Upgrading multimode channels for multi-Tb/s/inch bandwidth densities in board-level optical interconnects

Daniel Erni[1, 2], Daniel Lenz[2], Jan-Marc Lehky[2],
Bert Jan Offrein[3] and Tobias Lamprecht[3]

Abstract – To keep up with the increasing demand for data rate in high-end servers, and especially in configurations encompassing e.g. symmetric multi-processor (SMP) systems, I/O memories and ultra-fast system bus links, board-level optical interconnects have become increasingly important even for very short link topologies "inside the box" being typically in the range of 10 cm that may scale up to several meters. Merging optical waveguide technology with state-of-the-art printed circuit board (PCB) production is reliable only if the involved waveguide cross sections are of considerably large extent, leading to a highly overmoded optical transmission channel. As in mobile communications, such "problematic" channels are prone to be exploited by advanced transmission schemes based on multiple-input multiple-output (MIMO) communications. We present the idea of an optical MIMO channel by having more than one laser source at the input and a detector array at the output. With proper tailoring of the underlying mode group multiplexing mechanism, aggregate data rates in the multiple 10 Gb/s range may be achievable supporting bandwidth densities of 10 Tb/s/inch already with present optical interconnect technologies.
Index Terms – Optical MIMO system (O-MIMO), Optical interconnects, Optical backplane communications, Mode group multiplexing, Multimode waveguides, Fast system models.

I. Introduction

Board-level optical interconnects are currently the most promising alternative to overcome the capacity limitations inherent to copper-based electronic data transmission. Optical channels have therefore to be integrated into the electronic plug-in cards, mid-planes as well as into the backplane of e.g. a server's multiple rack configurations. As the term "interconnect" implies, a lot of severe packaging challenges have to be resolved too. Thus, linear bandwidth density (i.e. the overall data rate per connector width) has become an important key figure because it might be less the potentially large bit-rate-length-product that may cash in for the optical interconnect than the promising perspective of this specific density measure, especially because electrical connectors start to become cross talk limited at densities around 2-5 Gb/s/mm^2. This paper explores a novel approach to extend the "bandwidth density" within each single multimode wave-guides. After describing the waveguide technologies in Section II we then present a comprehensive channel model (Section III) followed by an upgrading scheme for such multimode channels (Section IV) making use of the various mode manifolds. A realistic outlook is given in Section V.

II. Waveguide technologies

As depicted in Figure 1 two alternative competing technologies for waveguide arrays have been developed (with typical pitches of e.g. 250 μm down to 62.5 μm) in order to explore the feasibility of low-loss optical channel waveguides in printed circuit board (PCB) fabrication environments. Multimode channel waveguides [cf. Figure 1 (a)] were ion-exchanged in different borosilicate thin glass substrates from copper stripes that are processed either by direct wet etching of sputtered copper films after photolithographic patterning or by lift-off. The electric field assisted ion exchange takes place in an Argon atmosphere at temperatures around 370 $^\circ$C while involving voltages between 60 V and 500 V [2]. The waveguide are designed for widthsbetween 40 μm and 100 μm whereas core profile depths up to 30 μm are achievable depending on the exchange durations (i.e. exchanged charge densities). Optimization of the processing window has been pursued towards both fast waveguide fabrication (yielding 6 μm deep profiles within only 90 seconds) and accurate step-like index profiles [3]. Typical loss values ranges from 0.22 dB/cm – 0.08 dB/cm for the associated wavelengths of 850 nm – 1550 nm [4].

One of the most advanced waveguide process has been developed by the IBM Zurich Research Laboratory and encompasses an acrylate-based polymer technology [cf. Figure 1 (b)], where the channel waveguides are fabricated in a layer-by-layer technique using doctor blading or spray coating [5,6], depending on the actual board size. The patterning of the core layer is achieved with UV proximity mask lithography, or alternatively, with direct UV writing, and subsequent solvent development. Best performing structures have core dimensions of 50 μm $\times$ 50 μm showing extraordinary low loss figures of $<$ 0.03 dB/cm at λ =850 nm [7]. Owing to the large cross sections these waveguides feature mode numbers between some

Received May 29th, 2007. Revised July 25th, 2007.

