean path*
4.	*core bulk scattering scale = clad bulk scattering scale*
5.	*core-clad interface azimuthal scattering = clad-air interface azimuthal scattering*
6.	*core-clad interface axial scattering = clad-air interface axial scattering*

Fibre core and clad refractive indices were left equal to the values given by the manufacturer ($n_{core} = 1.492$, $n_{clad} = 1.402$), fibre clad bulk attenuation was assumed to be 10 000 dB/km [7]. As the minimal value of core bulk attenuation 106 dB/km was used, as representing the intrinsic attenuation of a PMMA core [7].

Optimised values of parameters are discussed in paragraph 5. For both aged and non-aged fibre samples a good agreement between simulated and measured far field profiles was found, a confirmation of the model validity. An example for a 3.2 m non-aged fibre is given in Fig. 2.

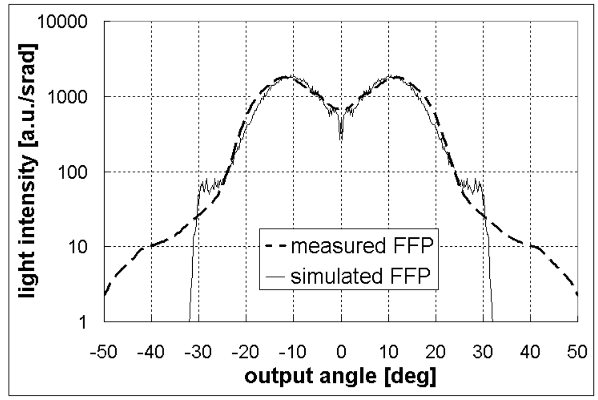

Fig. 2. Sample pair of measured and computed far field profiles (FFPs) of a 3.2 m non-aged POF.

5 Optimisation results

Parameter values minimising the target function are shown in Table 4. The parameters are numbered as in Table 3.

Table 4. Parameters characterising investigated fibres.

	non-aged	aged
1.	*106…116 dB/km*	*146…166 dB/km*
2.	*0…0.25 mdB*	*0.8…1.1 mdB*
3.	*1 mm*	*1 mm*
4.	*0.023 %*	*0.027 %*
5.	-	-
6.	*0.005…0.015 deg*	*0.010…0.026 deg*

Intervals in place of single values are given if statistical dispersion of fit function result was too big to find an exact parameter value. Those intervals may be shortened or eliminated at the cost of additional time by increasing number of traced rays used to compute each simulated FFPs (to decrease the dispersion). Increasing the longest fibre length may also help decrease the uncertainty of reflection/transmission coefficient *2*. For subsequent computations the middle value of the interval was used.

Note that the computed intrinsic attenuation (parameter *1)* of non-aged fibre is close to the minimal value of 106 dB/km, what suggests fibre core of high quality. The values of azimuthal interface scattering scale (parameter *5*) were not specified, because it turned out that the fit function (and so probably FFPs) are almost independent of it, at least within a broad range 0.1…10 deg.

Scattering parameters *3* and *4* were found to be strongly correlated, i.e. for each mean free path length (tested was the interval 1…10 mm) exists a corresponding value of scattering scale that preserves the same fit quality. Some of the computed pairs for both fibres are shown on Fig. 3, they lie along a narrow crack leading towards the origin. As a basis for the rest of the computations 1 mm free mean path and the corresponding bulk scattering scales were used, as specified in Tab. 4. The scale of axial imperfections of the interface (parameter *6)* was found to be generally independent of the bulk scattering (*3* and *4*), i.e. increase in axial interface scattering could not be compensated by a decrease in bulk scattering.

Comparison of measured and simulated FFPs (Fig. 2) shows that during future investigations it may be reasonable to decrease assumed value of core attenuation or optimise it separately, as it seems to be too high.

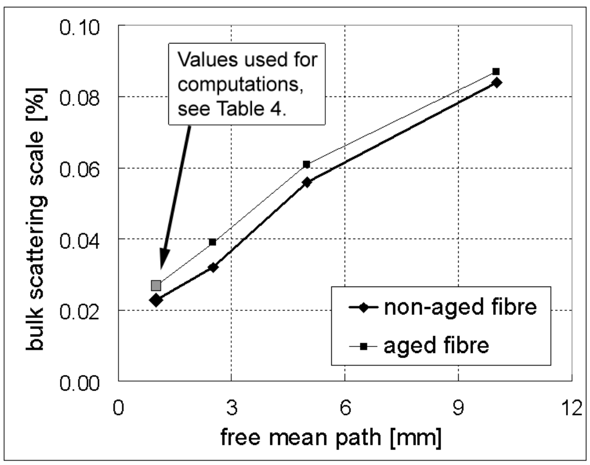

Fig. 3. Pairs of free mean path and bulk scattering scale parameters preserving the best fit.

6 Aging influence

The change of parameter values between both columns of Table 4 is a direct result of one month (676 h) temperature stress on the fibre.

More detailed data analysis reveals an interesting pattern: the aging influence may be, besides general attenuation increase, related to upward shift in parameters related to fibre core-clad interface (mainly reflection/transmission attenuation coefficient but also interface axial scattering scale). This is in good agreement with results of chemical investigations showing that besides general aging-related degradation influence, aging-related loss may come from purely physical changes as increase in core-clad interface imperfections.

Conclusion

We have proposed a POF raytracing model and showed that it is suitable for modelling and investigating of non-aged as well as aged fibres. It was also showed, that the model can by used as a tool to characterise aging influence on fibre basic optical properties.

We have investigated two real fibres: one non-aged and one aged for approx. 1 month with low humidity at 100 °C. The analysis showed considerable differences between their basic optical properties, especially between properties related to fibre core-clad interface. In accordance with this result and referred chemical investigations it may be stated that loss of optical properties due to aging is caused mostly by deterioration of core-clad interface.

Further investigation are planned to:

- Verify the model on longer fibres and fibres from other manufactures.
- Investigate influence of other aging times and conditions (temperature alone and combination of temperature and humidity).
- Try to optimise separately some of the parameters grouped together in Table 3.
- Introduce in the model improved scattering mechanisms.

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