Planar-Integrated Free-Space Optical Fan-Out Module for MT-Connected Fiber Ribbons

Matthias Gruber, *Member, OSA*, Ralf Kerssenfischer, and Jürgen Jahns, *Member, IEEE, Fellow, OSA*

***Abstract*—This paper reports on the design, the fabrication, and the testing of a compact planar-integrated free-space optical 1 → 4 fan-out module for fiber ribbons with multifiber-terminated connectors. It supports 12 parallel optical channels and consists of a cascade of basic cells with 1 → 2 fan-out. The module was implemented with surface-relief diffractive-phase elements; design and fabrication of the optical system were optimized for low loss by various measures such as the use of dielectric and silver reflective coatings. In experimental tests, a coupling efficiency of -11.4 dB per fan-out channel was obtained.**

***Index Terms*—Optical communication, optical interconnects, optical system design.**

I. Introduction

ALTHOUGH optical interconnects are superior to electrical ones in terms of bandwidth, scalability, suitability for multiplexing, crosstalk, electromagnetic interference immunity, and power consumption [1], they are, until now, an established commercial standard only for the long-distance communication domain, whereas over short distances (order of meters and less), communication is still largely based on electrical technology. The reason is that the established glass fiber technology cannot simply be scaled down to meet the specials requirements of short-haul interconnects. Rather, optical system concepts need to be applied that support the high degree of spatial parallelism (concerning density and total number of channels) that is characteristic for communication at the board level and below. In addition, photonic packaging concepts need to be developed that are compatible with the *de facto* technological standards for very-large-scale integration (VLSI) (opto)electronic hardware set by the semiconductor industry.

Free-space optical interconnect approaches have been identified in the international technology roadmaps for semiconductors (ITRS) [2] to be able to support the required parallelism and are now seriously considered as a potential solution of the formidable interconnect problems that are projected in the ITRS. Compatibility with VLSI standards can be achieved through a variety of integration and packaging approaches that have been studied during the past decade [3]–[7]. The one this paper is based on, planar-integrated free-space optics (PIFSO) [8], is particularly suitable for "in-the-box" interconnects and has meanwhile reached a level of maturity [9], [10] that warrants its application in real-world demonstrator systems [11]. At this stage, optimizing the energetic efficiency of PIFSO-type interconnects and developing robust and reliable coupling mechanisms between PIFSO and established (commercial) "box-to-box" interconnect platforms based on fiber and waveguide optics have become the most crucial research and development issues.

This paper describes an experimental demonstration that tackles both these issues. It is about a compact PIFSO-type fan-out module that performs a homogeneous 1 → 4 splitting of optical signals that are coupled in and out via fiber ribbons with multifiber-terminated (MT)-type connectors. A cascaded systems approach was chosen for this fan-out module, which is presented and compared with alternative approaches in Section II. Section III discusses the optical design of the basic cell of the cascaded system. Issues related to its practical realization are the topic of Section IV, and in Section V, the experimental performance of the fan-out module is evaluated. Conclusions follow in the final Section VI.

II. System Concept

In a PIFSO system, the optical components are monolithically integrated into the surfaces of a transparent planar substrate with a typical thickness of a few millimeters in such a way that optical signals are relayed from their sources to their destinations along zigzag paths inside the substrate (see Fig. 1). The system can thus exploit all the advantages of a three-dimensional architecture, which includes in particular the implementation of densely packed, highly parallel interconnection schemes with high topological complexity. At the same time, the optical system is compatible with planar VLSI technology and can be fabricated using two-dimensional lithographic batch processing and replication techniques.

Looking at the current status of optical interconnect technology [6], [7], we find that for the long-haul communication domain, glass fibers are firmly established and will certainly continue to be the hardware of choice. For shorter communication distances, plastic optical fibers (POFs) have been gaining ground in recent years, and in optical transmission systems and networks, components with integrated waveguide structures have become standard for tasks like switching, multiplexing, and modulation. To provide compatibility between PIFSO and such optical hardware that is based on the physical principle of waveguiding, robust and reliable coupling mechanisms are needed. A first technological concept was developed and

---

Manuscript received February 11, 2004; revised May 24, 2004.