[1]General and Theoretical Electrical Engineering (ATE), Faculty of Engineering, University of Duisburg-Essen, Bismarckstr. 81, D-47057 Duisburg, Germany.
Phone: +49(0)203/379-4212; Fax: +49(0)203/379-3499;
E-mail: daniel.erni@uni-due.de;
[2] Communication Photonics Group, Electronics Laboratory, ETH Zurich, Gloriastrasse 35, CH-8092 Zurich, Switzerland;
[3] IBM Research GmbH, Zurich Research Laboratory, Säumerstr. 4, CH-8803 Rschlikon, Switzerland.

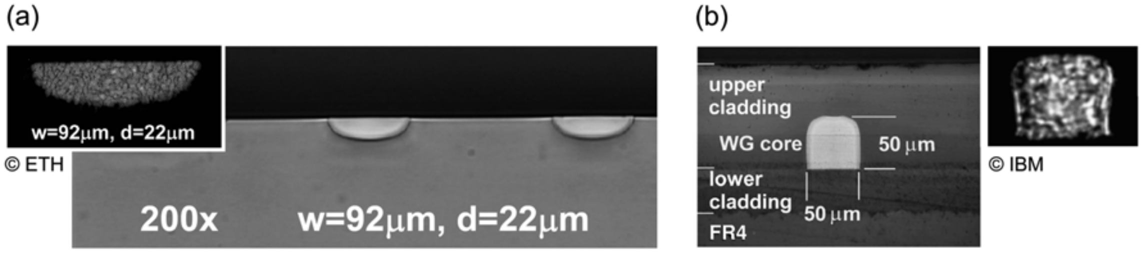

Fig. 1. Waveguide technologies for board-level optical interconnects: (a) dry copper film ion-exchange process in borosilicate; (b) low-loss polymer waveguide technology.

hundreds up to several thousand, where e.g. the polymer waveguide supports 488 modes.

III. Modeling highly-multimode optical transmission channels

A generic multimode channel for board-level optical interconnects comprises the signal source at the input, typically an intensity modulated (IM) vertical cavity surface emission laser (VCSEL) array, whose light is launched into the multimode waveguide either by passively-aligned butt-coupling [7,8], or using additional components such as micro-prisms in combination with in-coupling lenses [9,10].

A) The VCSEL model

The VCSEL simulation relies on a comprehensive and extremely efficient spatio-temporal, rate-equation based large-signal laser model [11] that includes noise issues [12], optical feedback as well as spatial hole burning, carrier diffusion losses [11], and the carrier-transport dynamics with respect to the quantum well active material [13]. As shown in Figure 2 the model provides temporal evolutions of mode field distributions. The efficiency is mainly achieved with the application of the method of moments to the spatio-temporal laser equations. Within this scheme spatially defined test functions enable a reduction of the model complexity by its spatial dimension providing a model representation based on a system of ordinary differential equations (ODEs) in the time domain only instead of the corresponding spatio-temporal partial differential equations [14]. This semi-analytical model thus strongly resembles to the well-known simple rate equations; however, the underlying accuracy is still comparable to a device simulator. The overall VCSEL model has been confined into the free software package VISTAS that is public accessible under www.sourceforge.net [11].
The mapping of laser modal field onto the input facet of the multimode waveguide (i.e. butt-coupling) is performed using Rayleigh-Sommerfeld integrals [14] where the formalism also allows the introduction of micro-prisms and lenses. Even dynamic coupling-effects, such as time varying coupling efficiencies due to temporal mode redistributions in the VCSEL cavity are tractable [15]. The latter can be aggregate into a figure such as a time-dependent numerical aperture.

B) The waveguide channel model

Since the propagating fields in the multimode waveguide can be decomposed into the waveguide's eigenmodes, the optical signal transmission is fully characterized by the set of its corresponding modal amplitudes. In this framework the coupling between e.g. the VCSEL output field and the waveguide modes confines into a complex amplitude relation, where the latter is tantamount to the coupling matrix. A fast but still accurate analysis of the multimode bend [16] is also part of the model as well as both, guided mode coupling and radiation loss [17] if surface roughness is assumed at the core-cladding interfaces. Interestingly both mechanisms tends to counteract pulse broadening by intermodal dispersion if the guided mode coupling is limited to neighboring modes only, whereas microbending losses implied by the slowly varying periodic deformation of the waveguide substrate yields the opposite. Microbending could appear because of the inlaid glass tissue in the PCB, whose meshes modulate the surface of the substrate with a typical rms amplitude of 1 μm and a periodicity around 800 μm (yielding an additional loss contribution of around 0.04 dB/cm [14] for a 50 μm $\times$ 50 μm polymer waveguide). The channel output is treated similarly as the input, where the waveguide fields at the output facet are mapped onto the detector array while using the same integral transformation. We assume a simple direct detection

