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Optical Interconnection Technology on the Printed Circuit Board Level

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Abstract
An optical interconnection technology for multi-layer printed circuit boards is presented. The application of this technology enables onboard data rates of several Gbps whereas at the same time a significant improvement on the electromagnetic compatibility (EMC) can be achieved. After an introduction, the most important properties of electrical interconnects are compared with those of optical interconnects. Moreover, requirements are derived which are essential to be met for an industrial use of optical interconnection technology on the printed circuit board level. The most important one of these requirements is to ensure compatibility with the existing design, manufacturing, and assembly processes. In the second part the current state of the art of this new technology, which takes into account the different demands and requirements, is presented. Technologies for the manufacturing of optical layers, their integration into the printed circuit board, as well as coupling concepts enabling furthermore the pick & place process are presented and discussed. As an efficient employment of this new technology requires also an enhanced and efficient design process, the necessary extensions are introduced. This includes an overview on modeling and simulation techniques for the active and passive components whereas again compatibility with the existing printed circuit board design tools is essential.

Introduction
The continuously growing need for information and communication of the modern knowledge society requires a continuous increase of the performance of computers and data networks. Memory- and computation intensive application software, internet services like video-conferencing and tele-engineering as well as the demand for a very fast data and information access at any location and any time are already today part of usual private and business communications. This means on the one hand that future data networks as well as subscriber terminals have to provide sufficiently high data-rates, which must be much higher than those of today. With the aid of the broadband transmission technology ADSL (Asymmetric Digital Subscriber Line) already today data-rates of 8Mbit/s are possible using the existing telephone lines. Also the mobile networks follow this trend and using new technologies like UMTS (Universal Mobile Telecommunication System data-rates of 2Mbit/s per mobile device are enabled. Compared to the current GSM technology (Global System for Mobile Communications) this is a more than 200 times higher data-rate. This high subscriber terminal data-date lead to the necessity to increase the data-rate of data networks significantly. Already now it is obvious that in a few years data-rates of some Tbit/s can be transferred over one single-mode fiber using multiplex technologies like DWDM (Dense Wavelength Division Multiplex). This huge amount of data is – assuming 4000 characters per sheet – equivalent to 30 million written sheets of paper, a stack with the height of approximately 3km.

The processing of this amount of data within the network nodes requires on the other hand high-performance switches, routers, and servers, whose performance must not be limited by the physical properties of the electrical interconnection technology. A solution to this interconnection problem is provided by the optical interconnection technology, which is able to overcome the data-rate of electrical interconnects many times. These given facts show the importance of signal transmission within electronic systems taking into account bandwidth, noise emission, and susceptibility to external electromagnetic noise. Especially interconnects representing high-bandwidth communication channels determine more and more the overall performance of the entire system.

Today's microprocessors, being the key components of computers and servers, are commercially available with a clock-rate of up to 2GHz and through a continuous reduction of the feature size to less than 100nm a continuous increase of the clock-rates is enabled within the next years. But the theoretical achievable performance can be obtained only, if also the periphery as well as the communication channels provides corresponding bandwidths. These bandwidth demands will become even stronger in the near future as in the next 10 to 15 years the further development of the semiconductor technology will not be limited by fundamental physical effects and a 40nm process leading on-chip clock-rates of about 11GHz seems to be possible in 2011 as forecasted in.[29] Considering this, the challenge of getting signals in the GHz frequency range off-chip and into the system after packaging will be even greater than the challenge of realizing on-chip performance at this frequency.[29]

The performance of the conventional electrical interconnection technology is limited through the underlying physical properties. The most important disadvantages and problems respectively are:

- emission of and susceptibility to electromagnetic radiation,
- limited data-rate-length product caused by attenuation and dispersion, mainly affected by the high frequency skin effect and the frequency dependent loss factor tan δ of the dielectric materials,
- high number of single interconnects (pin-count) at component- and connector level caused by the limited data-rate per single interconnect, and
- high effort to guarantee a high level of signal integrity.

In the area of long haul data transmission the electrical transmission technology is nearly completely substituted by the optical transmission technology. Using wavelength division multiplex technologies (WDM) data-rates of several 100Gbit/s over a distance of more than 500km are currently state of the art and due to latest research results data-rates in the Tbit/s area is expected to be reality within the next years. This application example indicates the potential provided by transmitting data optically:

- data-rates in the Gbit/s-area,
- no electromagnetic radiation and complete susceptibility of the optical waveguides to external electromagnetic fields, leading to reduced EMC problems, and
- bandwidth reserve using multiplex technologies (e.g. wavelength division multiplex).

The logical consequence is to utilize this potential also for inter- und intrasystem interconnects in order to compensate completely the before mentioned disadvantages of the electrical interconnection technology by the advantages of the optical interconnection technology. By a consequent use of optical technologies further advantages can be obtained:

- Through the significant increased data-rate per interconnect the pin-count of components and connectors can be reduced leading to an increase of reliability where at the same time the costs can be reduced.
- Medium-term a general cost advantage over electrical interconnects can be obtained using low-cost components (e.g. VCSEL = Vertical Cavity Surface Emitting Laser and POF = Polymer Optical Fiber).

Printed circuit boards continue to belong to the most important subsystems of electronic equipment. These substrates for microelectronic components have to provide interconnects with very high bandwidth in the future. Innovative concepts and technologies are necessary in order to provide next generation printed circuit boards with the required performance characteristics. As the current printed circuit board technology is sufficient for a high number of interconnects and further on there is some performance reserve, further development of the existing printed circuit board technology is much more efficient than the development of a completely new technology, taking also into account the economic point of view.

An additional and very important pre-condition for the industrial use of the electrical-optical interconnection technology is the availability of capable and low-cost optical transmitters and receivers. The development of suitable optical receivers (e.g. in GaAs-technology) seems to be no real problem. Suitable laser-diodes, acting as optical transmitters, were so far only available in edge-emitter technology. These laser-diodes are established for telecommunication and long haul applications but they do not meet the economic requirements of optical intra- and intersystem interconnects. With the new VCSEL-technology this problem seems to be solved.[28,7,5,6] Modulation frequencies leading to data-rates of 10Gbit/s[24] and more could successfully be demonstrated. The optical transmitters within commercial available optical fiber-links, providing data-rates of 2.5Gbit/s per channel, are already realized in VCSEL technology. The MTBF (Mean Time Between Failures) of VCSELs, quoted by the suppliers in the range of 10^5 hours (approx. 11.5 years), proves the grade of quality of this technology.

In the following an overview on the optical interconnection technology on the printed circuit board level is given. First of all the characteristic properties of electrical transmission lines and optical interconnects are described and compared with each other. Before the current state of the art of the optical interconnection technology is presented, the different requirements are pointed out, this new technology has to meet taking into account that it has to be a further development of the electrical interconnection technology. In the last section the design process for hybrid electrical-optical printed circuit boards is addressed. The proposed process is an extension of the existing printed circuit board design process and therefore it ensures compatibility to the established processes.

Fundamental Characteristics of Electrical Transmission Lines

Electrical transmission lines cannot be deemed to be ideal interconnects. In fact, their dynamical properties have to be considered during the design of electronic equipment and components. Apart from propagation delay caused by the finite propagation velocity of electromagnetic waves also attenuation and dispersion have to be taken into account.

Furthermore, the electromagnetic coupling between neighboring transmission lines called cross talk is a physical effect, whose impact must be minimized. Moreover, by an appropriate termination of each transmission line reflection effects have to be minimized. Apart from this transmission line properties, influencing the signal integrity significantly, it has to be taken into account that data transmission on electrical transmission lines can be disturbed by external electromagnetic fields and that transmission lines radiate themselves.

Propagation Delay of Electrical Transmission Lines

Important quantities for the characterization of electrical transmission lines are the characteristic impedance and the signal velocity. Especially the latter one is of high interest when comparing electrical and optical interconnects. With a very good approximation the signal velocity of a single transmission line can be computed by

$$v = c_0 / \sqrt{e_r}$$

where v is the signal velocity, c_0 the speed of light within vacuum, and e_r is the relative dielectric constant of the surrounding printed circuit board material. Typical values are between 2.6 and 3.5 and the corresponding velocity range is:

$$0.54\, c_0 \le v \le 0.62\, c_0$$

These propagation velocities correspond to characteristic propagation delay $t_d^{'}$ being in the range

$$5.38 \frac{ns}{m} \le t_d^{'} \le 6.17 \frac{ns}{m}$$

For comparison, the characteristic propagation delay of a signal propagating with vacuum speed of light is 3.34ns/m.

Attenuation and Dispersion

The maximum data-rate which can be transferred by electrical interconnects is determined by the attenuation and dispersion of the waveguide. In the case of frequencies above 1GHz transmission line's losses as well as the frequency dependence of the transmission line parameters have to be taken into account. A transfer function can be defined describing the static and dynamic transfer behavior of a transmission line with the length l:

$$H(jw) = e^{-a(jw)l} \cdot e^{-jb(jw)l}$$

The magnitude $|H(jw)|$ and the phase $-b(jw)l$ of this transfer function is depicted in Figure 2 and Figure 3 where a typical micro-strip line on a FR4 substrate was assumed (Figure 1).

These curves represent only the transmission line's influence. The unavoidable capacitive parts of the drivers output and the receivers input impedance result in an additional low-pass behavior leading to the fact, that the transfer behavior of the overall transfer system, consisting of transmitter, transmission line, receiver, and termination network has to be investigated.