M. Gruber and J. Jahns are with the Optical Microsystems Group, Electrical and Information Engineering Department, University of Hagen, Hagen 58084, Germany (e-mail: Matthias.Gruber@FernUni-Hagen.de).

R. Kerssenfischer was with the Optical Microsystems Group, Electrical and Information Engineering Department, University of Hagen, Hagen 58084, Germany.

Digital Object Identifier 10.1109/JLT.2004.833262

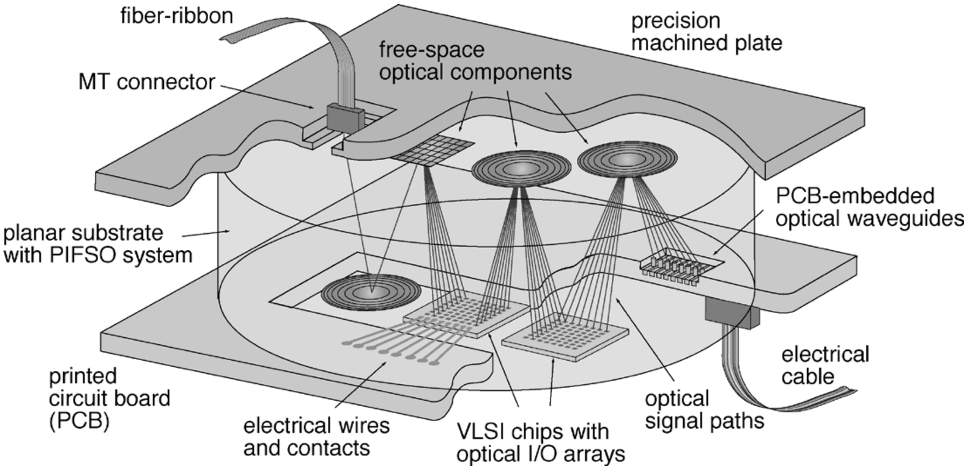

Fig. 1. PIFSO as a platform for "in-the-box" and "box-to-box" optical interconnects. Free-space optics can be combined with waveguide and fiber technology.

practically demonstrated recently [12]. It is designed for the so-called MT standard, which is based on ribbons with (a maximum of) 12 optical fibers and MT connectors and has emerged as a *de facto* industrial standard for parallel short-haul interconnects in recent years. The interface consists of a precision micromachined metal plate that is attached to the PIFSO substrate; MT connectors can be plugged onto (densely packed arrays of) docking slots on the opposite side of the plate as shown schematically in Fig. 1.

The fan-out module we present here is based on this interface type and was designed with the goal of obtaining, in a compact geometrical arrangement, an energetically efficient homogeneous 1 → 4 splitting of 12 parallel optical signals that are coupled in and out via fiber ribbons with MT-type connectors.

A popular method to achieve a $1 \rightarrow N$ fan-out in free-space optics is based on $1 \rightarrow N$ beam splitting by means of specially designed diffractive-phase elements (DPEs) [13] that are usually called array illuminator (AI) gratings. In a PIFSO realization, however, this approach is sometimes not possible due to geometrical constraints. This is illustrated in Fig. 2(a). If the AI grating is to generate a $1 \rightarrow N$ fan-out in the depicted cross section and if the pitch of the generated spot array cannot be reduced below the (rather large) limit that is set by the finite size of the connectors, then the desired out-coupling perpendicularly to the substrate surface requires a strong deflection of the outermost signal beams. With diffractive optical elements, this can often not be achieved due to fabrication limits (lithographic minimum feature size). To avoid this problem, we chose a systems approach with a cascade of (nearly) identical 1 → 2 fan-out cells that amounts to a $1 \rightarrow N$ fan-out in total, as depicted in Fig. 2(b). Our fan-out module can be seen as a more advanced successor of the basic grating coupler proposed in [14]. The cascaded approach harmonizes well with the zigzag-type signal propagation inside the planar substrate that is a typical feature of the PIFSO concept, and it can easily be matched for any desired total fan-out.

