Computer aided design of board-level optical interconnects

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C-LAB Report

Vol. 8 (2009) No. 4

Cooperative Computing & Communication Laboratory

ISSN 1619-7879

C-LAB ist eine Kooperation
der Universität Paderborn und der Siemens AG
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C-LAB Report

Herausgegeben von
Published by

Dr. Wolfgang Kern, Siemens AG
Prof. Dr. Franz-Josef Rammig, Universität Paderborn

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ISSN 1619-7879

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Abstract

Novel design and simulation tools are introduced to provide CAD support for board-level optical interconnects. Two ray optical simulation techniques based on hybrid ray tracing are presented and their capability are demonstrated for selected examples of use. Furthermore a comprehensive design environment is introduced that integrates the simulator in order to provide a holistic design process for board-level optical interconnects.

1 Introduction

Board-level optical interconnects based on integrated multimode dielectric waveguides are a promising technology for future high-speed communication on printed circuit boards (PCB) [1]. These interconnects are well adapted to the needs of PCB assembly requirements and allow a high degree of freedom in routing high speed interconnects within inner and outer layers of the PCB. As progress continues in the development of reliable manufacturing technologies the need for appropriate numerical simulation and design tools is arising to promote the adaption of this new emerging optical interconnect technology into commercial PCB systems.

Numerical simulation techniques are always balancing between desired accuracy of simulation results and required computing time consumption. This applies to CAD for optical interconnect as well. During a design process rapid simulation techniques are required to find and optimize a functional design. Therefore a fast simulation technique called Analytic Ray Tracing (ART) has been developed that uses simplified models and boundary conditions for board-level optical interconnects at the expense of accuracy. In order to verify a functional design more accurate techniques are needed that consider more complex models at the expense of computing time. For this purpose a comprehensive simulation technique called Semi-sequential Ray Tracing (SRT) has also been developed. In order to support both simulators with input data the prototype of a sophisticated design environment for board-level optical interconnects has been implemented. It integrates the numerical simulation tools, enables the evaluation of simulation results and provides a comprehensive CAD support for optical interconnects. Both the numerical simulation tools and the design environment are subsequently introduced and their capabilities are demonstrated for selected examples of use.

2 Simulation techniques

The purpose of numerical simulation tools for board-level optical interconnects is the prediction of the static (e.g. loss, cross coupling, state of polarization, near field- and far field pattern) as well as the dynamic transfer behavior (e.g. delay, skew, dispersion, cutoff frequency) of wave-based optical signal transmission along multipoint interconnect topologies. Board-level optical interconnects are implemented as planar integrated step-index (SI) waveguides with large numerical apertures >0.2 and almost rectangular core cross sections. Their transversal core dimensions extend the optical wavelength λ by more than 30λ which enables the waveguide to guide hundreds of electromagnetic modes. This results in a quasi-continuous guided mode spectrum and allows the use of ray optics for the simulation techniques to compute wave propagation efficiently [2]. The numerical implementation of ray optics is commonly based on Ray Tracing algorithms that are suitable to compute the geometrical ray path in the core region along the waveguide. As pure Ray Tracing by itself does not obtain required electromagnetic parameters as optical power, phasing, state of polarization or propagation time it is extended by electromagnetic properties of local plane waves. This combination is classified as hybrid or physical ray tracing and computes the altering electrical field vector, phasing and optical power of the local plane waves traveling along traced geometrical ray paths. As the length of the waveguides extend the transversal core dimensions by far a high number of reflection points (r>100) emerge along each traced ray path. This requires a precise model of the plane wave interaction at the reflection points. Therefore a diffuse reflection model based on a polarization dependent scattering matrix $\mathbf{\Psi_r}$ is applied [3]. It describes the diffuse reflection of plane waves impinging on core interfaces with surface roughness up to one tenth of the optical wavelength. In case of smooth core interfaces the scattering matrix $\mathbf{\Psi_r}$ reduces to a diagonal matrix describing the common specular Fresnel reflection of a plane wave.