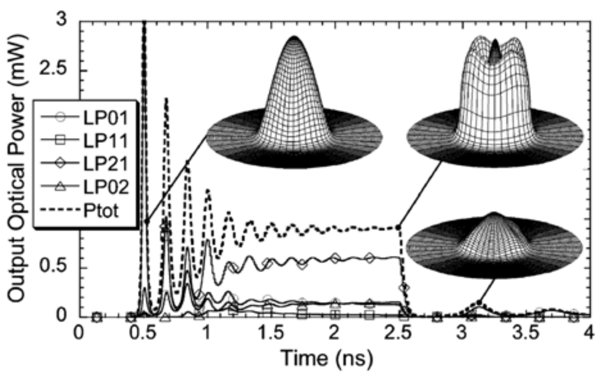

Fig. 2. Transient simulation showing the VCSEL's response to a square current pulse. The laser is turned off to a current slightly below laser threshold. The response contains four lasing modes, the fundamental mode's intensity profile, and the overall intensity distribution. The after bumps are due to spatial hole-burning effects [11].

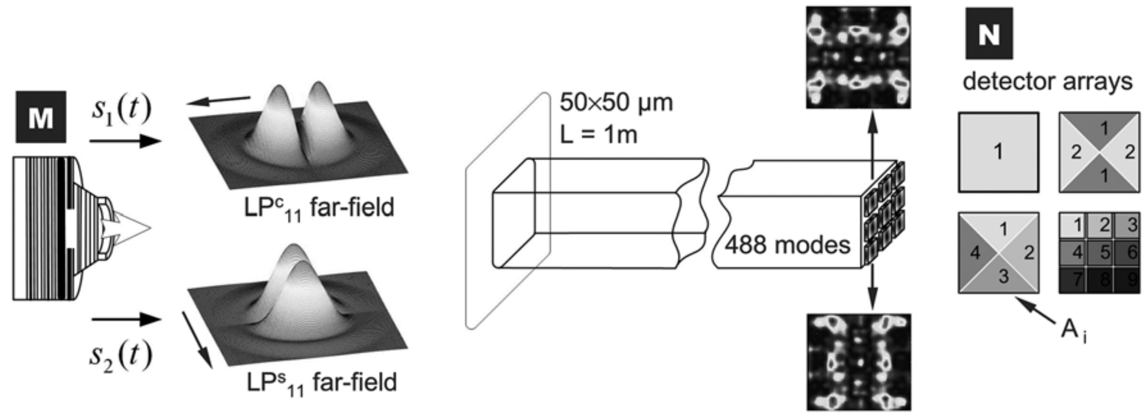

Fig. 3. Schematics of the proposed optical MIMO system (O-MIMO) for mode group multiplexing in the spatial domain. The underlying waveguide system is based on a low-loss polymer technology and the operating wavelength is around 850 nm.

(DD) with current signals proportional to the integration of the Poynting flux over the associated detector segment. The overall channel model implemented on a 2 GHz-PC is capable to "transmit" 550 pulses/s of a corresponding 10 Gb/s IM-NRZ-data stream. This allows preliminary estimates of bit-error rates (BER) while transmitting e.g. 10^6 symbols (i.e. NRZ pulses) within less than 30 minutes.

IV. The optical MIMO system

Pulse broadening due to intermodal dispersion displays the main limitation for high-speed short-range data transmission in board-level optical interconnects. To give an illustrative (but unrealistic) example: Assuming a single pulse representative for a 10 Gb/s-IM-NRZ signal to be transmitted over 4 m long straight polymer waveguide with core dimensions of 20 μm $\times$ 20 μm (i.e. carrying only 77 guided modes) results in a pulse broadening at the waveguide output by a factor of four, which is roughly halved if realistic roughness parameters are considered. The scenario becomes unrealistic because this transmission channel is operated far beyond the dispersion limit. Nevertheless, multimode wave propagation at very large mode numbers is usually appraised as worst-case scenario with respect to optical signal transmission.