The seemingly easiest way to realize the 1 → 2 fan-out in a basic cell of the module would be to use a semi-transparent mirror (SM) via which part of the signal is coupled out and the rest is relayed further through the optical system [Fig. 3(a)]. However, in a cascade of basic cells each semi-transparent mirror would have to have a different precisely adjusted splitting ratio to lead to an overall homogeneous $1 \rightarrow N$ fan-out. The fabrication of the respective mirrors would therefore be a challenging and expensive task. More favorable is our alternative approach of performing a 1 → 2 fan-out scheme in which the two beams are spatially separated [Fig. 3(b)]. This can be done with high accuracy (e.g., by means of AI gratings) and does not increase fabrication complexity by requiring special sophisticated processes. The spatial separation also provides additional design freedom because, for out-coupling and relaying, separate optical elements can be used, which can be optimized independently of each other for their respective tasks.

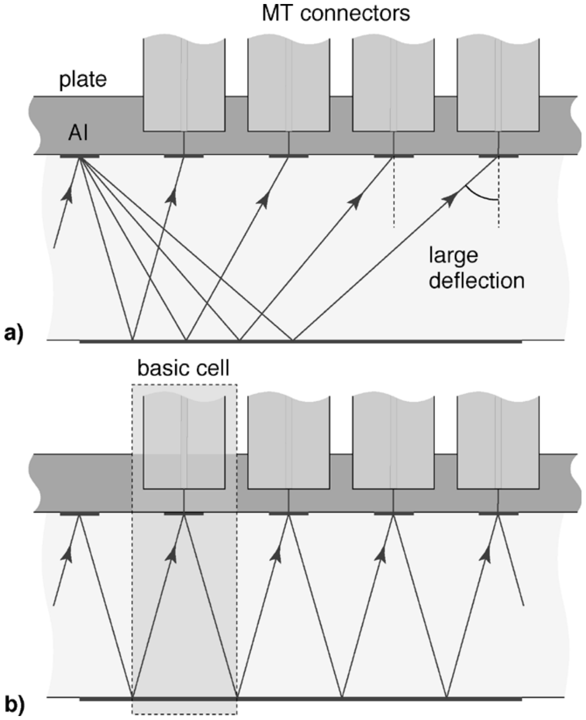

Fig. 2. System concepts: (a) one-step $1 \rightarrow N$ fan-out with an AI grating and (b) cascade of basic cells with 1 → 2 fan-out.

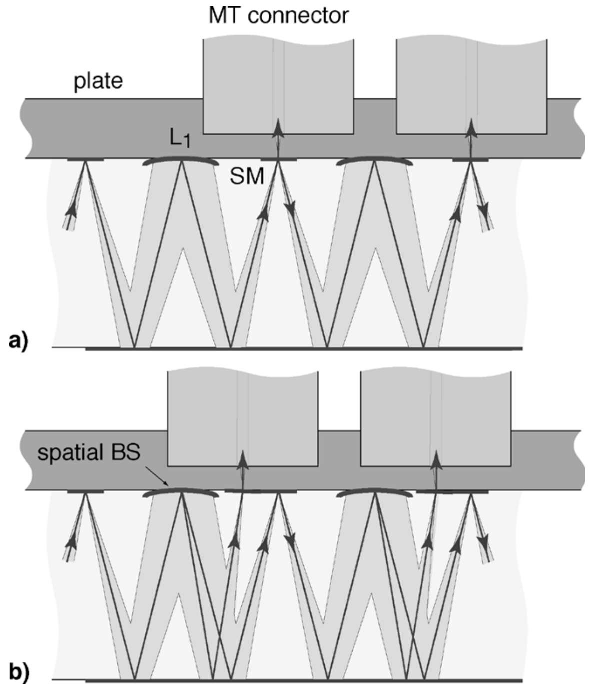

Fig. 3. Beam splitting (a) with semi-transparent mirrors SM and (b) based on spatial beam separation, for example, with AI gratings.