$$P_R(t) = P_0\left(t - \frac{\Re(\underline{n})L_g}{c_o}\right) exp(-\Im(\underline{n}) * L_g) \prod_{r=0}^{R-1} |\underbrace{\mathbf{\Psi_r} \cdot \mathbf{E_r}}_{=\mathbf{E_{r+1}}}|^2 |\mathbf{E_r}|^{-2} \quad (1)$$

Integrating the diffuse reflection model into the hybrid ray tracing simulation the electrical field vector E_R and the transient optical power flow $P_R(t)$ can be derived along a ray path of length L_g with R reflection points by (1). Therefore an initial electrical field vector E_0, an initial propagation direction k_0 as well as an emission point s_0 and an initial transient optical power $P_0(t)$ must be determined. In order to consider intrinsic absorption of the core material a complex refractive index n is applied in (1). In order to simulate optical wave propagation a sufficiently high number of ray paths and their electromagnetic properties must be computed and superposed.

2.1 Semi-sequential Ray Tracing

Semi-sequential Ray Tracing (SRT) allows the computation of monochromatic wave propagation in planar integrated optical SI-waveguides with rough core interfaces, almost any transversal core contours and multipoint routing topologies. It considers surface roughness up to one tenth of the wavelength, intrinsic material absorption of core and clad material as well as the numerical aperture of the waveguide. Due to the homogenous core material of SI-waveguides the piecewise rectilinear ray path is determined by consecutive intersection point computation with the core boundary. In parallel the state of polarization, propagation time and optical power flow of the local plane waves is coevally calculated by (1) along each traced ray path. The required functional description of the core boundary for intersection computation is obtained by an analytic extrusion of a designed transversal core contour along a designed continuously differentiable planar routing topology [5]. The extrusion algorithm requires a closed transversal core contour composed of N rectilinear section and a routing topology assembled by M cascaded straight lines or circular bends. As a result the extrusion algorithm provides a modular description of the boundary composed of M cascaded core segments. Their boundaries are again split into planar or curved square surfaces which are geometrical described by a set of parametric vector functions $H_{mn}(s,t)$ with $m \in [0,M-1]$ and $n \in [0,N-1]$.