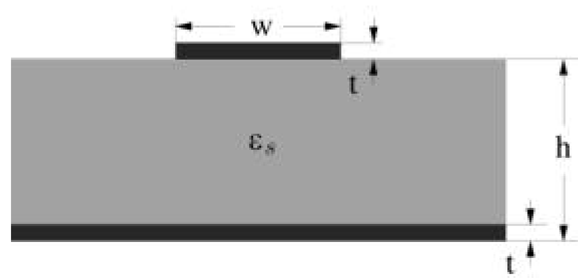

Figure 1 – Ideal Cross Section of a Typical Micro-Strip Line on a Printed Circuit Board (w=100µm, t=40µm, h=410µm, e_s=3.95, k_{CU}=5.815x10^7S/m, tand=0.0264)

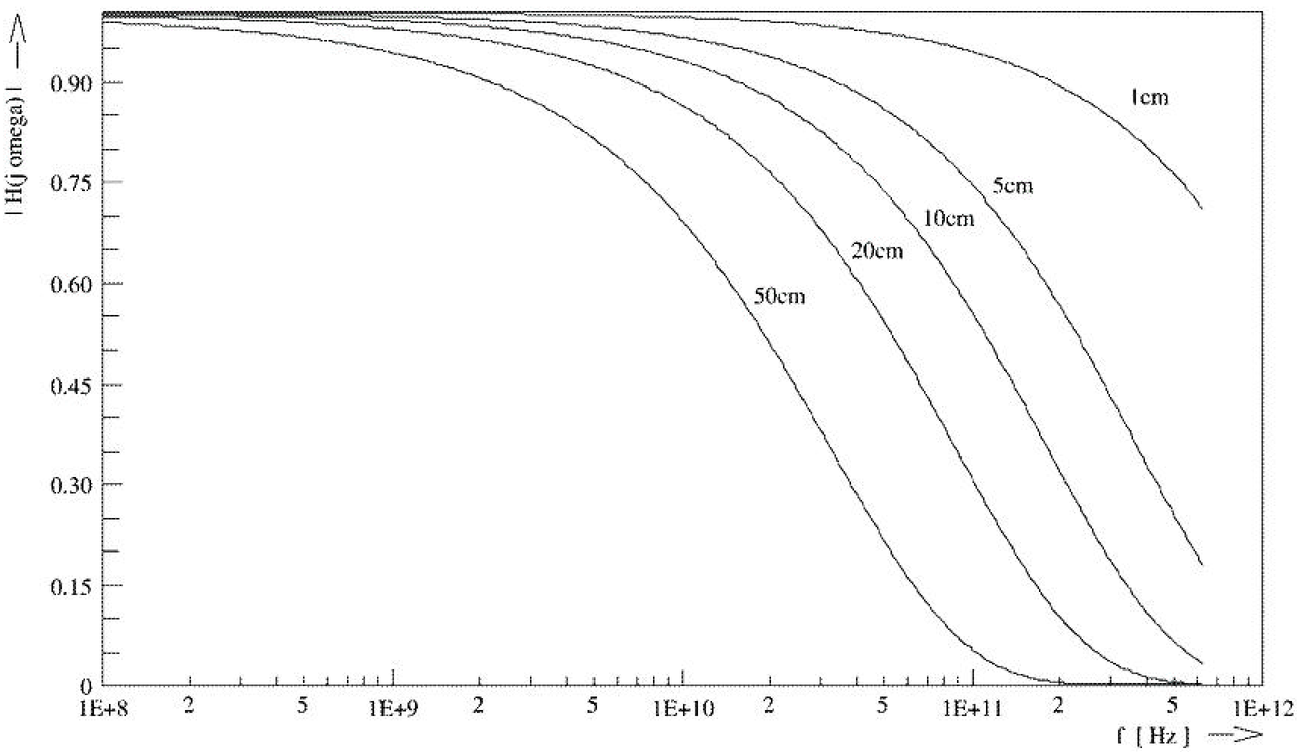

Figure 2 – Magnitude of the Transmission Line's Transfer Function $H(jw)$ with the Transmission Line's Length l as Parameter ($\left|H(jw)\right| = e^{-a(jw)l}$)

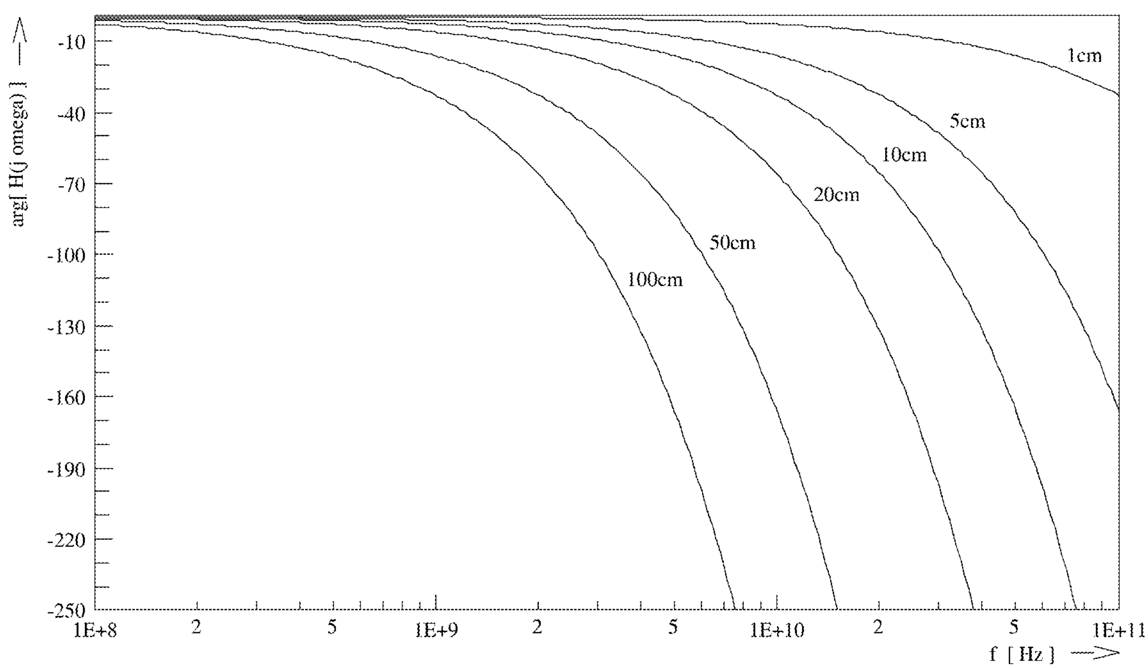

Figure 3 – Phase of the Transmission Line's Transfer Function $H(jw)$ with the Transmission Line's Length l as Parameter ($\arg\{H(jw)\} = -b(jw)l$)

Figure 4 and Figure 5 depict the voltages at the beginning and the end of a typical micro-strip line with different lengths, where additional capacitive parts of each 1.5pF at the beginning and the end of the transmission line were considered. A data transfer with a NRZ (Non Return to Zero) bit sequence '101001' at a clock-frequency of 1GHz and an initial delay of 1ns was analyzed. Figure 5 depicts the voltages at a data-rate-length product of 2Gbps·m and confirms the often-mentioned value of 2.5Gbps·m to be the physically caused limit of the electrical interconnection technology.

During the computation of the voltages the frequency dependence of the loss factor tan$d$ as well as the temperature-dependence of the material was not taken into account. This means that a best-case-assumption was made leading to the fact that in reality the transmission line's behavior is even worse than the computed one. The presented example shows very clearly the physical limits of the electrical interconnection technology.

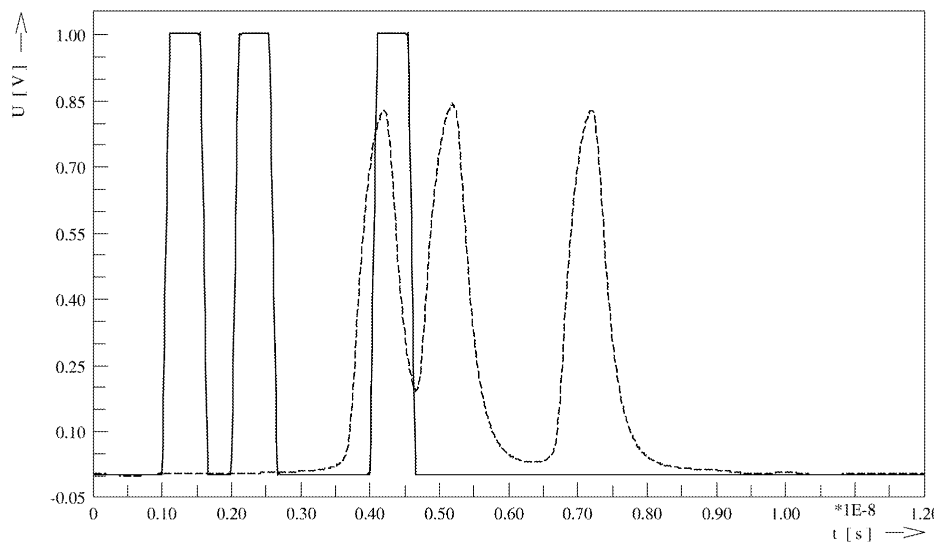

Figure 4 – Voltage at the Beginning (—) and the End (- - -) of the Transmission Line System with a Length of l=50cm

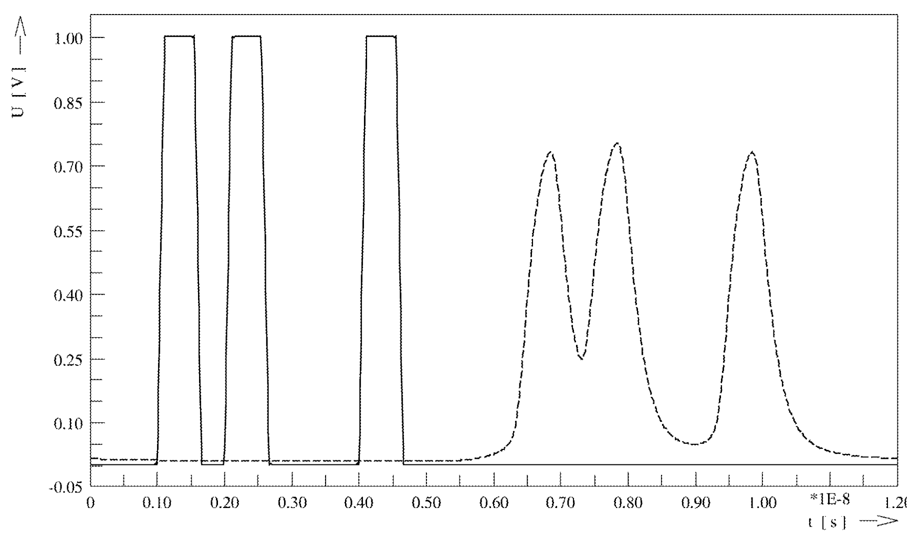

Figure 5 – Voltage at the Beginning (—) and the End (- - -) of the Transmission Line System with a Length of l=100cm

Fundamentals of Optical Waveguides

Optical waveguides are used for guiding electromagnetic waves and for the transmission of signals and news, just as electrical transmission lines do. The guidance of electromagnetic waves by a dielectric waveguide can be described very well by the so-called physical effect *total internal reflection* of a homogeneous plane wave at a dielectric interface, separating two materials with different refractive indexes. Some general relationships and properties can be derived from investigating the reflection and refraction behavior of a plane wave by a plane dielectric interface, which can be easily assigned to other types of waveguides.

