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A SIMULATION MODEL FOR AN OPTICAL-ELECTRICAL COMBINATION CONDUCTOR SYSTEM

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ABSTRACT

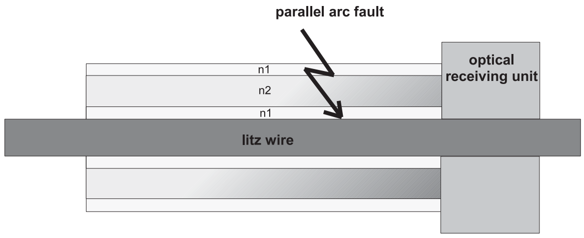
Over the past few years the University of Applied Sciences Nordhausen investigates und develops the innovative optical-electrical combination conductor system ”CONDUS” [1, 2] . This invention is patented in many countries (in Germany under No. DE 103 42 370) and opens completely new fields for applications. The principal item of the optical-electrical combination conductor CONDUS is a combination of an electrical conductor (e.g. copper wire) with a coat of an optical polymer.
The aim of this work is to present a simulation model for such conductors and to use it in order to investigate the influence of different designs, materials and geometries. The model is based on the ray tracing software FRED of the US-American company ”Photon engineering”. The development of the model and the investigations described below are part of a research project at the University of Applied Sciences in Nordhausen.

Index Terms— optical-electrical combination conductor, POF, simulation, ray tracing, optical design

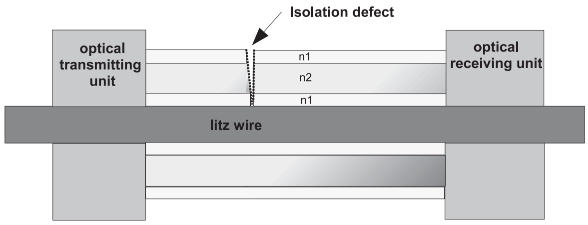
1. INTRODUCTION

The combination conductor described in the abstract has many possible applications. A first application lies in the automotive sector where it is important to detect defects in the isolation of the cable system. The optical cover of the electric wires enables the immediate detection of arc faults. Arc faults caused either by internal cable defects (serial arc faults) or by accidental arcing towards other electrically conducting parts (parallel arc faults). The information about the occurrence of an electric arc can be transferred by the polymer tube and used, e. g. in order to automatically switch off the power supply in the systems involved (see Fig.1)

The corresponding investigations, together with the development of modules for sending and receiving optical signals have been undertaken in Nordhausen since 2005 [3].
There are certain requirements to the light transferring



(a) Detection of an arc fault



(b) Monitoring of isolation defects

Fig. 1. Applications of the combined optical-electrical conductor

cover:

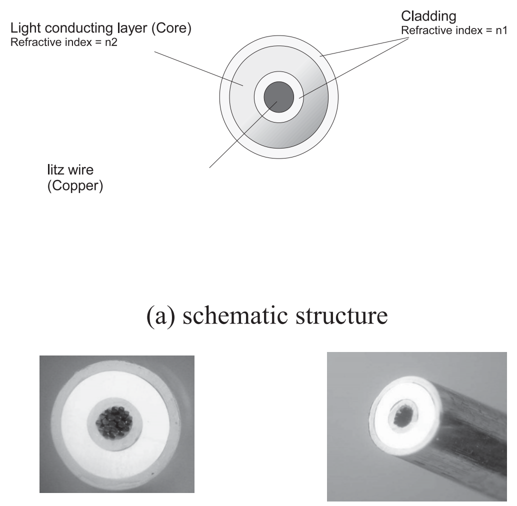
- high transmission
- low attenuation
- low surface roughness
- high dielectric strength
- high thermal stability for applications in automotive sector or aircraft industry
- high mechanical stability (in particular high longitudinal strength, tensile strength, elongation at

break, abrasion resistance and E-modules).

After first patterns made on the test-extruder were successful, the material properties of the chosen polymers have been investigated and improved in order to minimize absorption while respecting the mechanical and thermal requirements listed above.

A second application is the use of the combined conductor for information processing. Here, it is important to investigate the peculiarities of ”hollow” conductors as compared to ordinary light-wave cables. Corresponding results will be presented in sec. 3.

The main problems in the transfer of the described idea into a practically applicable system lie on the one hand in the selection of a suited polymer-optical material together with the technology for its fabrication. On the other hand, a simulation model for the combined conductor has to be developed in order to perform investigations on the influence of different materials, cable geometries and ways of extracting optical signals, and to provide suggestions for an optimal design.