A) Exploiting the mode diversity in the spatial domain

In order to circumvent this degradation one has to favor a very different view point: Large mode numbers could also be interpreted as a large amount of degrees-of-freedom ready for extending the information content to be transmitted either by enhancing the complexity of the transmitted symbol or using distinct mode groups as independent transmission channels. Both kinds of space-time signal processing are feasible in the framework of an optical MIMO system. In our recent work we have proposed optical MIMO transmission schemes which relies on mode group multiplexing, where the guided mode diversity is exploited either in the spatial domain (c.f. Figure 3) or in the reciprocal space (associated to the mode's transversal wave vector) [18-20]. With our channel model we have studied the optical MIMO system as depicted in Figure 3 for mode group multiplexing in the spatial domain [1], where two orthogonal VCSEL LP_{11} far-field patterns are injected into an 1 m long polymer wave-guide with core dimensions of 50 μm $\times$ 50 μm. Hence, for a raw data rate of 10 Gb/s the system is operated at the dispersion limit, rendering useless any SISO (i.e. 1 $\times$ 1-MIMO) transmission scenario. The light field at the waveguide output facet is sampled with the corresponding detector array while integrating the Poynting flux over the detector's patch area A_i. As receiver we have implemented a maximum likelihood vector detection scheme with simple symbol-by-symbol processing. While transmitting 10^6 bits per scenario we have extracted BER against SNR dependencies for different output diversities (i.e. different detector patch segmentations), proving the superiority of the 4 $\times$ 2-O-MIMO channel for an aggregate data rate of 20 Gb/s (cf. Figure 4). As both configurations namely the 4 $\times$ 2-O-MIMO scheme as well as the 2 $\times$ 2-O-MIMO scheme en-

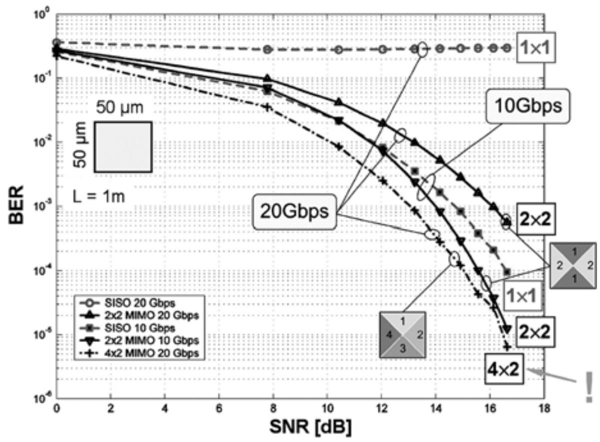

Fig. 4. Bit error rate (BER) against signal-to-noise (SNR) for three different N $\times$ M-O-MIMO transmission scenarios each for an aggregate data rate of 10 Gb/s and 20 Gb/s, respectively (proper assignment cf. inset).