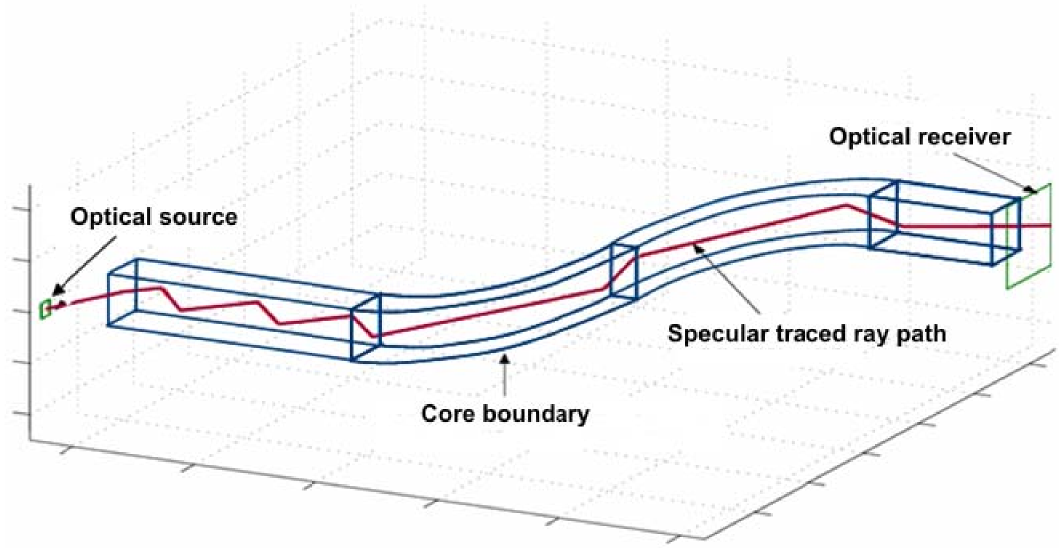

Figure 1: Specular ray path propagation in four cascaded core segments

A major benefit of these functions is given by an analytic algorithm for intersection point calculation that strongly accelerates the computing time for ray tracing [4]. In order to describe multipoint waveguide topologies (e.g. crossings, splitters, combiners) two or more point-to-point overlapping waveguides with a spatial subset of their core segments are merged. SRT is based on a novel semi-sequential ray tracing engine that takes advantage of the modular representation of the core boundary. The semi-sequential ray tracing, a combination of classical sequential and non-sequential ray tracing approaches, reduces the number of parametric vector functions to be considered for intersection point computation. This comes along with a significant computing time reduction especially for long waveguides with several core segments. The intersection point calculation is limited to the parametric vector functions of the core segment in which the current emission point of the ray path is placed. This intersection computation is carried out for all vector functions of the core segment by a non-sequential approach. If an intersection is identified with one of the two transversal faces of the core segment the intersection point calculation is continued in the adjacent core segment which represents a sequential ray tracing approach.

In case of surface roughness of an intersected core interface a diffuse spectrum of scattered local plane waves has to be considered requiring a diffuse ray tracing algorithm. As each of scattered plane waves splits up again into a diffuse spectrum of plane waves at the next intersected rough interface the number of traced plane waves increases exponentially. In order to cope with this a Monte Carlos strategy was recommended in [3]. SRT instead uses a much faster deterministic approach based on ray path classification. This classification is motivated by the diffuse reflection model introduced in [3] that invariably provides a specular scattered plane wave with an optical power of several magnitudes of the ones of the diffuse scattered plane waves. Thus ray paths that always arise from the specular component of the scattering spectrum show the highest optical power and are classified as 0^{th} order ray path. Each time the ray path arises from a diffuse scattered wave its optical power decreases by magnitudes of the incident power and the ordinal number of the ray path is therefore incremented. SRT exploits this by introducing a scalable diffuse ray tracing that allows scattering processes for ray path of specified order. If the ray path extends this order and intersects a rough interface a modified specular reflection is carried out instead of a diffuse scattering process. In this case ordinal number is kept constant. Then the optical power of the incident plane wave is reduced by the radiated power caused by surface roughness and a specular reflected outgoing plane wave is computed for further tracing of the ray path.

2.2 Analytical Ray Tracing

SRT enables a precise, flexible but quite time consuming prediction of wave propagation in planar integrated optical SI-waveguides. It makes a compromise between the capabilities to simulate waveguides with arbitrary core geometries and higher computing time consumption which is caused by the high number of consecutive intersection point calculations during simulation. If the transversal core geometry is limited to rectangular shapes and the routing is always in-plane an Analytic Ray Tracing (ART) technique can be used to determine the ray path properties without applying time consuming consecutive intersection point calculations [6]. ART can likewise be extended to Hybrid Ray Tracing by utilizing (1) and again requires a modular representation of the waveguide assembled by cascaded straight-line or circular bent core segments. ART exploits the transversal symmetry and planarity of the core and is based on a disassembly of the spatial ray path into planar ray paths along two derived slab waveguides.