Reflection and Refraction of an Electromagnetic Plane Wave by a Plane Dielectric Interface

If an electromagnetic plane wave impinges a plane dielectric interface, one part of it is reflected and the other part is transmitted as depicted in Figure 6.

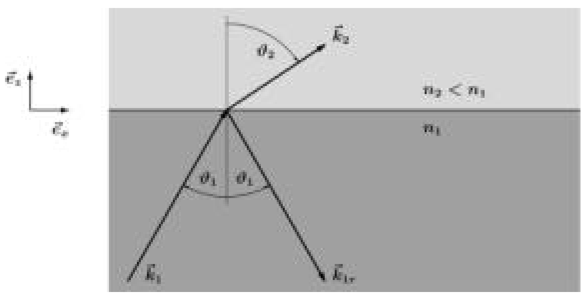

Figure 6 – Reflection and Refraction of a Plane Wave by a Plane Dielectric Interface

The propagation direction of each wave is determined by the corresponding wave vectors $\vec{k}_1$, $\vec{k}_{1r}$, and $\vec{k}_2$, where their magnitudes are given by

$$\left|\vec{k}_1\right| = \left|\vec{k}_{1r}\right| = n_1 \cdot \frac{2\pi}{\lambda} \qquad \left|\vec{k}_2\right| = n_2 \cdot \frac{2\pi}{\lambda}$$

In these equations λ is the optical wavelength in free space and n_1 and n_2 are the corresponding refractive indexes as give in Figure 6. The propagation angles ϑ_1 and ϑ_2 follow *Snell's Law*:

$$n_2 \cdot \sin \vartheta_2 = n_1 \cdot \sin \vartheta_1$$

If the angle of incidence ϑ_1 reaches for $n_1 < n_2$ the value

$$\vartheta_{1c} = \arcsin(n_2/n_1)$$

the angle ϑ_2 goes to $\pi/2$ and the transmitted wave is propagating parallel to the dielectric interface. This means that not power is transmitted into medium 2 and the incident wave is totally reflected. This effect remains also in case of larger values of the angle of incidence ($\vartheta_{1c} < \vartheta_1 \leq \pi/2$). This effect is called *total internal reflection*.

Fundamentals of wave propagation within optical waveguides

The principle of guidance of light within optical waveguides is based on the total internal reflection and can be illustrated very clearly with the aid of a planar waveguide often called slab waveguide. For this reason please consider the dielectric waveguide guiding an electromagnetic wave as depicted in Figure 7.

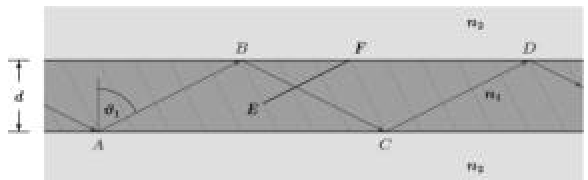

Figure 7 – Dielectric Slab Waveguide: Equivalent Ray Trajectory and Phase Fronts of a Guided Wave

This wave can be described through a plane wave, which is reflected at the waveguide core's boundary (with the angle ϑ_1) and thus propagating on a zigzag-path through the waveguide. A typical propagation path is given by the polygonal connection through the points $ABCD$ depicted in Figure 7. Furthermore, the phase fronts are depicted belonging to the plane wave during its propagation from point A to B or from point C to D, respectively. In order to get a self-consistent field distribution, after two reflections the wave has to repeat itself in the phase. This means that the phase front in the connection BE on its way from E to F has to result in the same value which is obtained for the traveling of the plane wave from B to C with an additional consideration of the corresponding phase shifts caused by the total internal reflection. The phase difference must be an integer multiple of 2π. With $\Delta\varphi_B$ being the phase shift in point B and $\Delta\varphi_C$ being the phase shift in point C this condition is:

$$k_1 \cdot \left(\overline{EF} - \overline{BC}\right) + \Delta\varphi_B + \Delta\varphi_C = -2m\pi$$

Taking into account the geometrical relations

$$\overline{BC} = \frac{d}{\cos \vartheta_1}$$

$$\overline{EF} = \overline{BF} \cdot \sin \vartheta_1$$

$$\overline{BF} = d \cdot \tan \vartheta_1 - \frac{d}{\tan \vartheta_1}$$

the so-called eigenvalue equation of the slab waveguide is

$$\Delta j\,(J_{1m}) = k_1 \cdot d \cdot \cos J_{1m} - mp$$

where $\Delta j\,(J_{1m})$ is the phase shift during the total internal reflection. In general this equation, which results in discrete angles J_{1m}, can be solved solely with graphical or numerical methods. In a physical sense this means, that exactly for this propagation angle the homogeneous waves fit into the waveguides where they are superposed to a guided wave. It has to be considered that due to different polarization directions (TE- or TM-polarization) the different phase shifts ($\Delta j_{TE}(J_{1m})$ or $\Delta j_{TM}(J_{1m})$, respectively) have to be taken into account.

If the angle of incidence of a local plane wave within domain 1 is larger than the critical angle of total internal reflection ($J_{1c} \le J_1 \le p/2$) and in addition if the eigenvalue equation is fulfilled, the wave do not lose any energy and it is guided towards the axial coordinate of the waveguide.

Numerical Aperture of Optical Waveguides

Guided rays propagating with an angle J_{1c} within a waveguide are radiated from the waveguide's end to air ($n = 1$) with an angle g_N as depicted in Figure 8. This angle g_N defines the light shadow boundary of the far field outside of the waveguide and therefore, this angle can be determined easily by measurement. With Snell's law as well as $\sin J_{1c} = n_2/n_1$ and $\cos\sqrt{1-n_2^2/n_1^2}$ respectively, one obtains

$$\sin g_N = n_1 \cdot \sin(p/2 - J_{1c}) = n_1 \cdot \cos J_{1c}$$

$$= \sqrt{n_1^2 - n_2^2}$$

The right hand side of this equation describes a very important properties of the waveguide and it is called *Numerical Aperture* (NA) :

$$NA := \sqrt{n_1^2 - n_2^2}$$

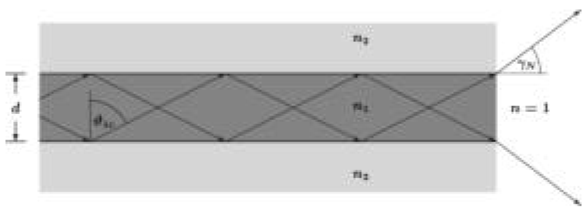

Figure 8 – Numerical Aperture of a Dielectric Slab Waveguide

The numerical aperture is a number, which is used for characterizing the properties of all optical waveguides. Waveguides with a large numerical aperture are called *strongly guiding*, because they are characterized by a relatively large range of angles where total internal reflection can be observed. In contrast to this waveguides with a small numerical aperture are called *weakly guiding*. Becomes the difference between n_1 and n_2 sufficiently large, NA can exceed the value one and there is total internal reflection at the waveguide's cross-section. In this case NA cannot be assigned any longer to $\sin g_N$ and it represents only a theoretical number.

The numerical aperture NA is very important for the optical interconnection technology. On the one hand its determines the opening angle of the diverging beam radiated from an optical waveguide. This means that at a given cross-section of a waveguide and a given axial distance from the waveguide the minimum size of the photo-diode is determined.

The numerical aperture is also of significant importance for coupling of light into an optical waveguide. Taking into account the reciprocity of waveguides it is obvious that solely incident rays with an angle of incidence being equal to or less than the angle l_N (Figure 8) can be guided by the waveguide. Each ray with an angle of incidence being larger than l_N impinges the core-cladding-interface inside of the waveguide outside of total internal reflection and thus, the ray will be attenuated trough transmission and cannot contribute to signal transmission through the waveguide. This means, that the optical source (e.g. laser-diode, LED) must be adapted to the waveguide concerning the emission spectrum. Strictly speaking, the numerical aperture of the optical transmitter must not be larger than the numerical aperture of the waveguide; otherwise there will be high coupling losses.

Solution of the Eigenvalue Equation

In order to obtain a graphical solution of the waveguide's eigenvalue equation, leading to the discrete angles J_{1m} or the propagation constants k_{1xm}, which are the x-components of the corresponding wave vectors $\vec{k}_{1m}$, respectively, a transformation of the eigenvalue equation is introduced. With

$$U = d \cdot k_{1z} = d \cdot \sqrt{k_1^2 - k_{1x}^2}\ ,$$

$$V = d \cdot |k_{2z}| = d \cdot \sqrt{k_{1x}^2 - k_2^2}\ ,$$

$$\begin{aligned} V^2 + U^2 &= d^2 \cdot \left(k_1^2 - k_{1x}^2 + k_{1x}^2 - k_2^2\right), \\ &= d^2 \cdot \left[(n_1 \cdot k_0)^2 + (n_2 \cdot k_0)^2\right], \\ &= \left(2\pi \frac{d}{\lambda}\right)^2 \cdot \left(n_1^2 - n_2^2\right), \end{aligned}$$

$$V = \sqrt{\left(2\pi \frac{d}{\lambda} NA\right)^2 - U^2}$$

the characteristic equation in case of TE-polarization is

$$\sqrt{\left(2\pi \frac{d}{\lambda} NA\right)^2 - U_m^2} = \\ = \begin{cases} U_m \cdot \tan \dfrac{U_m}{2} & m = 0, 2, 4, \ldots \\ -U_m \cdot \cot \dfrac{U_m}{2} & m = 1, 3, 5, \ldots \end{cases}$$

The intercept points of the quarter circles with the radius $R = 2\pi \cdot NA \cdot d/\lambda$ with the branches of the tan- and cot-functions in Figure 9 yield the discrete solutions and determine the eigenvalues or the propagation constants k_{1xm}, respectively. The corresponding waves with the electrical field strength

$$\vec{E}_m(\vec{r}) = \vec{E}_m(z) \cdot e^{-jk_{1xm} \cdot x}$$

are called modes of the optical waveguide. The radius of the circles depicted in Figure 9 is determined through the thickness of the slab waveguide scaled to the optical wavelength (d/λ) and the numerical aperture NA. After the introduction of a new term $\tilde{v}$

$$\tilde{v} = \frac{d}{\lambda} \cdot NA$$

which is build-up solely by the geometrical data as well as well as the waveguide's numerical aperture, the number of propagating modes can be determined very easily. With the aid of Figure 9 it is obvious that for $\tilde{v} < 0.5 \cdot (\Rightarrow 2\pi \cdot NA \cdot d/\lambda < \pi)$ the quarter circle can only intercept with the first branch $m = 0$ of the tan-function, meaning that solely the basic mode is able to propagate. At an arbitrary value of $\tilde{v}$ the total number N of the propagating modes is given by the integer part of $2\tilde{v} + 1$ (e.g. $\tilde{v} = 2.6 \Rightarrow N = 6$).