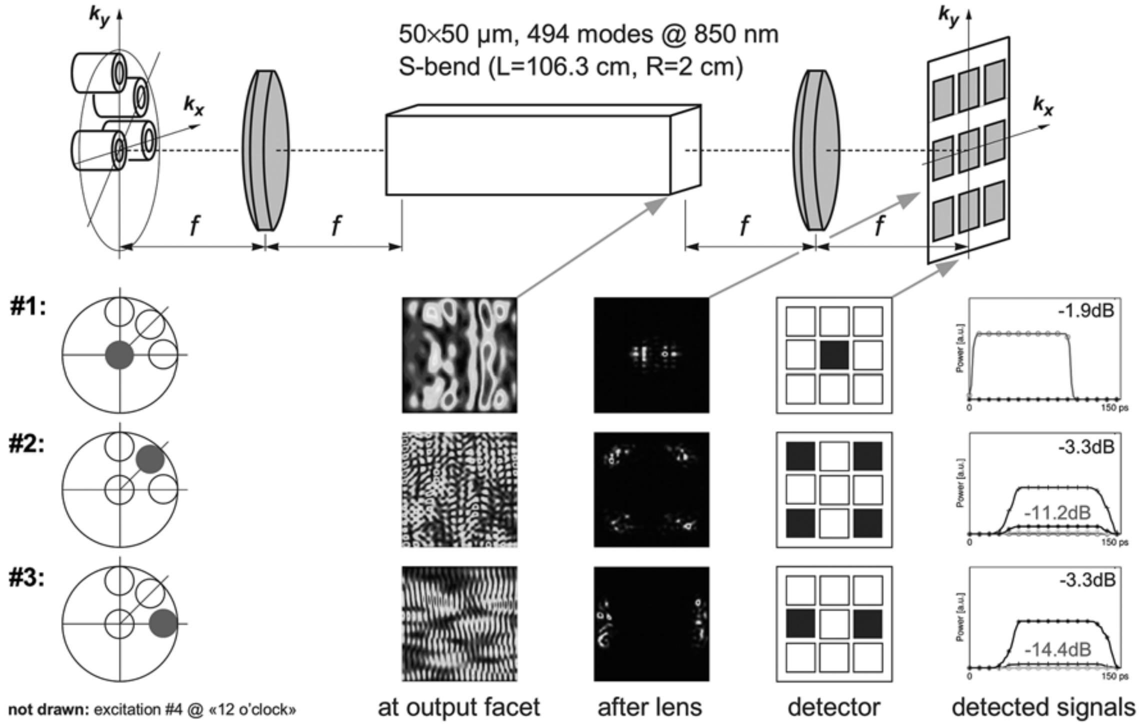

Fig. 5. Schematics of the proposed optical MIMO system (O-MIMO) for an aggregated data rate of 4 × 10 Gb/s using mode group multiplexing in the reciprocal space domain (i.e. the transversal wave number domain). The VCSEL array is shown at the left (input) side in conjunction with the excitation scheme below and the Fourier lens (with f is a variable). The multimode channel consists of a polymer waveguide in an S-bend configuration. The waveguide output is followed again by a Fourier lens and subsequently by the 3 × 3-detector array. The fields are depicted as intensity distributions and the output signals correspond to detected powers (in arbitrary units for IM/DD-NRZ) in the assigned blue detector patches, where the blue figures stand for power transmission loss and the red ones for the maximal crosstalk level.

able two independent 10 Gb/s transmission channels, the aforementioned superiority is not solely explicable by the increased signaling interval (i.e. the reduced ISI), but due to the increased spatial diversity.

B) Exploiting the mode diversity in the reciprocal space (i.e. the wave number domain)

Correlating input and output field patterns, i.e. accessing mode groups in the spatial domain will result in a spatial variation of the channel capacity along the waveguide, because transversal field distributions are prone to multimode interference. Sampling the field in the reciprocal space, however, allows accessing modes or mode groups according to their spatial frequency, and, hence, according to their transversal wave vector (i.e. their propagation constant), which is virtually independent of the location along the waveguide. Using two Fourier lenses as depicted in Figure 5, one at the waveguide input (for mode selective excitation) and the other at the output (for mode selective detection) allows setting up a mode selective optical MIMO channel. We have analyzed a 9 × 4-O-MIMO channel (with a 4-VCSEL array and 3 × 3 detector segments) for an aggregate data rate of 4 × 10 Gb/s (IM-NRZ) using the same polymer waveguide system as depicted in Figure 3, but now having two 90 ° bends, in order to set up a 106.3 cm long S-bend [14,18-20]. The S-shaped waveguide channel therefore undergoes distinct mode coupling due to the onsets of the corresponding waveguide bending, and hence, leads to slightly perturbed output field distributions as depicted in Figure 5. This preliminary MIMO system shows overall signal attenuation levels lower than 3.3 dB and crosstalk levels lower than – 11 dB. Please note that crosstalk refers here to a scheme where perfect mode-selective multiplexing is intended. Changing the viewpoint towards output diversity, crosstalk may become again a constitutive part in MIMO signaling (using now a correspondingly extended multiple patch configuration for mode group selection) with the promise for an even better channel performance.

V. Conclusion and outlook

The O-MIMO channel based on mode-group multiplexing still supports simple intensity modulation-direct detection (IM/DD) schemes and does not rely on the increased complexity of e.g. sub-carrier modulation. The number of addressed mode groups – i.e. the number of virtually independent transmission channels – becomes either a direct measure for the increase in the aggregate data rate, or for the gain in channel reliability if alternative space-time coding schemes are applied. A large number of accessible mode groups is always tantamount to inherently small mode groups, where the latter enables an additional gain in channel capacity due to a reduced intermodal (here: intra mode group) dispersion.

A fundamental limit with respect to the performance of the proposed O-MIMO channel is posed by the maximal resolution in the reciprocal space, which is roughly defined by the waveguide's core dimensions. Thus, perfect mode selectivity is hardly achievable. Proper alignment at the channel input and output defines an additional challenge because the Fourier lenses are single-lens configurations being much more sensitive to lateral displacement than two-lens settings such as a collimators. The sensitivity of the collimator setup against lateral misalignment has been measured to be in the order of $\pm$ 60 μm for 1 dB loss and – 25 dB crosstalk respectively [21], whereas the impact of misalignment on the proposed O-MIMO scheme due to the vignetting effect in compact Fourier lens settings are still under investigation.