(a) schematic structure

(b) top view

(c) side view

Fig. 2. combined optical-electrical conductor

2. SIMULATION GOALS AND METHODS

In Fig.2 the structure of the combined optical-electrical conductor is shown. The different layers around the litz wire (copper or other materials) are the inner and outer cladding layer, and between them the light guiding layer is arranged. The two cladding layers have one and the same refractive index which is lower than the refractive index of the light guiding layer (typical values are 1.34-1.36 and 1.49-1.53, correspondingly). The ratio between the refractive index of the cladding and the refractive index of the core determines the numerical aperture NA and consequently the amount of coupled light, which is transported trough the optical waveguide.

Each designated system application requires an optimal construction of the combined conductor. The investigation of the properties of the conductor requires the derivation of a mathematical model and – on its basis – a numerical simulation of different design specifications. The behavior of the conductor depends on:

- Geometric properties (length of the combined conductor, diameters and thicknesses of inner and outer cladding layers and of the core)
- Materials used (refractive indices, absorption properties, influence of scatterers)
- Properties of the arc fault as the optical light source (threshold energy, optical spectrum).

In addition, the geometry of in- and outcoupling of the light and the spectral sensitivity of the photodiodes has to be specified. The number and positioning of the laser diodes, if such are used for incoupling and the geometry for decoupling the light are considered in sect. 4.

FRED as the chosen simulation software is capable to compute the propagation of light through any optical system by ray tracing. This simulation method is appropriate if length and thickness of the cable are significantly greater than the wavelength of the investigated light. A graphical user interface (GUI) has been developed to make the optical design easily configurable.

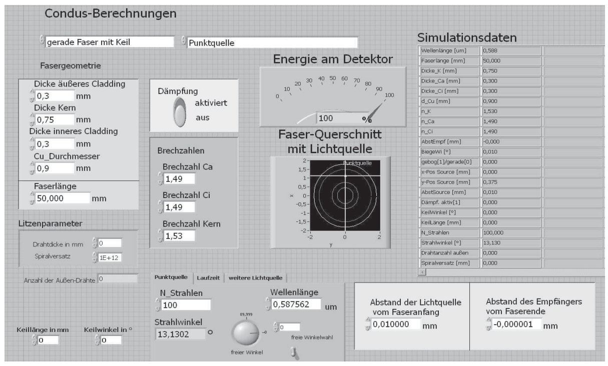


Fig. 3. GUI

3. LENGTH SPECTRUM IN HOLLOW LIGHT CABLES

Fig.5 shows the geometry of the combined conductor and some of the parameters used.

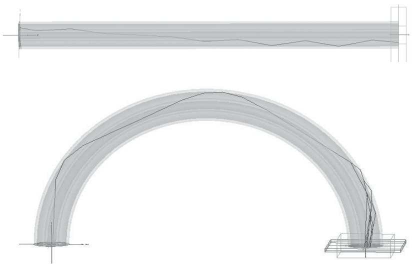


Fig. 4. light propagation in straight and bent fibers

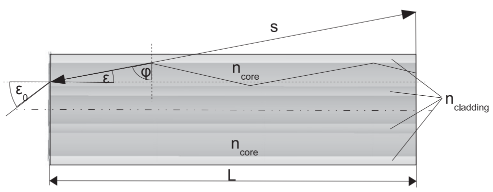


Fig. 5. section trough the combined conductor

The model described below uses the following parameters:

- L: the length of the conductor
- s: the optical path length
- ϵ_0: axial incidence angle
- ϵ: axial angle in the fiber
- φ: angle to the normal vector of point of impact
- φ_{tot}: angle of total reflexion
- NA: the numerical aperture
- $r_{\mathrm{Cu}}, r_{\mathrm{in}}, r_{\mathrm{core}}, r_{\mathrm{out}}$: the radii of the copper kernel, the inner cladding, the light transmitting core and the outer cladding, correspondingly
- λ: the wavelength of the light
- n_{core} and n_{cladding}: the refractive indices of the core and the cladding, correspondingly
- a_{core} and a_{cladding}: the corresponding absorption coefficients (both n and a can be wavelength-dependent)
- $I(\lambda, r, \epsilon)$: the intensity distribution of the light source

Depending on the parameters defined above both the power distribution as well as the ray length distribution have been investigated.
For data transmission the propagation time differences should be small. The propagation time difference Δt results from the difference of the propagation time of the longest (ϵ_{max}) and the shortest guided rays ($\epsilon = 0^o$). Assuming for the beginning that the source of light is close to the axis of the fibre, the angle ϵ of the highest mode which is transportable is determined by the condition of total reflexion.

$$\begin{aligned} \epsilon_{\mathrm{max}} &= \frac{\pi}{2} - \varphi_{\mathrm{tot}} \\ &= \frac{\pi}{2} - \arcsin\left(\frac{n_{\mathrm{cladding}}}{n_{\mathrm{core}}}\right) \end{aligned} \quad (1)$$