The first branch of the tan-function in Figure 9 starts at the zero-point. Therefore, arbitrary small values of d as well as arbitrary large optical wavelengths λ (equivalent to arbitrary small optical frequencies) will yield a solution of the eigenvalue equation. This means that the basic mode of a symmetric slab waveguide has the cut-off-frequency *zero*. But at a small value of R the transversal attenuation constants are very small and the field decreases very slow within the cladding of the waveguide. This property cannot be observed at all optical waveguides. A not-symmetric slab waveguide (different refractive indexes of both claddings) is only able to guide waves at a minimum value of R with $R > 0$.

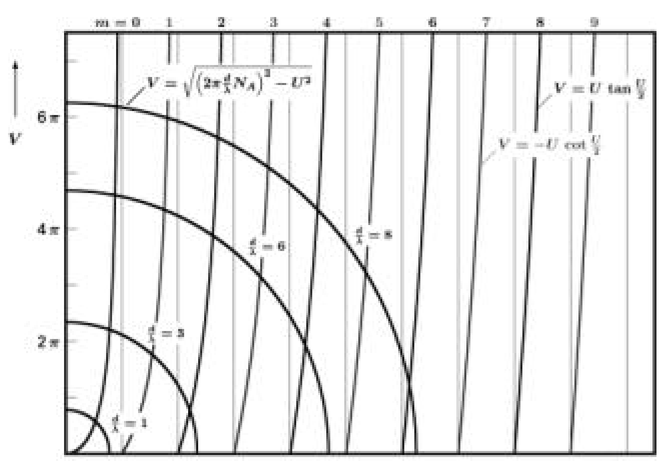

Figure 9 – Graphical Solution of the Eigenvalue Equation in Case of TE-Polarization with the Thickness (Scaled to the Optical Wavelength) of the Slab Waveguide d/λ as Parameter (n_1=1.55, n_2=1.5, ⇒ NA ≈ 0.39)

Transfer Characteristics of Optical Waveguides

The graphical solution of the eigenvalue equation of the slab waveguide yields that the number of propagating modes depends of the cross-sectional dimensions. The smaller the dimensions are, the less the number of propagating modes is. This important property is also valid for optical waveguides with different cross-sections. Waveguides, which can only guide the basic modes (E_0 and H_0), are called single-mode- or mono-mode waveguides. Waveguides being able to guide several modes are called multi-mode waveguides.

In general it applies to each dielectric waveguide, which is homogeneous in the axial direction that at each optical frequency a finite number of modes can be guided. These modes transfer optical power without losses in the direction of the axial waveguide coordinate. This ideal property is limited by some effects in reality. Real waveguides are characterized by losses, which occur due to interference of the optical wave with the material itself, due to material internal pollutions, and due to roughness of the boundary between core and cladding. Furthermore, they depend on the optical wavelength. Typical attenuation values of optical fibers used for telecommunication networks are 2dB/km (at λ=850nm) and 0.15dB/km (at λ=1.55µm).[8]

Moreover, curvatures as well as a change of the waveguide's cross-section result in losses by the excitation of radiation modes. Polymer-waveguides suitable for the integration into printed circuit boards show a much higher attenuation. Dependent on the manufacturing process an attenuation of about 0.1dB/cm to 0.2dB/cm can be achieved. It is very important to consider that this relatively high attenuation is caused mainly by the roughness of the waveguide boundaries between core and cladding. This roughness occurs due to the manufacturing process (e.g. hot embossing[12]), which has to be low-cost. The attenuation of the material itself is of lower importance.

A further important property of optical waveguides is the dispersion, which is limiting bandwidth as well as the maximum length of the waveguide. Within a single-mode waveguide an optical pulse excites due to its finite spectral width the corresponding mode within a range of neighboring optical frequencies. This is equivalent to a small range of neighboring angles of incidence J_1 (Figure 7), which results in different delays from the beginning to the end of the optical waveguide. This effect is called *chromatic dispersion* and its unit is $ps \cdot km^{-1} \cdot nm^{-1}$. Typical values are –100 +20 $ps \cdot km^{-1} \cdot nm^{-1}$ within the wavelength range 0.85µm<λ<1.55µm.[8]

At a constant optical frequency the modes within multi-mode waveguides are propagating with different propagating constants, which corresponds again to different propagation angles J_1 depicted in Figure 7. This means that the propagation delays of the modes are also different. This effect is called *mode dispersion*. Typical values of the difference of propagation delay in case of optical fibers are 0.5 up to 50 $ns \cdot km^{-1}$. Using multi-mode waveguides the chromatic dispersion can be neglected compared to mode-dispersion because both effects differ by some orders of magnitude.

Another effect limiting the achievable bandwidth is the so-called *modal noise*. It is caused by the time variant speckle pattern, which occurs due the interference of all modes (Figure 10). Discontinuities of the waveguide (e.g. optical connectors, curvatures, etc.) interact as spatial filters leading to time-dependent losses at each discontinuity. This in turn, induces additional noise of the total optical power at the receiver side of the optical interconnect.

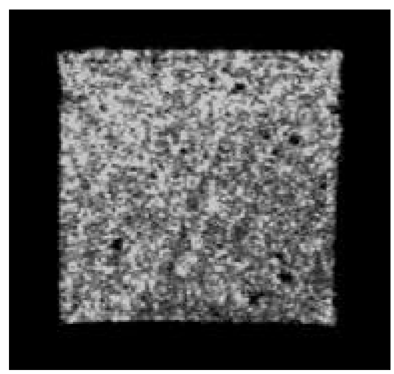

Figure 10 – Speckle Pattern on a Cross-Section of a Rectangular Multimode Waveguide

Propagation Velocity of Optical Signals

In the previous paragraphs the active principle of dielectric waveguides was illustrated with the aid of a slab waveguide. This active principle is also valid for real optical waveguides (fibers, rib waveguides, etc.). As a result it can be pointed out that the transmission of an optical signal is based on the excitation and propagation of discrete modes, whose propagation constants k_{xu} can in general be determined solely numerically. An exception to this is for instance a circular-symmetric dielectric waveguide with a step-index profile. The corresponding eigenvalue equation can be solved analytically using the well known separation approach.

For designing optical interconnects the propagation velocity of optical signals as well as the bandwidth of optical interconnects is of significant importance. The range of propagation velocities of all modes can be determined very easy with the ray-optical model of the slab waveguide.

In Figure 11 the propagation paths of the fastest (straight line) and the slowest ray (zigzag line) within an optical waveguide is depicted. It is obvious that the maximum velocity $v_{\max}$ is given by

$$v_{\max} = \frac{1}{n_1} \cdot c_0$$

where n_1 is the refractive index of the waveguide's core and c_0 the speed of light within vacuum. The minimum velocity $v_{\min}$ is equal to the effective velocity in axial waveguide direction of a ray which is traveling with on a zigzag line under the angle J_{1c} with $v_{\max}$ along the waveguide. With $\sin J_{1c} = n_2/n_1$ $v_{\min}$ becomes:

$$v_{\min} = \sin J_{1c} \cdot v_{\max} = \frac{n_2}{n_1^2} \cdot \frac{1}{c_0}$$

This equation is valid for arbitrary dielectric step-index waveguides characterized by the refractive indexes n_1 (core) and n_2 (cladding).

Optical materials provide refractive indexes being in the range of 1.45 to 1.6. Taking into account a small numerical aperture (to be realized through a small difference between the refractive indexes of core and cladding) aimed at, the achievable velocity range is approximately given by:

$$0.625 \cdot c_0 \le v \le 0.69 \cdot c_0$$

Thus, the range of the corresponding propagation delays $t_d^{'}$ is:

$$4.83 \frac{ns}{m} \le t_d^{'} \le 5.34 \frac{ns}{m}$$

The comparison of these values with those valid for electrical micro-strip lines given in section 2.1 shows no significant difference. This means that there is no significant advantage concerning the propagation delay of optical waveguides over electrical transmission lines. The real advantage of optical interconnects is the bandwidth or the bandwidth-length product, respectively, which is some orders of magnitude higher than that of electrical interconnects.

Bandwidth-Length Product of Optical Multimode Waveguides

The bandwidth-length product of optical multi-mode waveguides is mainly determined by mode dispersion resulted from the different propagation delays of the waveguide's modes. The mode dispersion effects a prolongation in respect of time and a simultaneous decrease of the signal's magnitude (Figure 11).