But one of the most demanding issues is power assignment. Providing equal power to the mode groups poses a complicated boundary condition for the mode excitation as well as for the proper shape of the detector array.

A first step towards implementation will encompass the exploitation of the mode diversity in the vertical direction only [19-20] because this mode set is less prone to perturbations such as bending that takes place in the horizontal board plane. Using cylindrical lenses the input light from e.g. a 1 $\times$ 4-VCSEL array is injected into the multimode waveguide and then imaged onto a 1 $\times$ 4-detector array at the waveguide output. High-speed 4 $\times$ 10 Gb/s CMOS transceivers for such array configurations with a pitch of 250 μm have already been successfully developed in the framework of "conventional" high-density optical interconnects [22]. It's worth pointing out that any such efforts will always discharge into extensive research and development with respect to packaging issues [8].

Nevertheless we shall conclude with a realistic performance estimate: In March 2006 NEC has released VCSELs that are capable to handle 25 Gb/s using direct current modulation [23]. For the mode selective optical MIMO channel as depicted in Figure 5 this would already amount to an aggregate data rate of 100 Gb/s leading to a linear bandwidth density of 10 Tb/s/inch. We feel that this is pretty good reason to conduct further investigations.

VI. Acknowledgment

We gratefully acknowledge the support of the Swiss Federal Innovation Promotion Agency (CTI); contract/grant No. KTI-5488.1.

References

[1] Lenz, D.; Rankov, B.; Erni, D.; Bächtold, W.; Wittneben, A.: MIMO channel for modal multiplexing in highly overmoded optical waveguides, 2004 International Zurich Seminar on Broadband Communications, (IEEE Proc. 04TH8732), ETH Zurich, Switzerland, 18-20 February 2004, 196-199.

[2] Lehky, J.-M.; Erni, D.; Robin, F.; Dellmann, L.; Bona, G.-L.; Straub, P.; Bächtold, W.: Optical wave-guides for backplane communication using metal film ion-exchange in glass, 12th European Conf. on Integrated Optics ECIO'05, Grenoble, ThP038, France, 6-8 April 2005, 526-529.

[3] Lehky, J.-M.; Erni, D.; Robin, F.; Dellmann, L.; Dangel, R.; Offrein, B. J.; Bächtold, W.: Low-loss copper film ion-exchanged optical waveguides with step-like index profiles in glass, The 18th Annual Meeting of the IEEE Lasers and Electro-Optics Society, LEOS, Sydney, Australia, ThJ 5, 23-27 October 2005, 784-785.

[4] Lehky, J.-M.: Optical waveguides with copper film ion-exchange in glass. Diss. ETH, No. 16496, Zürich, March 2006.

[5] Dellmann, L.; Dangel, R.; Beyeler, R.: Berger, Ch.; Horst, F.; Offrein, B. J.; Bona, G. L.: Polymer waveguides for high-speed optical interconnects, *EOS Topical Meeting on Optics in Computing 2004*, Engelberg, Switzerland, 21-23 April 2004, 131-132.

[6] Dangel, R.; Bapst, U.; Berger, C.; Beyeler, R.; Dellmann, L.; Horst, F.; Offrein, B. J.; Bona, G. L.: Development of a low-cost-low-loss polymer wave-guide technology for parallel optical interconnect applications, Technical Digest, LEOS 2004, IEEE Lasers & Electro-Optics Society, Summer Topical Meeting, San Diego, CA, USA, 28-30 June 2004, 29-30.

[7] Dellmann, L.; Lamprecht, T.; Oggioni, S.; Witzig, M.; Dangel, R.; Beyeler, R.; Berger, C.; Horst, F.; Offrein, B. J.: Butt-coupled optoelectronic modules for high-speed optical interconnects, CLEO Europe/EQEC 2005, Conference on Lasers and Electro-Optics/European Quantum Electronics Conference, Munich, Germany, 12-17 June 2004.

[8] Lamprecht, T.; Horst, F.; Dangel, R.; Beyeler, R.; Meier, N.; Dellmann, L.; Gmür, M.; Berger, C.; Offrein, B. J.: Passive Alignment of Optical Elements in a Printed Circuit Board, 56th Electronic Components and Technology Conference (ECTC 2006), San Diego, CA, USA, 30 May – 2 June 2006, 29-30.