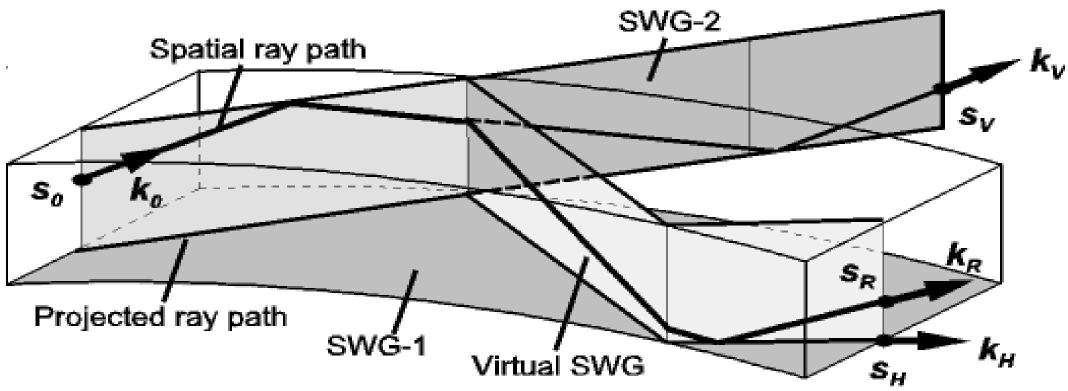

Figure 2: Disassembly of the core boundary into two slab waveguides

Therefore the initial propagation direction k_0 of the spatial ray path is projected onto the bottom interface of the core boundary which forms a circular bent or straight line slab waveguide for this projected ray. The obtained projected ray is traced along the slab waveguide and provides a planar ray path that determines the horizontal location s_H and direction k_H of the spatial ray path. In order to determine the vertical location s_V and direction k_V of the spatial ray path a virtual slab waveguide is constructed by extruding the planar ray path by the height of the core boundary. By unfolding this virtual slab waveguide a second straight-line slab waveguide is derived that shows a core diameter equal to the core height and a length equal to the determined planar ray path. Again the initial propagation direction k_0 is projected onto the virtual slab waveguide and traced along its unfolded representation. Superposing the obtained results of the vertical and horizontal locations and directions respectively, the spatial location and propagation direction of the spatial ray path is obtained.

Instead of computing the planar ray path along the two slab waveguides by consecutive intersection point calculations ART exploits the steadiness of the angle of incidence in slab waveguides to predict the ray path property at the end of the waveguide. These properties include the propagation direction and intersection point at the end of the slab waveguide, the length of the ray path and the number of passed reflections. Applying these results to (1) the optical power flow and propagation time of the ray path can be determined. In a straight-line slab waveguide the determination of these properties is achieved by computing the first intersection point and its angle of incidence with the core boundary of the slab waveguide. Based on the results the prior listed path properties at the end of the waveguide are easily derived by evaluating scalar geometrical equations [6]. In circular bent slab waveguides the first two intersection points and their angles of incidence must be computed in order to distinguish between whispering-gallery rays and zigzag rays [2]. Based on the results the desired properties can be again derived by evaluating scalar geometrical equations for both ray path classes [6]. The essential benefit of ART technique in regard to SRT is the efficient computing time that does not scale with the waveguide length nor the number of intersection points. It provides hybrid ray path properties at the end of the applied waveguide without time consuming consecutive intersection point computation.

3 Design environment

Suitable design environments are vital for computer-aided design of board-level optical interconnects. They should yield to design and technology requirements of optical interconnects and adapt to standard design flows of electronic interconnects. Therefore a software prototype of a sophisticated design environment for board-level optical interconnects has been developed.