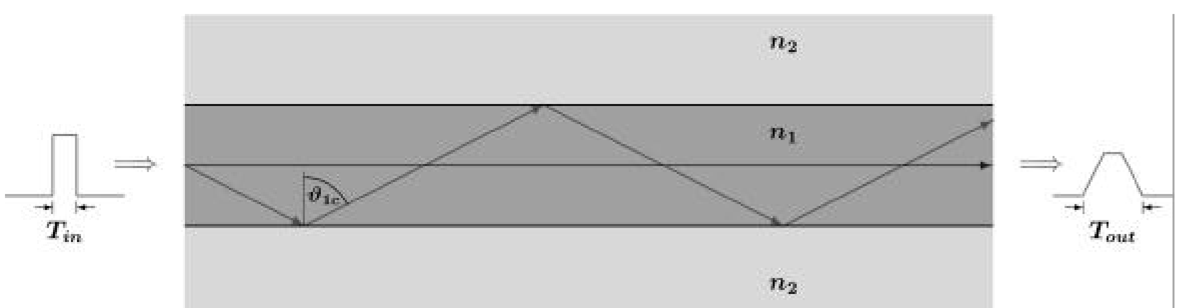

Figure 11 – Illustration of Propagation Velocity and Mode Dispersion within a Dielectric Optical Waveguide

With the maximum velocity $v_{\max}$ and the minimum velocity $v_{\min}$ two characteristic propagation delays $t'_{d_{\min}}$ and $t'_{d_{\max}}$ can be defined and the dispersion is determined by the difference $\Delta t'$:

$$\Delta t' = t'_{d_{\max}} - t'_{d_{\min}} = \frac{1}{v_{\min}} - \frac{1}{v_{\max}} = \frac{1}{c_0} \cdot \frac{n_1 \cdot (n_1 - n_2)}{n_2}$$

The bandwidth-length product $f_{\max}$ is approximately given by the reciprocal value of $\Delta t'$:

$$f_{\max} \cdot l \approx \frac{1}{\Delta t'} = c_0 \cdot \frac{n_2}{n_1 \cdot (n_1 - n_2)} = \frac{n_2 \cdot (n_1 + n_2)}{n_1} \cdot \frac{c_0}{AN^2}$$

$$f_{\max} \cdot l \approx \frac{2\, n_1\, c_0}{AN^2}$$

This equation points up, that the numerical aperture of the waveguide has a vital impact on the bandwidth-length product. Table 1 shows this product for different values of the numerical aperture for a given refractive index of the waveguide's core $n_1 = 1.5$. The fact that the bandwidth-length product decreases with an increasing numerical aperture can be explained very easily and demonstratively. A large numerical aperture corresponds to a large range of angles J_1, which leads to large propagation delay difference between the fastest, and the slowest mode. The result is a large dispersion and a small bandwidth-length product.

It should be taken into account that for digital applications the data-rate-length product is approximately twice the bandwidth-length product if the NRZ coding is applied.

Table 1 – Bandwidth-Length Product of Optical Waveguides in Relation to Numerical Aperture

n_1	A_N	n_2	ϑ_{1c}	$f_{max} \cdot l$
1.5	0.1	1.4966	86.18°	90 GHz·m
1.5	0.2	1.4866	82.34°	22 GHz·m
1.5	0.3	1.4697	78.46°	10 GHz·m
1.5	0.4	1.4457	74.53°	5 GHz·m

Optical Interconnection Technology: State of the Art

Since printed circuit boards will continue to be among the most important components of electronic equipment, innovative concepts and technologies are essential in order to be able to provide next generation printed circuit boards with the required performance characteristics. It has to be mentioned, that electrical interconnection technology will be necessary further on. This is obvious taking into account that not every interconnect on a printed circuit board has to be designed for high-speed or high bandwidth data transmission. This means that conventional printed circuit board technology will remain adequate for transporting the majority of mainly low-bandwidth signals. For this reason, – and especially from the economic point of view – priority should be given to further developing the existing technology rather than developing totally new technologies, e.g., a completely optical board technology.

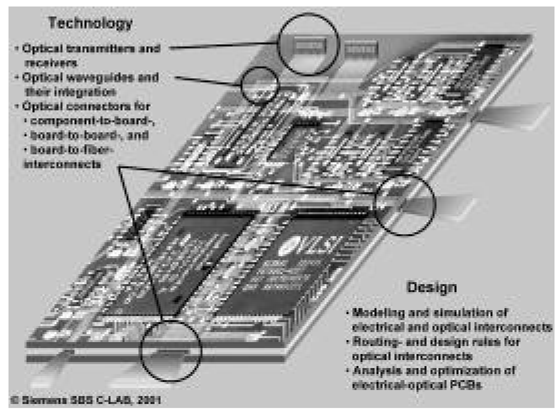

Figure 12 – Enabling Technologies for Optical Interconnects on the Printed Circuit Board Level

A promising solution for the interconnection problem is the extension of conventional electrical circuit boards by optical interconnects, as depicted in Figure 12. This solution is able to combine the advantages of microelectronics and optics whereas the disadvantages of both technologies can be avoided. An industrial employment of this hybrid electrical-optical printed circuit board technology requires practical solutions at reasonable costs for the manufacturing technology as well as for the design process (Figure 12). It has to be considered that the design process is of the same importance within the value supply chain than the manufacturing process.

The most important components and manufacturing technologies to be developed are

- optical waveguides and techniques for their integration into printed circuit boards,
- electrical-optical and optical-electrical converters for realizing optical transmitters and receivers, and
- robust coupling concepts to realize optical
  - component-to-board connectors,
  - board-to-board connectors, and

- o board-to-fiber connectors.

To provide an efficient design of electrical-optical printed circuit boards the following tools, models, algorithms and methodologies are necessary:

- Simulation models and algorithms to enable time domain simulation of optical interconnects,
- routing and general design rules for optical interconnects and entire electrical-optical printed circuit boards,
- methodologies for the analysis and optimization of electrical-optical printed circuit boards in respect of functional, technological, and cost requirements.

Demands on optical interconnection technology for printed circuit board application

The necessary technologies and components mentioned above have fulfill a lot of technological as well as functional requirements, which have to be met in order to enable an effective industrial use of this new technology. The super-ordinate requirement is to guarantee compatibility with the existing printed circuit board technology. This means that there must not be a need to modify neither the design process nor the manufacturing process of printed circuit boards significantly. In particular the processes for manufacturing and assembling the electrical parts have to remain mainly unchanged. Moreover, the unavoidable tolerances of manufacturing the optical waveguides have to be in the range of manufacturing tolerances of micro-strip lines on printed circuit boards.

A very important requirement, – also from the economic point of view – is to guarantee further on the automatic pick and place process to equip electrical-optical circuit boards with all necessary active and passive components, which also include the electrical-optical and optical-electrical converters. To guarantee surface mountability of these components is a very hard requirement as well as a pretentious task. This requirement includes that a robust and low-loss coupling of the converters to the optical on-board waveguides has to be guaranteed without any active adjustment process, which cannot be accepted due to the resulting high effort and costs.

Taking into account the above mentioned manufacturing tolerance requirements and the positioning accuracy of conventional pick-and-place equipment, which is currently in the range of ± 50 µm to ± 90 µm, only multi-mode technology is able to lead to an acceptable and practical solution. The cross sectional sizes of the optical waveguides have to be comparable to those of electrical micro-strip lines which are in the range of 100 µm$\times$ 100 µm. Although the positioning accuracy of pick-and-place equipment is – compared to cross sectional sizes of the waveguides – rather low, the postulated passive adjustment of the optical transmitters and receivers is possible introducing micro-mechanical positioning aids realized during the waveguide manufacturing process. Through this proceeding it can be guaranteed that the micro-mechanical positioning aids are positioned very accurately in respect of the waveguide's cross-sections.

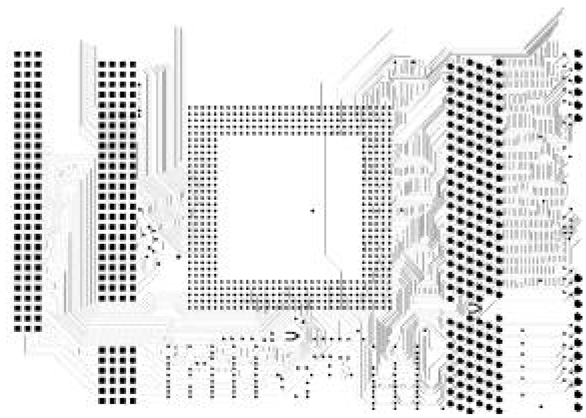

Figure 13 – Example for a Complex Routing of Electrical Transmission Lines on One Layer of a Multi-Layer Printed Circuit Board

Apart from these technology and compatibility demands there are some very essential functional requirements to the optical interconnection technology. The first one is that an optical wiring has to be enabled, which provides the same degrees of freedom, which are self-evident for the electrical wiring on printed circuit boards. An example showing this degrees of freedom is depicted in Figure 13. Meandering transmission lines were implemented in order to adjust the propagation delay of different signals very accurately. This routing requirement results on the one hand from the need to combine the electrical and optical part in an optimum way without significant routing and placement restrictions in order to achieve a very high grade of integration. On the other hand there is a need for arbitrary optical wiring in order to realize not only point-to-point interconnects – necessary to implement for instance data-links – but also multi-point interconnects necessary to implement for instance high-performance data-busses, whose realization requires passive optical components such as power-splitters and combiners. These passive elements should be integrated directly into the printed circuit board taking into account the economic point of view. A direct consequence of these requirements is that a fiber-in-board approach, e.g. described in,[30] cannot lead to a real practical solution as it leads to very cost intensive manufacturing processes which are completely inappropriate for high-volume production. The much better solution seems to be the realization of an *optical layer*, which contains the optical waveguides, and all needed passive optical structures and which can be integrated into the printed circuit board using the standard lamination process.

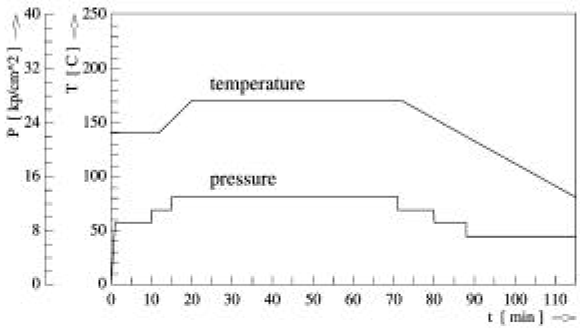

Figure 14 – Temperature and Pressure Profile During the Lamination Process of Printed Circuit Boards (FR4)

To be widely compatible to the existing manufacturing process for printed circuit boards the high pressure and temperature conditions during the lamination process has to be taken into account. Within this process a temperature of about 170°C and more at a pressure of about $15kp/cm^2$ ($\approx 150N/cm^2$) is needed for FR4 material during a time period of more than one hour (Figure 14). Moreover, the soldering of the entire printed circuit board has to be taken into account where the temperature reaches 230°C during a short time period within the reflow process. This temperature will still increase in the near future as the introduction of lead-free solder requires higher process temperatures.