III. Basic Cell

Based on the systems approach of Fig. 3(b), we will now discuss the technical optical design of the basic cell. For use in a cascade, it is necessary that successive cells are properly connected. Since they essentially perform image relay operations, this means that the (final) image plane, i.e., the output, of a cell, coincides with the object plane, i.e., the input, of the subsequent cell. In addition, the magnification in each image relay step has to be unity to avoid a change of size and pitch of the signal spots.

The most straightforward system design that satisfies these two conditions would be a simple light pipe composed of lenses L_1 as depicted in Fig. 4(a); for clarity, an unfolded representation of the planar-integrated optical setup is shown here. In addition to L_1, each basic cell contains a coupling element C and a spatial beam splitter, here a $1 \rightarrow 2$ AI grating. Also note that Fig. 4(a) depicts two successive basis cells to illustrate how they are optically connected. The solid lines thereby correspond to the upper surface of the planar substrate, and the dashed lines to the plane of the end faces of the MT connectors when they are plugged onto the docking slots of the plate. In our experimental hardware, the distance between these two planes is 0.7 mm. This is much more than the depth of focus that can be achieved by imaging lens L_1 of the basic cell. With a setup like in Fig. 4(a), the optical signals that are to be coupled out into the MT connector would therefore not be focused, which means that an efficient coupling would not be possible.

The alternative of designing the optical system such that the conjugate planes of the imaging operation coincide with the connector plane [Fig. 4(b)] would allow efficient coupling, but it violates the unit magnification condition. Nevertheless, it can serve as a basis to construct an optical system that fulfills all design goals.

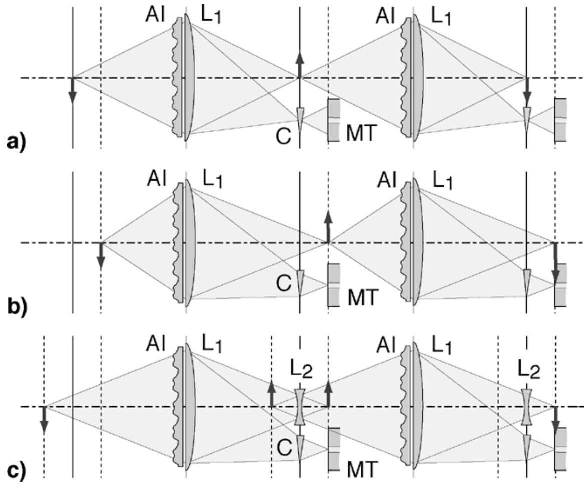

Fig. 4. Technical optical system design: (a) symmetric light pipe; (b) asymmetric light pipe; and (c) symmetric light pipe with virtual imaging.

Such a system is shown in Fig. 4(c). It is derived from the one in Fig. 4(b) by moving the object plane of the basic cell "backward" such that lens L_1 performs a symmetric imaging with unit magnification. To ensure proper connection of successive cells, an additional lens L_2 is now needed that relays the (real) image generated by lens L_1 also "backward" into the input plane of the next cell. Since this is a virtual imaging operation, the focusing power of L_2 needs to be negative.

IV. Practical Realization

The practical realization of a homogeneous fan-out demonstrator consisting of four basic cells based on the optical design of Fig. 4(c) requires a realistic estimation of the optical loss in the system because this quantity determines which splitting ratio for the beam intensities is required in every cell.

If, as in our case, the optical components are implemented as multilevel DPEs, their diffraction efficiency η depends on the phase quantization [15]. For a partitioning scheme of Q equidistant phase levels, the upper limit for η was found to be $\mathrm{sinc}^2(1/Q)$. This expression is suitable to estimate the efficiency of diffractive lenses or beam deflectors. For AI gratings, an additional limitation factor must be taken into account; it expresses the fact that, independently of the phase quantization, a certain fraction of the intensity is always lost in unwanted diffraction orders. This fraction depends on the particular splitting scheme and cannot be estimated generally. In a PIFSO system, some intensity is furthermore lost due to absorption by the reflective coating material and in the form of Fresnel losses when a signal beam enters or exits the planar substrate.