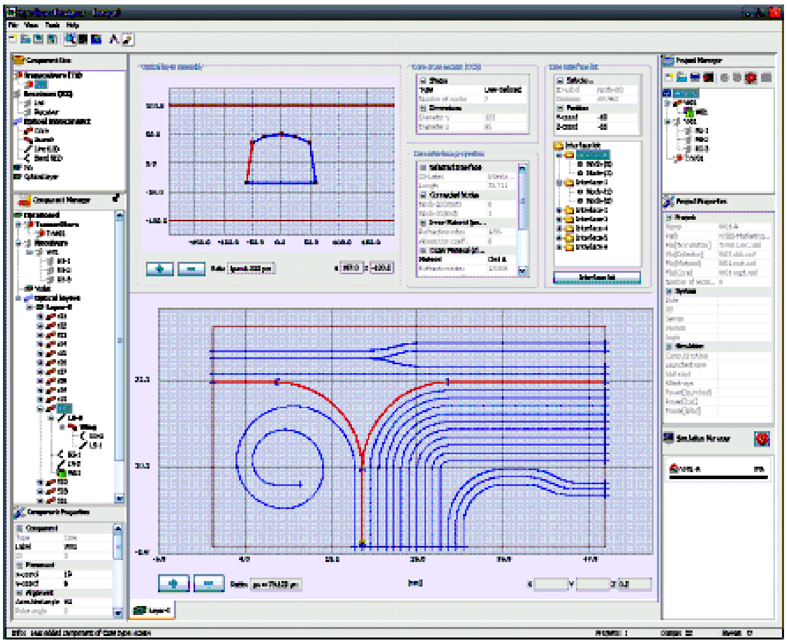

Figure 3: Prototype of a design environment for optical interconnects

It provides an integrated development environment (IDE) as depicted in Fig. 3 that enables the control and monitoring of simulation processes based on the SRT technique. Furthermore the IDE enables the layout compilation of optical layers including routing of multipoint core topologies and the design of specific transversal core contours. For the hybrid ray tracing material properties of the core and clad can be assigned to the designed core topology and extended by surface properties for the core boundary. Integrated model extraction functionality within the IDE provides the required simulation models for SRT-based simulation. As both simulation techniques SRT and ART require a ray-optical launch condition the IDE provides surface-emitting optical source with editable near- and far field pattern. Supplementary a receiver model is integrated to provide initiated simulation processes with an evaluation unit which allows the static and dynamic evaluation of the trace optical power at any specified positions along the interconnect.

4 Simulation Results

Circular bends represent an elementary routing element for waveguide topologies. They appear in branches, splitters or s-bends and thus a deeper insight into their optical transmission behavior is essential. ART as well as SRT were applied to compute static and dynamic transmission behaviors of a waveguide with a topology consisting of three basic core segments shown in Fig. 4.

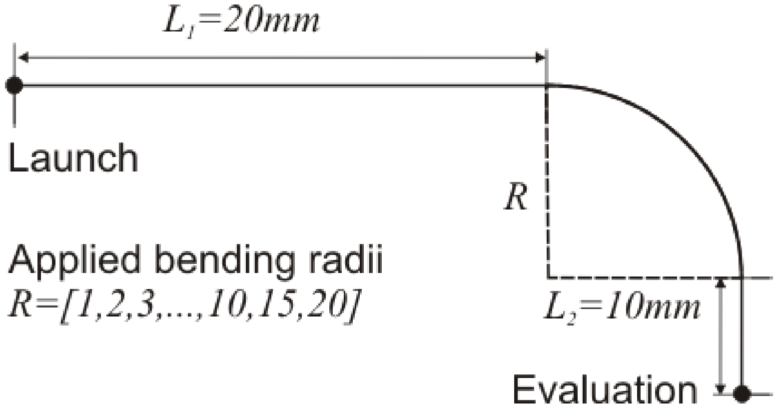

Figure 4: Topology considered for examples

Intrinsic material losses were not considered. The optical launch condition used for both, ART and SRT, illuminates the numerical aperture (NA) of the waveguide and its core cross section homogeneously at an optical wavelength of λ=0.85μm. The evaluation of the optical transmission was carried out at the end of the second straight-line core segment.

4.1 Static Analysis

The static analysis comprises the computation of bending losses for different bending radii, core widths and numerical apertures. A rectangular core cross section with constant core height h=70μm and several core width w was considered. In Fig. 5 the simulated bending losses obtained by SRT and ART simulations are depicted over the bending radius for three numerical apertures of the waveguide with a core width of 70μm. As expected the bending loss increases for decreasing bending radius and decreasing numerical aperture.