[9] Berger, C.; Bapst, U.; Bona, G. L.; Dangel, R.; Dellmann, L.; Dill, P.; Kossel, M. A.; Morf, T.; Offrein, B. J.; Schmatz, M. L.: Design and implementation of an optical interconnect demonstrator with board-integrated waveguides and microlens coupling, Technical Digest, LEOS 2004, IEEE Lasers & Electro-Optics Society, Summer Topical Meeting, San Diego, CA, USA, 28-30 June 2004, 19-20.

[10] Bona, G.-L.; Offrein, B. J.; Bapst, U.; Berger, C.; Beyeler, R.; Budd, R.; Dangel, R.; Dellmann, L.; Horst, F.: Characterization of parallel optical-interconnect waveguides integrated on a printed circuit board, Proc. SPIE Vol. 5453, Photonics Europe – Conference on Micro-Optics, VCSELs and Photonic Interconnects, Session 4, Strasbourg, France, 27-28 April 2004.

[11] Jungo, M.; Erni, D.; Bächtold, W.: VISTAS – A comprehensive system-oriented spatiotemporal VCSEL model, IEEE J. Select. Topics Quantum Electron., Special Issue on Optoelectronic Device Simulation **9** (2003), 939-948. (The VISTAS model is provided as a free software package from: www.sourceforge.net/projects/vistas).

[12] Jungo, M.; Erni, D.; Bächtold, W.: 2D VCSEL model for investigation of dynamic fiber coupling and spatially filtered noise, IEEE Photon. Technol. Lett., vol. 15, no. 1, 3-5 January 2003.
[13] Jungo, M.; Erni, D.; Bächtold, W.: Alternative formulation of carrier transport in spatially-dependent rate equations, Optical and Quantum Electronics (OQE) **36** (2004), 881-891.
[14] Lenz, D.: Modeling of highly-multimodal optical communication systems. Diss. ETH, No. 16497, Zürich, March 2006. (www.e-collection.ethz.ch).
[15] Sialm, G.; Lenz, D.; Erni, D.; Bona, G. L.; Kromer, C.; Jungo, M. X.; Morf, T.; Ellinger, F.; Jäckel, H.: Comparison of simulation and measurement of dynamic fiber-coupling effects for high-speed multimode VCSELs, J. Lightwave Technol. **23** (2005), 2318-2330.
[16] Lenz, D.; Erni, D.; Bächtold, W.: Quasi-analytical formalism for mode characteristics in highly over-moded rectangular dielectric waveguide bends, J. Opt. Soc. Am. A **22** (2005), 1968-1975.
[17] Lenz, D.; Erni, D.; Bächtold, W.: Modal power loss coefficients for highly overmoded rectangular dielectric waveguides based on free space modes, Opt. Express **12** (2004), 1150-1156.
[18] Lenz, D.; Erni, D.; Bächtold, W.: Advanced detection scheme for highly-multimode waveguide based optical interconnects, The 89th OSA Annual Meeting – Frontiers in Optics 2005/Laser Science XXI, Tucson, AZ, FtuB6, USA, 16-20 October 2005, 66.
[19] Erni, D.; Lenz, D.; Lehky, J.-M.; Offrein, B. J.; Lamprecht, T.: Upgrading multimode channels in board-level optical interconnects, IEEE LEOS 17^{th} Annual Workshop on Interconnections within High-Speed Digital Systems (HSD 2006), Session "(Mostly) Inside the Box", Santa Fé, NM, USA, MB3, 14-17 May 2006. (invited presentation)
[20] Erni, D.; Lenz, D.; Lehky, J.-M.; Offrein, B. J.; Lamprecht, T.: Modal multiplexing in highly overmoded waveguide channels for high-speed board-level optical interconnects, 12^{th} MICROCOLL – Colloquium on Microwave Communications / Mediterranean Microwave Symposium (MMS 2007), Budapest, Hungary, 14-16 May 2007, 53-56. (invited paper)
[21] Bona, G. L.; Offrein, B. J.; Bapst, U.; Berger, C.; Beyeler, R.; Budd, R.; Dangel, R.; Dellmann, L.; Horst, F.: Characterization of parallel optical-interconnect waveguides integrated on a printed circuit board," Proc. SPIE Vol. 5453, Photonics Europe – Conference on Micro-Optics, VCSELs and Photonic Interconnects, Session 4, Strasbourg, France, 27-28 April 2004.
[22] Kromer, C.; Sialm, G.; Berger, C.; Morf, T.; Schmatz, M.; Ellinger, F.; Erni, D.; Bona, G. L.; Jäckel, H.: A 100 mW 4×10 Gb/s transceiver in 80-nm CMOS for high-density optical interconnects, IEEE Int. Solid-State Circuits Conference (ISSCC 2005), Session 18, San Francisco, CA, USA, 6-10 February 2005, 334-336.
[23] Press release for NEC's launch of the fastest VCSEL in March 2006 including some key figurs: http://www.nec.co.jp/press/en/0603/0701.html.