Finally, there are some requirements, which seem to be obvious, but which are very important in order to achieve acceptable quality and liability of printed circuit boards wherefore they are mentioned here. The first one is the compatibility of the waveguide material with conventional printed circuit board material such as FR4 or polyimide, respectively. Of the same matter are the requirements to lifetime as well as to mechanical, thermal, and climatic properties on electrical-optical printed circuit boards. The fulfilling of these requirements, which have to be derived from the board's final application area, must be proven by tests concerning for instance changes of temperature, absolute humidity, and corrosive atmosphere.

In order to guarantee trouble-free mounting of the active and passive components on electrical-optical printed circuit boards, the same planarity – of the entire board as well of the chip area itself – has to be postulated which is state of the art for electrical printed circuit boards. Further on, the electrical properties such as dielectric strength and isolation resistance of the optical material has to be considered.

General Concept of Electrical-Optical Printed Circuit Boards

The consideration of the above mentioned requirements results in a new concept for printed circuit boards, which is characterized by a hybrid layer-stack consisting of electrical and optical layers (Figure 15). This concept is able to provide the required compatibility concerning the design- und manufacturing process, and it enables the required *free optical routing*. The optical waveguides are part of separate optical layers.

During the manufacturing of the waveguides it has to be taken into account that the applied process in combination with the used materials yield waveguides with sufficiently good transmission properties. Especially the attenuation determined the maximum waveguide length as well as the signal-noise ratio affecting the bit error rate vitally. Intensive investigations have shown, that the intrinsic attenuation of the material itself is of secondary relevance. Much more important is the manufacturing process itself which determines the significant part of the attenuation through the achievable optical quality of the waveguide boundaries. This means, that optical layers made of glass, a material with excellent optical properties, will lead to an acceptable solution only if the structuring process is able to provide sufficiently smooth waveguide surfaces. The current known processes lead to a very high surface roughness and therefore to an unacceptable attenuation.

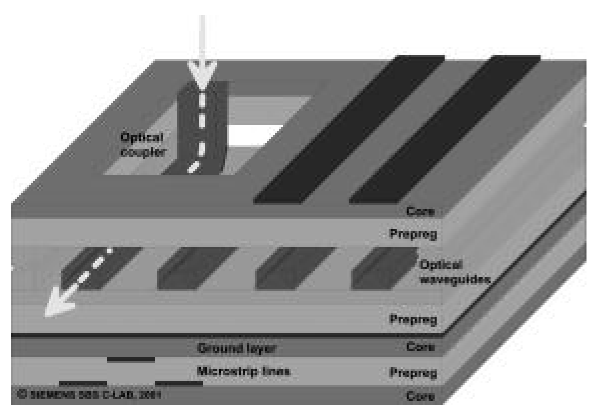

Figure 15 – Concept of a Printed Circuit Board with an Integrated Optical Layer, Containing Optical Multimode Waveguides

Using polymers for waveguide core and cladding, so-called hot embossing processes [19,21,12,15] can be applied in order to manufacture the optical layers. This technology enables the required degrees of freedom as well as a precise fabrication of arbitrary passive structures like power splitters and star-couplers. The entire fabrication process of the optical layer is widely compatible to standard lamination processes. One possible way of fabrication is depicted in Figure 16. It is based on the structuring of a polymer foil, filling the resulting grooves with fluid pre-polymeric core material, and curing. Finally, a second polymer foil is laminated on the first one.[12,18,19]

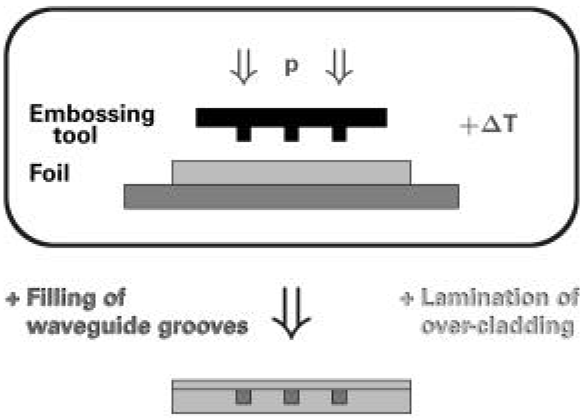

Figure 16 – Manufacturing of Optical Layers by Means of Hot Embossing (Groove Filling Process)[12,18,19]

Another hot embossing process, shown in Figure 17 is based on manufacturing firstly rib waveguides, which are laminated in a second step on a polymer substrate. Finally, the optical layer is obtained after filling with the over-cladding.[20,21,15] In order to meet the high-temperature requirements already mentioned, high-Tg materials such as COC[18] or special polycarbonate[20,21] can be used.

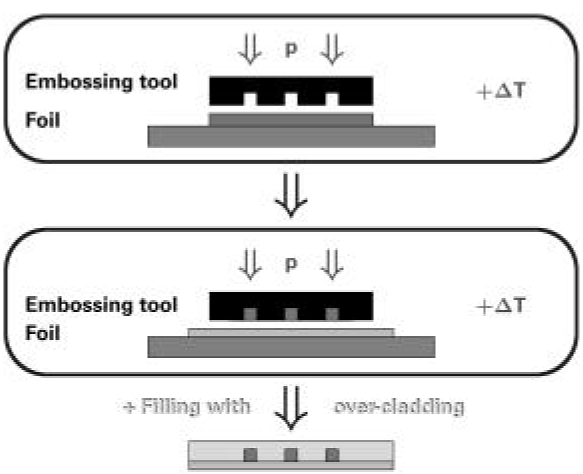

Figure 17 – Manufacturing of Optical Layers by Means of Hot Embossing (Rib Cladding Process)[20,21,15]

Key components for the hot embossing processes are the embossing tools, which determine the achievable tolerances and the surface quality of the waveguides. One possible way of fabrication is given e.g. by realizing a primary structure – the so-called master – by UV deep lithography and a following electro-forming process in order to get a nickel shim [18] This lithographic technique is able to meet the very important requirement to provide an arbitrary and any-angle routing of the optical signals. Depending on the tool manufacturing process and the hot embossing process itself very accurate surface qualities can be obtained. The remaining surface roughness can be investigated experimentally, for instance by the atomic force microscopy. The maximum depth of first engineering samples was measured to be in the range of 50 to 100 nm. After an optimization of the processes roughness depths of less than 20 nm could be obtained leading to an attenuation of less than 0.1db/cm.

The final step is to integrate the optical layers into printed circuit boards without a significant modification of the established lamination process. First experimental results with engineering samples (The waveguides were manufactured by order of Siemens AG at the University of Dortmund (Department of Electrical Engineering), the integration into the printed circuit boards was performed by ILFA Feinstleitertechnik GmbH/Hanover.), depicted in Figure 18, had proved that there remain no major problems to be solved. The compatibility to the existing printed circuit board manufacturing process could be guaranteed through a minor modification and adaptation, respectively of the process parameters.

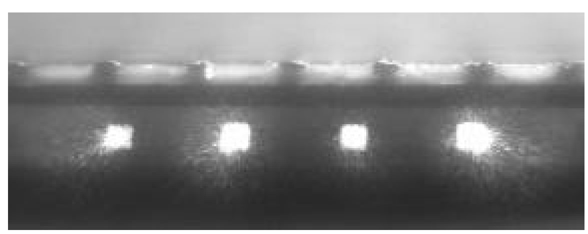

Figure 18 – Cross section of a multiplayer printed circuit board with integrated optical waveguides, illuminated with VCSELs

Within the German project OptoSys (In the frame of OptSys, funded by the German government, the companies Siemens AG, Infineon Technologies AG, ILFA Feinstleitertechnik GmbH and DaimlerChrysler AG are collaborating intensively in order to develop an optical interconnection technology for printed circuit board application. Furthermore, the Universities of Paderborn, Dortmund, and Ulm as well as the Fraunhofer Institute for Applied Solid-State-Physics in Freiburg are participating on a sub-order basis.) already at the end of 1999 electrical-optical printed circuit boards could be developed, manufactured, and demonstrated which enable onboard data-rates of 3Gbit/s.[25,26]

Electrical-Optical and Optical-Electrical Converters

Apart from the technology for the manufacturing of optical waveguides and their integration into printed circuit boards the electrical-optical and optical-electrical converters acting as interfaces between the microelectronic components and the optical waveguides are of significant importance. The realization of these components requires low-cost optical transmitters as well as low-cost and fast optical receivers.

The optical transmitters are based on VCSELs emitting at 850nm and below. This emission wavelength is of great interest using polymer waveguides due a local attenuation minimum of polymer material. In the meantime VCSEL-technology has reached a high grade of quality and it has the potential to realize on the one hand very high data-rates (10Gbit/s and more[24]) and to become a low-cost technology on the other hand.

The optical receivers, also realized as so-called OEICs (Opto-Electronic Integrated Circuits), are based on photo-diodes with mainly integrated amplifiers. The design of the photo-diode's sizes is affected by a conflict. As illustrated in section 4.1 the printed circuit board manufacturing as well as the pick-and-place process requires optical waveguides with large cross-sections. This means that the size of the photo-diode must be sufficiently large in order to avoid an outshining taking into account the numerical aperture of the waveguide and the axial distance between waveguide and the photo-diode or to keep the outshining with given limits. On the other hand, a large photo-diode has a large capacitance limiting the achievable bandwidth resulting in the fact that in dependence of the required data-rate the cross-sectional dimensions must be reduced along with the photo-diode's diameter. One possibility to overcome this problem is to use micro-optical components (e.g. micro lenses), which are able to focus the entire optical power, leaking from the waveguide's cross-section, onto the photo-diode. However, this solution leads to an increase of costs and therefore, its acceptance will be very low. The photo-diodes can be realized as PIN- or MSM diodes where MSM diodes should be preferred for higher data-rates due to their three times lower capacitance compared to PIN diodes of the same size.

Apart from the active components described above a robust and standardized concept for coupling the waveguides to the optical transmitters and receivers is a very important pre-condition for an industrial use of the optical interconnection technology.