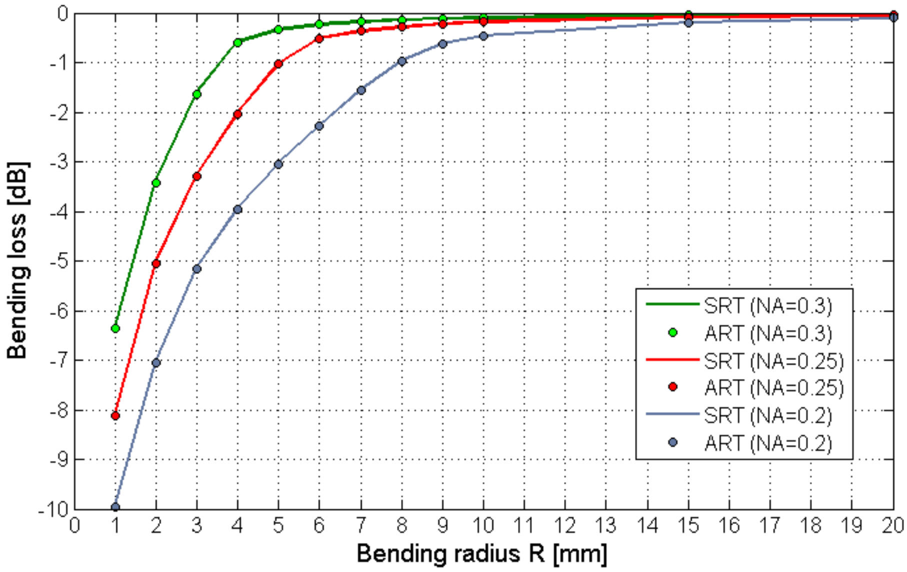

Figure 5: Losses vs. bending radius for different numerical apertures

In Fig. 6 bending losses obtained by SRT and ART simulations are depicted over the bending radius for three different core widths and a constant numerical aperture of 0.25. The core height (h=70µm) was again kept constant. Interestingly the core width shows a significantly influence on the bending loss.

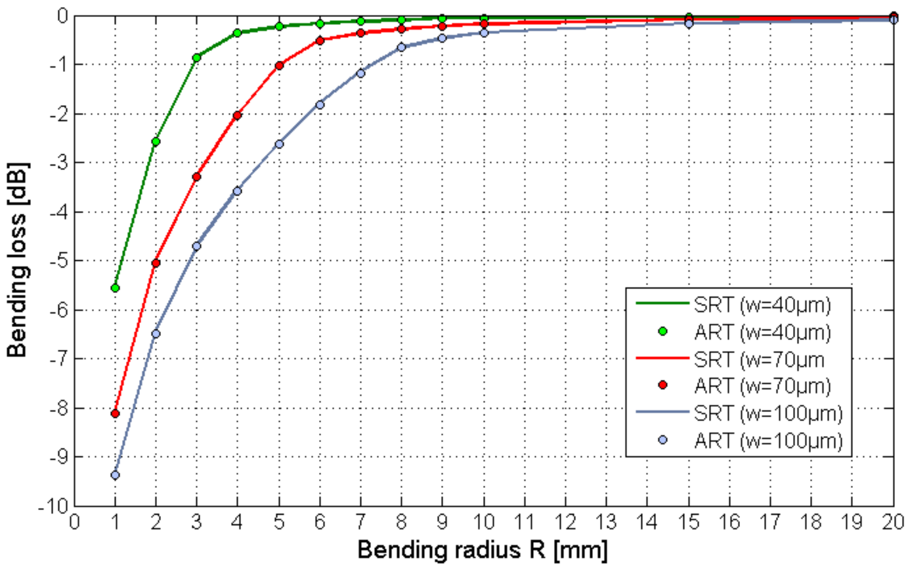

Figure 6: Losses vs. bending radius for different core width

A decreasing core width results in a decrease of bending loss. This motivates a new presentation in which the bending losses are depicted over a normalized bending radius R/w. Fig. 7 shows nine loss curves for the core width of 40, 70 and 100µm and for the three numerical apertures of 0.2, 0.25 and 0.3.