Using Snell's law of refraction the maximum axial incidence angle $\epsilon_{0_{\mathrm{max}}}$ is:

$$\epsilon_{0_{\mathrm{max}}} = \arcsin\left(\sqrt{n_{\mathrm{core}}^2 - n_{\mathrm{cladding}}^2}\right) \quad (2)$$

Usually the range of incoupled light is given by the numerical aperture NA. This dimensionless quantity is the sinus of the maximum incoupling angle, including all totally reflected rays:

$$\begin{aligned} NA &= \sin(\epsilon_{0_{\mathrm{max}}}) \\ &= \sqrt{n_{\mathrm{core}}^2 - n_{\mathrm{cladding}}^2} \end{aligned} \quad (3)$$

With an actual refractive index $n_{\mathrm{cladding}} = 1.49$ and $n_{\mathrm{core}} = 1.53$ the numerical aperture is $NA = 0.35$ and the angle of total reflexion is $\varphi_{tot} = 76.71^o$.
The optical path lenght is defined as:

$$s_{\mathrm{opt}} = n_{\mathrm{core}} \cdot s \quad (4)$$

Now the maximal optical path lenght $s_{\mathrm{opt}_{\mathrm{max}}}$ of a single ray and the maximal propagation time differences can be calculated:

$$s_{\mathrm{opt}_{\mathrm{max}}} = n_{\mathrm{core}} \frac{L}{\cos(\epsilon_{\mathrm{max}})} \quad (5)$$

$$\Delta t_{max} = \frac{s_{\mathrm{opt}_{\mathrm{max}}} - n_{\mathrm{core}} \cdot L}{c} \quad (6)$$

with c being the speed of light. It follows, that the layer thickness of the core doesn't have an influence on the propagation time. If the combined conductor should transmit data with a great bandwidth, the numerical aperture should be small, that's known in communications.

For the investigation of the influence of the layer thicknesses on the propagation time with FRED an optical source was created. All materials were supposed to have zero absorption, no scatterers, and the refractiv index was assumed to be constant (not wavelength dependent).

The source placed at one end of the conductor consists of a single point with one million random (uniformly distributed) ray directions in an angular range.
If the angular range of the optical point source would be limited by the angle of total reflection, the results of simulation (spectrum of the optical path length, energy at the fiber end) were always the same, independent of layer thicknesses or the local position of the optical source.
Fig.6 shows the spectrum of propagation times. ρ_N denotes the proportional share of rays normalized according to:

$$\int_0^{\Delta t_{max}} \rho_N(\Delta t) d(\Delta t) = 1 \qquad (7)$$

The distribution of optical path lengths respectivily propagation times is nearly constant, with a slight falling off towards the longer pathes. The position of the point light source was assumed to be always in the middle of the core.

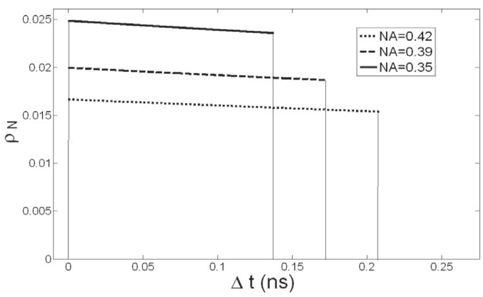


Fig. 6. spectrum of the propagation time

In the following simulations the aperture angle of the light source was increased to $\epsilon_{\max} = 90^o/n_{\text{core}} = 41.81^o$ (corresponding to $\epsilon_0 = 90^o$, i. e. the greatest angle which could be coupled in).
For short fibers a sloping intensity at the first centimeters can be detected. Just the influence of the Fresnel losses are significant, especially because the cladding layers haven't any absorption and so the reflected rays come back to the core layer.
However, by moving the point source from the inner cladding layer towards the outer boundary layer (outer cladding) much longer path lengths are possible.
This also increases the energy transported by the fiber (see Fig. 10). The reason for this is the rising value of the angle of total reflection in the vicinity of the outer cladding, where non-meridional rays play an important role.

Higher modes will be also totally reflected and they

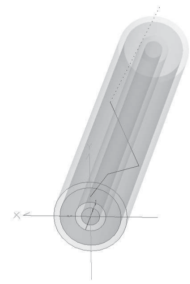


Fig. 7. non-meridional ray

wind spirally along the outer boundary layer.

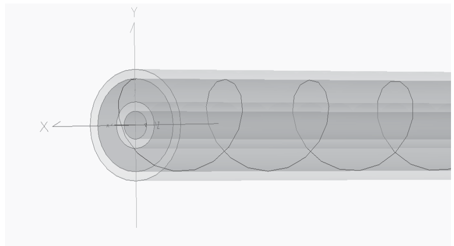


Fig. 8. spirally winded non-meridional ray

In Fig.9 the dependence of the optical path length on the position of the point light source Y_{source} in relation to the radius of the core r_{core} is shown. In order to reduce calculation time the combined conductor length L was choosen to be $L = 100\text{mm}$. Therefore the minimal optical path length is $s_{\text{opt}} = 153\text{mm}$, ($n_{\text{core}} = 1.53$). However, the obtained results do not depend on the length of the conductor.