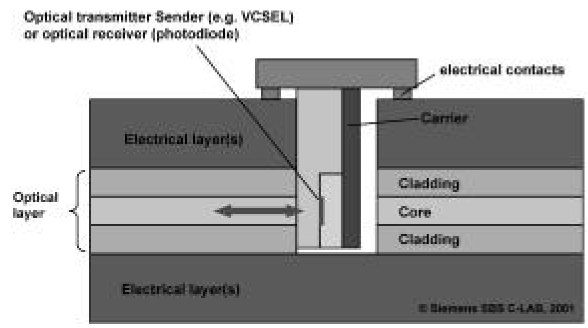

Figure 19 – Concept for Direct Coupling of the Optical Transmitters and Receivers to Board-Integrated Optical Waveguides

The coupling concept has to enable the pick-and-place assembly of the converter modules and a passive adjustment of these components relative to the cross-sections of the waveguides within given tolerances where the positioning accuracy of standard pick-and-place equipment has to be underlain. The requirement for a passive adjustment of the converter modules has to be fulfilled unconditionally because an active adjustment would lead to an expensive and therefore unacceptable solution.

In principle two different coupling mechanisms are possible: On the one hand the active components can be located directly in front of the cross-sections of the optical waveguides. This is called butt coupling (Figure 19). On the other hand beam deflecting elements can be used in order to realize an indirect coupling (Figure 20).

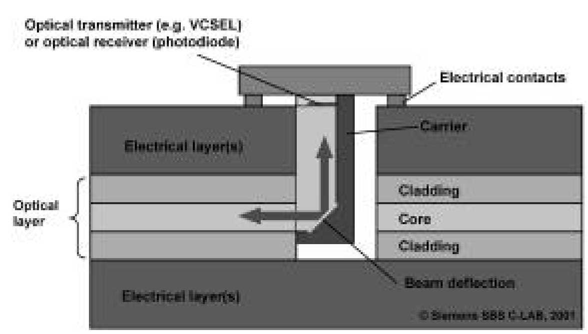

Figure 20 – Concept for Indirect Coupling (Through 90° Beam Deflection) of the Optical Transmitters and Receivers to Board-Integrated Optical Waveguides

The engineering sample depicted in Figure 21 shows a printed circuit board with integrated waveguides with a butt coupled transmitter module. This printed circuit board was developed and manufactured with the partners in the frame of the German EOCB project (The EOCB consortium consists of Andus GmbH, FhG IZM Berlin, ILFA Feinstleitertechnik GmbH, Mikropack GmbH, OECA GmbH, Robert Bosch GmbH, Siemens AG, and University of Paderborn.)

The transmitter module consists of a VCSEL array with 4 laser-diodes mounted on a sub-carrier, which dips into the printed circuit board in order to place the laser-diodes directly in front of the waveguides. The components and connectors observable in the background belong to the discrete realization of the VCSEL drivers. For an industrial use of the optical interconnection technology the entire driver circuits have to be integrated together with the laser-diodes into one package in order to obtain a compact and miniaturized module. This applies for the receiver side too. Figure 22 shows a printed circuit board with an entire electrical-optical interconnection. This board was developed and assembled in the frame of the EOCB project, too.

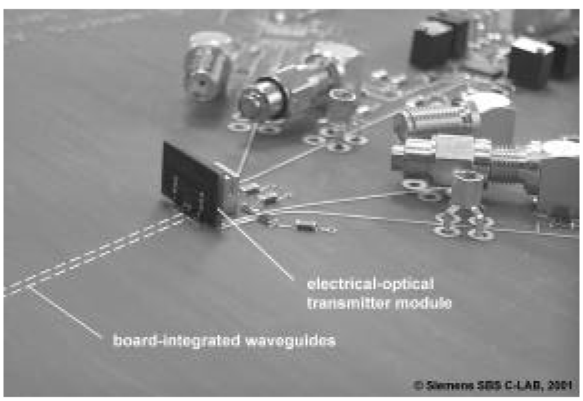

Figure 21 – Printed Circuit Board with Integrated Optical Multimode-Waveguides Butt-Coupled to a 4-Channel Transmitter Module

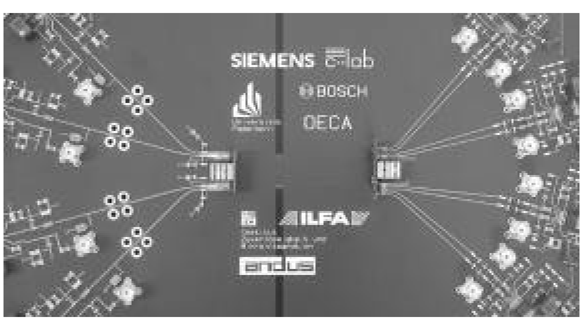

Figure 22 – Printed Circuit Board with an Entire Electrical-Optical Interconnection

An engineering sample of an electrical-optical printed circuit board with an indirectly coupled transmitter module is depicted in Figure 23. This prototype was developed and manufactured in collaboration with the partners of the German project OptoSys.

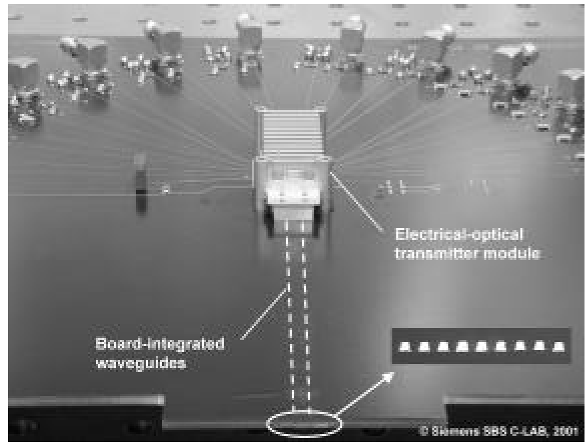

Figure 23 – Printed Circuit Board with Integrated Optical Multimode-Waveguides Indirectly Coupled (Through 90° Beam Deflection) to a 12-Channel Transmitter Module

The transmitter module provides 12 channels with a data-rate of 2.5Gbit/s per channel. Both coupling concepts are in principle suitable to fulfill the requirement of a passive pick-and-place assembly of the optical transmitters and receivers.

Design of Electrical-Optical Printed Circuit Boards

The design of any electronic equipment is based on the use of tools, which have been developed and continuously improved during the last years. Furthermore, experience of many years is used in terms of design rules in order to minimize development time and costs. Especially for printed circuit boards a lot of very efficient design tools are available which significantly support the entire design and development process.

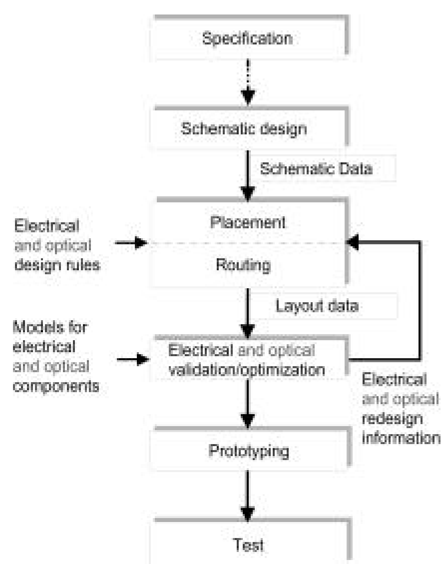

Figure 24 – Extended Process to Design Electrical-Optical Printed Circuit Boards

The design of electrical-optical printed circuit boards has to be based on the existing design process for conventional electrical circuit boards in order to take into account acceptability and effectiveness. This means that the existing process should be modified or extended, respectively within the relevant stages. Figure 24 depicts the extended process. Due to functional requirements it is obvious that there are no changes within the stages *Specification* and *Schematic design*. This means that it must be possible to consider optical interconnects during these stages but that there is no need for a process modification. The relevant modifications concern the stages *Placement/Routing* and *Validation/Optimization*. Apart from design, analysis, diagnosis, and optimization of electrical components and interconnects these process activities have to refer to the required optical components and interconnects.

This means too, that the sequence of all process stages needs no modification and that no additional stages have to be included. As a result the extension is limited to the provision and application of new design rules, simulation models and their integration into the corresponding design stages. Recapitulating, there is a need for:

- simulation models for optical (board-integrated) multi-mode waveguides,
- simulation models for optical transmitters and receivers,
- simulation models for optical fibers and connectors,
- simulation algorithms for time domain analysis of optical interconnects and transmission systems, and
- design rules for electrical-optical interconnects and transmission systems.

In order to obtain a homogeneous and efficient process, these new models and algorithms have to be integrated into the existing design, simulation, and analysis tools for electrical components and systems. This means that during the development of the models attention has to be paid for ensuring compatibility with the existing models, algorithms, and tools.

This requirement is not trivial, as time domain analysis of optical interconnects is not needed very often. In the area of long haul telecommunication, the classical application area of optical data transmission technology, the timing behavior of the signals is of secondary importance. Solely the achievable data-rate mainly limited by dispersion is of significant importance. Optical intra-system-interconnects have to meet the timing requirements given by the system architecture and the microelectronic components. Examples are the propagation delay of the interconnects, the delay of the active components and the skew in case of massively parallel interconnects. Figure 25 depicts a principle structure of a massively parallel electrical-optical interconnection system and the physical effects to be considered.

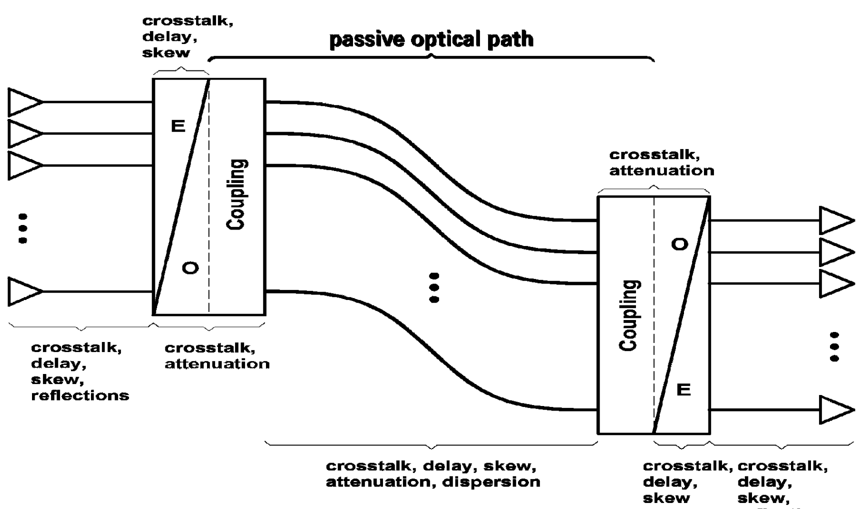

Figure 25 – Massively Parallel Electrical-Optical Interconnects and the Physical and Parasitic Effects to be Considered

Due to the transversal dimensions of the optical waveguides, which are huge compared to the optical wavelength, and due to the numerical aperture, being in the range 0.2 to 0.4, board-integrated waveguides are highly multi-modal. An estimation yields more than 1000 propagating modes. Taking into account the surface roughness[12] the modeling and simulation of signal propagation through these kind of waveguides is a sophisticated problem. Due to the high number of modes and the roughness depth of approximately 10% of the optical wavelength established wave optical analysis methods like the FEM (Finite Element Method) or the BPM (Beam Propagation Method) cannot be applied. The main reason is huge numerical complexity leading to unacceptable computation times and less trustworthy results.