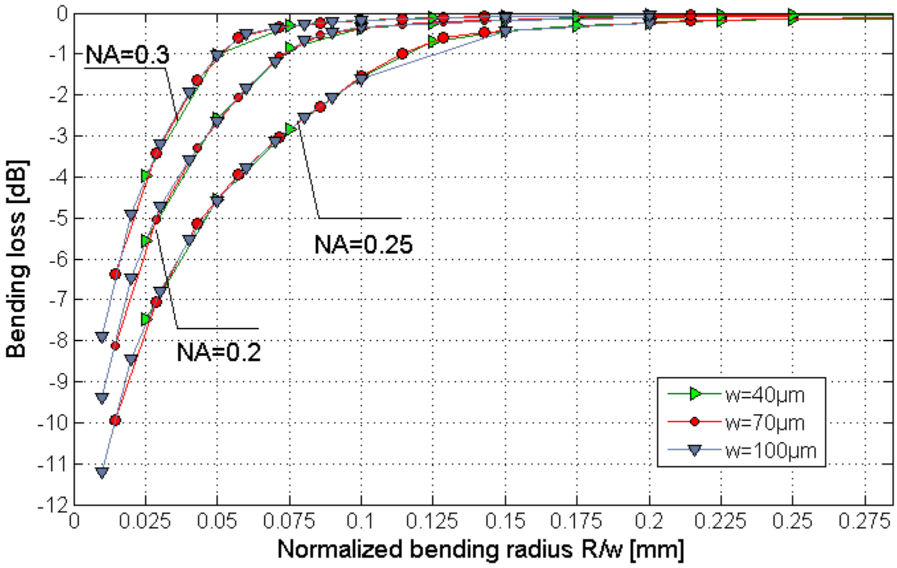

Figure 7: Losses vs. normalized bending radius

The bending losses for constant numerical aperture show equal curve shapes over the normalized bending radius. Thus bending losses can be considered constant for equal ratio of bending radius to core width and constant numerical aperture. The results obtained from SRT and ART depicted in Fig. 5 and 6 show a very good agreement and verify the correct implementation of ART and SRT.

4.2 Dynamic Analysis

For the evaluation of the dynamic transmission behavior of optical interconnects step responses $\sigma(t)$ have been identified as a suitable solution to describe dynamic transmission properties in time domain. In frequency domain transfer functions H(f) are deployed that can easily be derived from the step responses by time derivation and Fourier transformation. Step responses are obtained by SRT and ART simulations if the emission time of each ray launched by the optical source is constant. Then the integration over time of the optical power appearing at a receiver model normalized to the total emitted power of the optical source provides the step response. Beside the time domain description of the transfer behavior the step response function describes the static loss behavior by its final value as well.

The numerical analysis of the dynamic transmission behavior is exemplarily performed for the previously analyzed waveguide topology with a bending radius of 10mm and a numerical aperture of 0.25. This topology provides a waveguide length along the three core segments of 45.7mm and a core width and height of 70µm. In order to enable the comparison of differently delayed step responses they are all depicted over time t minus the offset delay T_o. In this context the offset delay describes the delay time at which the first ray strikes the receiver model. In Fig. 8 four step responses are depicted. The solid and marked blue curves show the step responses of the waveguide applying a quadratic core contour. Their final values of -0.183dB are equal to the one obtained from the static analysis of the bending loss. Both curves again show a very good agreement and verifies the correct implementation of ART and SRT for time domain simulation.

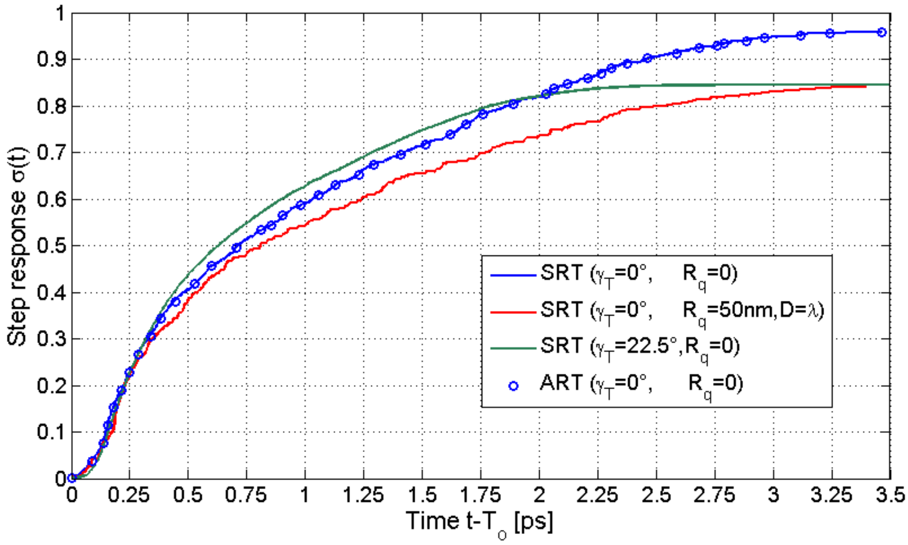

Figure 8: Step responses of bent waveguides (R=10mm)