Daniel Erni was born in Lugano, Switzerland, in 1961. He received an El.-Ing. HTL degree from Interkantonales Technikum Rapperswil HTL in 1986, and a Dipl. El.-Ing. degree from ETH Zurich in 1990, both in electrical engineering. Since 1990 he has been working at the Laboratory for Electromagnetic Fields and Microwave Electronics (ETH Zurich) on nonlinear wave propagation, laser diode modeling (multi-section DFB and DBR lasers, VCSELs), computational electromagnetics and on the design of non-periodic optical waveguide gratings e.g. by means of evolutionary algorithms. He got a Ph.D. degree in 1996 for the investigation of non-periodic waveguide gratings and non-periodic coupled cavity laser concepts. His current research includes advanced transmission schemes in board-level optical interconnects, such as optical MIMO systems as well as chip interconnects, dense integrated optics, nanophotonics and plasmonics. In 2001 he has been awarded the 2000 Outstanding Journal Paper Award by the Applied Computational Electromagnetics Society for a contribution on the application of evolutionary optimization algorithms in computational optics. From 1995-2006 Dr. Erni has been the founder and head of the Communication Photonics Group at ETH Zurich. Since fall 2006 he is a full professor for General and Theoretical Electrical Engineering at the University of Duisburg-Essen, Germany. He is Fellow of the Electromagnetics Academy and member of the Swiss Electromagnetics Research Centre (serec), of the Swiss Physical Society (SPS), of the German Physical Society (DPG), of the Optical Society of America (OSA), and of the IEEE.

Daniel Lenz was born in Chur, Switzerland, in 1971. He earned in 1996 an El.-Ing. HTL degree from the Applied University of Winterthur, Switzerland. In 2002 he graduated in electrical engineering at ETH Zurich. Since 2002 he has been with the Laboratory for Electromagnetic Fields and Microwave Electronics, ETH Zurich, where he also got his PhD degree in 2006 for the investigation of ultra-fast and comprehensive channel models for high-speed optical interconnects. In the same year he graduated in a masters program in business administration. Dr. Lenz has been a part-time lecturer at the engineering colleges IFA (Zurich) and ZTI (Zug), and is now working as a statistics consultant for Insightful Corporation. He is a member of IEEE.

Jan-Marc Lehky studied microengineering at the Swiss Federal Institute of Technology in Lausanne (EPFL) where he earned in 2000 a diploma degree in applied photonics. In 2004 he graduated from a post-graduate program in business administration and in 2006 he got a PhD degree from ETH Zurich for his development of a metal film based ion-exchange waveguide technology for optical interconnects. Since 2006 Dr. Lehky is a business associate of Lambda Laboratory Instruments.

Bert Jan Offrein received his applied physics (1990) and Ph.D. degree (1994) from the University of Twente, The Netherlands. His dissertation examined the measurement of optical nonlinearities and the design and realization of an all-optical switching device. In 1995 he joined the optical networking group of the IBM Zurich Research Laboratory and worked on the design and characterization of optical components for DWDM networks in SiON technology. In 1998, he changed to the JDS Uniphase 980 nm pump laser facility in Zurich as a technical marketing engineer and yield engineer. One year later, he returned to the Zurich Research Laboratory where he focused on the design and characterization of state of the art adaptive integrated optical components in SiON technology. In 2002, his research topic changed to polymer waveguide based optical backplane technology for next generation server systems. Since June 2004, Bert Jan Offrein is the manager of the photonics group at the IBM Zurich Research Laboratory.

Tobias Lamprecht is a research staff member at the IBM Zurich Research Laboratory. His research interests includes packaging issues in board-level optical interconnects.

Photograph of the Author not available at the time of printing.