A promising approach is the so-called *ray tracing*, which is based on geometrical optics. It can be applied if the dimensions of the configuration to be analyzed are large compared to the optical wavelength. This pre-condition is given in case of optical onboard-interconnects. But the roughness with a depth much less than the optical wavelength cannot be considered directly with this method. This problem can be solved by determining with the aid of Maxwell's theory special reflection- and transmission boundary conditions which can be derived from the analysis of the scattering of a plane wave through a rough dielectric interface.[2,3,4] The roughness can be represented in a statistical sense very well by the Fourier transform of its autocorrelation function, which can be approximated very well by a two-dimensional declining exponential function.[12] This function is characterized by only 3 parameters, being the *root mean square* B of the roughness depth and the *correlation lengths* D_y and D_z regarding two orthogonal directions. Applying a Monte Carlo method, the ray tracing methodology can be extended for the consideration of the roughness.[2,3,4]

Results of this new method were compared with results obtained by the Coupled Power Theory, which describes the power of the propagating waveguide modes versus the axial coordinate of the waveguide. The ray tracing results were transformed into an equivalent power distribution of the waveguide modes. The comparison depicted in Figure 26 shows a very good agreement.[4]

Time domain analysis can be performed by introducing a multi-port description of optical multi-mode waveguides, where the transfer behavior of the different transfer paths, described by the corresponding pulse responses can be determined from the step responses which can be computed with the aid of the ray tracing method very easily.[10,14] After an appropriate approximation of the pulse responses through exponential functions recursive and therefore fast convolution algorithms [14] can be used for fast and accurate time domain simulations.

Modeling and analysis of the entire optical path requires further on an appropriate modeling of the optical transmitters and receivers, suitable for the ray tracing analysis of the optical path. For this reason the emission characteristics of the optical source has to be discretized in order to describe the laser emission spectrum by a finite number of initial rays as depicted in Figure 28. Each ray is determined by its starting point, its propagation direction, and its behavior in respect of time [11] ,which includes an initial delay and a transient characteristics (Figure 29).

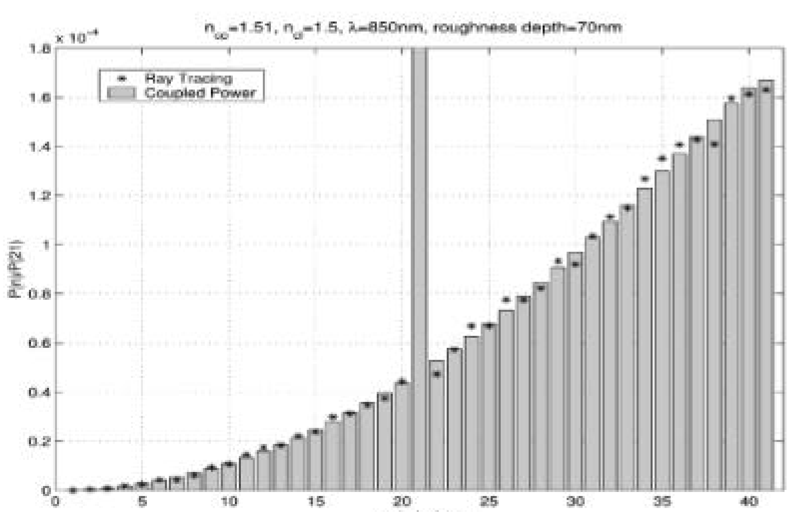

Figure 26 – Normalized Power of all 41 Guided Modes of a Slab Waveguide Excited by the 21st Guided Mode Calculated by the Coupled Power Theory and the Monte Carlo Based Ray Tracing

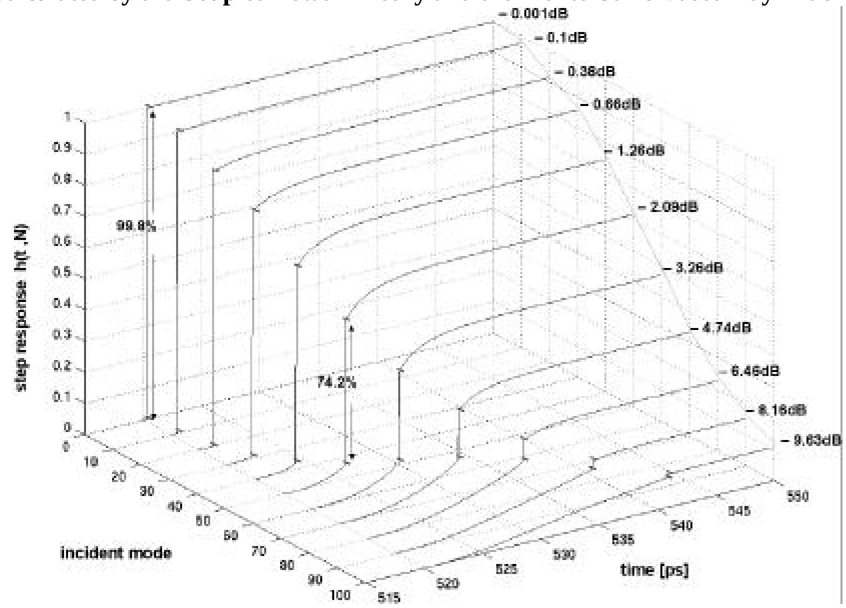

Figure 27 – Step Responses of the Modes of a Slab Waveguide Computed with a Ray Tracing Algorithm

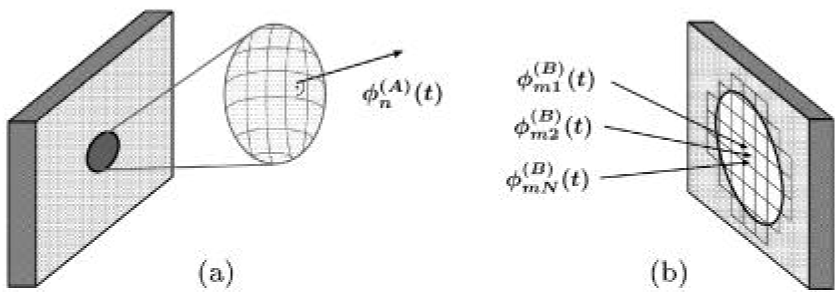

Figure 28 – Ray Tracing Compatible Modeling of the Optical Output Behavior of VCSELs (a) and the Optical Input Behavior of Photo-Diodes (b)

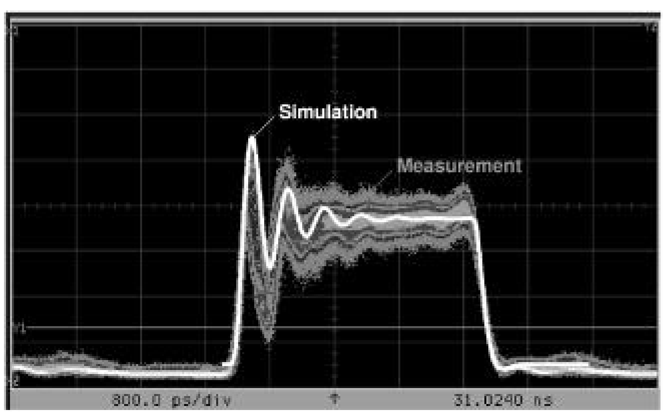

Figure 29 – Measured and Simulated Optical Output Power of a Laser-Diode

Equivalent to the modeling approach for laser-diodes the photo-diodes have to be modeled ray tracing adequate. This is obtained by discretizing the active area (Figure 28) in order to model a location and angular dependent sensitivity of the diode itself. From standard laser-diodes and photo-diodes macro models were derived which are represented by electrical circuits. This models were integrated into the HSPICE program in order to make a first validation and verification.[11]

Conclusion

The performance limitations of the electrical interconnection technology, caused by the underlying physical effects, can be successfully dealt with the introduction of the optical interconnection technology. The necessary basic technologies and components for its realization, which are manufacturing and integration technologies for optical waveguides, low-cost optical transmitters and receivers, adequate coupling mechanisms as well as simulation- and design tools, are currently under development. The technology, which is a key technology for future information and communication equipment, is widely compatible with the existing printed circuit board design and manufacturing processes and it provides the potential to meet the high-performance and high-bandwidth requirements of next generation printed circuit boards. The great advantage of this approach is that both electrical and optical interconnects are integrated into one carrier and that both tolerance requirements are in the same range. Using the presented hybrid approach, the performance potential of semiconductor technology leading to on-chip clock-rates of more than 10GHz within the next 10 years, can be used completely and a significant increase of the performance of electronic equipment will be the result.

After a description of the basic characteristics of electrical transmission lines the active principle of dielectric waveguides as well as the fundamental properties of optical waveguides was introduced. The most important properties like propagation delay and data-rate-bandwidth product of both interconnection principles were pointed out. The following section dealt with the technology of optical interconnects. The most important requirements were introduced and the state of the art concerning printed circuit board technology as well as electrical-optical conversion modules was discussed. In the last section an extended design process for electrical-optical printed circuit boards was presented which meets the compatibility requirements postulated before.

First application areas for this new technology will be high-end computers as well as switches and routers of telecommunication- and data networks. Products based on this technology will be on the market within the next 3 to 5 years.

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