In order to analyze the influence of the transversal core contour geometry on the dynamic transmission behavior a trapezoidal core contour was deployed for the waveguide and analyzed by SRT simulation. The trapezoidal core contour was modeled in a way that the core width at the vertical median was kept constant and the sloped side walls had a tilt angle γ_T of 22.5° in regard to the vertical side walls. The green curve depicted in Fig. 8 shows the obtained step response which differs significantly from the one of the quadratic waveguide. It rises up to a final value of -0.733dB and thus provides a four times higher bending loss compared to the one of the quadratic waveguide.

In order to analyze surface roughness on the transient transmission behavior an isotropic nano-rough surface with a roughness depth standard deviation of 50nm and correlation length of λ was applied to the entire core boundary. The transversal core contour was again chosen to be quadratic with a core height and width of 70µm. The step response was computed by SRT using a first order diffuse ray tracing. The results are represented by the red curve in Fig. 8. This curve reaches a final value of -0.754dB which is almost equal to the one of the trapezoidal waveguide. But its timing behavior differs significantly from the other ones. In order to estimate the impact of surface roughness on the loss behavior the final value of the blue curve in Fig. 8 are subtracted by the one of the red curve and normalized to the waveguide length. In this case this leads to a relative attenuation due to surface roughness of -0.125dB/cm and shows the effect that nano-rough surfaces might have on transmission behavior.

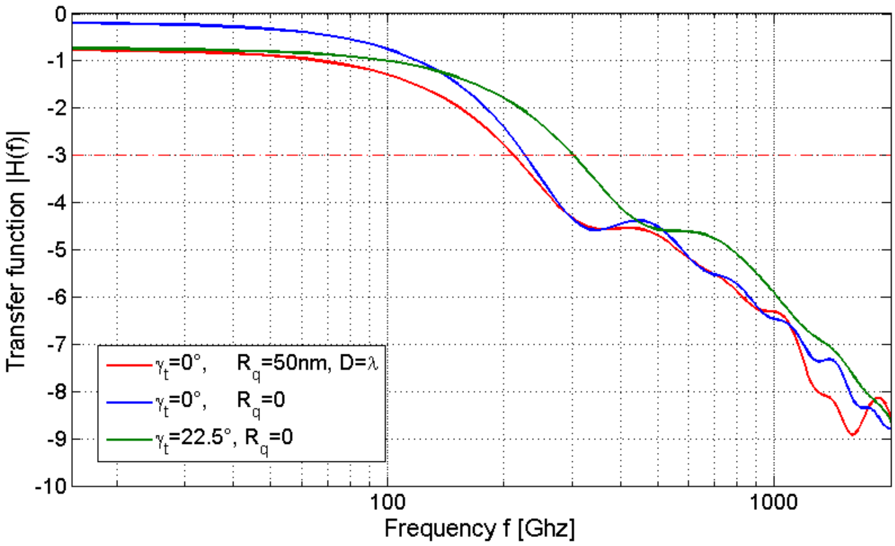

Figure 9: Transfer functions of bent wavguides (R=10mm)

In order to derive the bandwidth-length product (BLP) parameter the obtained step responses are transferred into frequency domain. The obtained transfer functions are depicted in Fig. 9.

5 Conclusions

With the introduced simulation techniques and the prototype of the design environment a significant contribution is given to CAD support for board-level optical interconnects. The integrated design environment enables fast simulation for rapid design during layout optimization and precise simulation for layout validation. The comparison of the introduced numerical results verifies the implementation of the new rapid ART technique and demonstrated the need of the more precise SRT simulation technique.

6 Literature

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