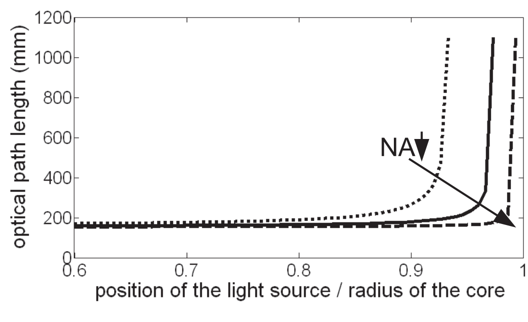


Fig. 9. dependence of the maximal optical path length on the position of the light source

Fig.10 shows a significant increase of the measured power, if the source comes near to the outer cladding. The results shown were obtained for a conductor length of $L = 1000$ mm. With rising value of the numerical aperture NA this dependence will be rising too.

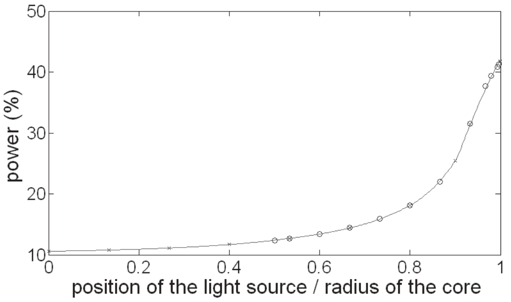


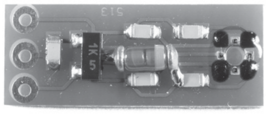
Fig. 10. dependence of the received power on the position of the light source

4. IN- AND OUTCOUPLING OF LIGHT

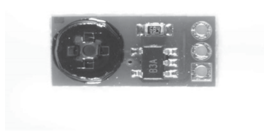
A particular challenge is the light coupling into the beginning of the fiber and the light detection at the fiber end. For this purpose laser diodes and photodiodes must be placed around the copper litz wire. There are already layouts with 4 or 8 photodiodes and one combined transducer with 4 laser- and 4 photo-diodes (see Fig.11 (a-c). The possibility of using transmitting and receiving diodes to observe the isolation of the cable depends on the damping characteristics of the polymer materials.

The spectral properties of these first design patterns of the diodes still have to be investigated. In order to detect an arc fault it is nessesary, that the sensitivity of the photo diode corresponds to the spectral intensity of the arc. The suited spectral range lies in the visible range (e.g. the green spectral component of copper). The other main spectral components of an arc fault are in the range of ultraviolet radiation, for which polymer materials are mostly untransparent. The corresponding metrological investigations are currently carried out by the authors.

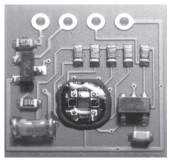
Fig.11 (d) shows an arc fault at the CONDUS cable and (e) the incidental detected spectrum at the end of the combined conductor. The gray line represents the spectrum of the light arc measured directly, the dark line the spectrum as observed after transmission through the optical fiber.



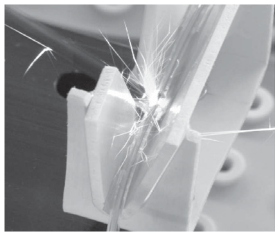
(a) transmitter



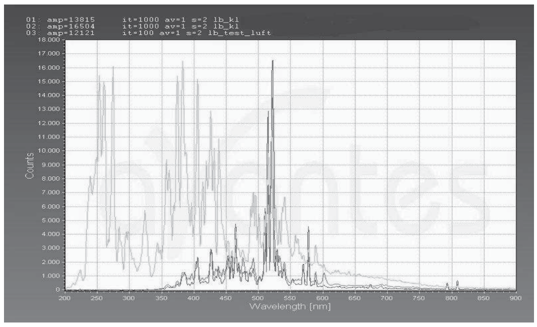
(b) receiver



(c) combined transducer



(d) arc fault on CONDUS cable



(e) spectrum of an arc fault

Fig. 11. transmission/receiving assembly (a-c) and arc fault (d) with spectrum (e)

5. SUMMARY AND OUTLOOK

A model for the combined optical-electrical conductor system CONDUS has been developed and used in order to investigate the peculiarities of hollow optical fibers. In particular, the effect of the position of the source of light on the spectrum of path lengths and on the transmitted power was described.

Future research will be concentrated on the in- and outcoupling of light by simulating the arrangement of laser and photo diodes. Here, the optimal configuration has to be found depending on the field of application.

6. REFERENCES

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