To minimize the above losses, we realize each DPE with as many phase levels as our fabrication technology based on (binary) lithography and reactive ion etching (RIE) permits in view of the lithographic minimum feature limit (≈ 1 μm). Thus, we get four levels for the coupling elements C and the connecting lenses L_2 and eight levels for lenses L_1. Since the reflectance of aluminum is comparatively low for our design wavelength of 850-nm ($R \approx 81\%$), silver, which reflects much better ($R \approx 99\%$), was chosen as coating material for the DPEs (albeit at

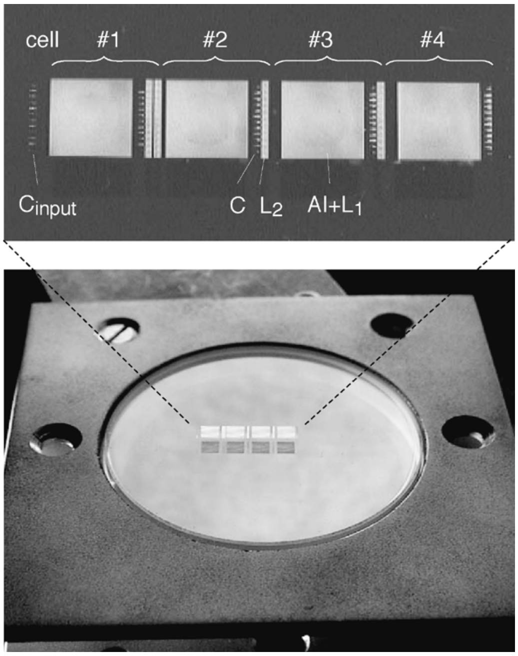

Fig. 5. Finished PIFSO module.

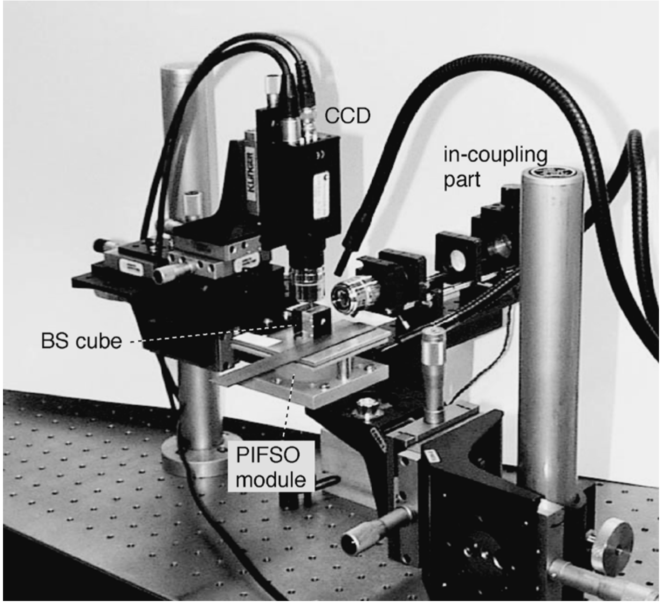

Fig. 6. Setup for the first experiment: visual evaluation of the fan-out performance.

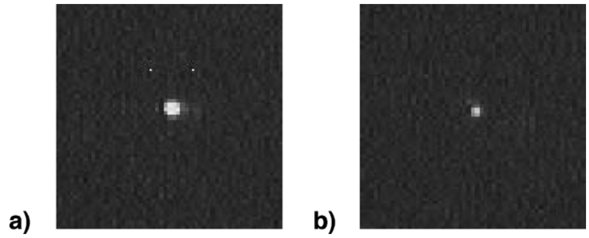

Fig. 7. Spot images obtained with the setup of Fig. 6 at (a) output 1 and (b) output 4.

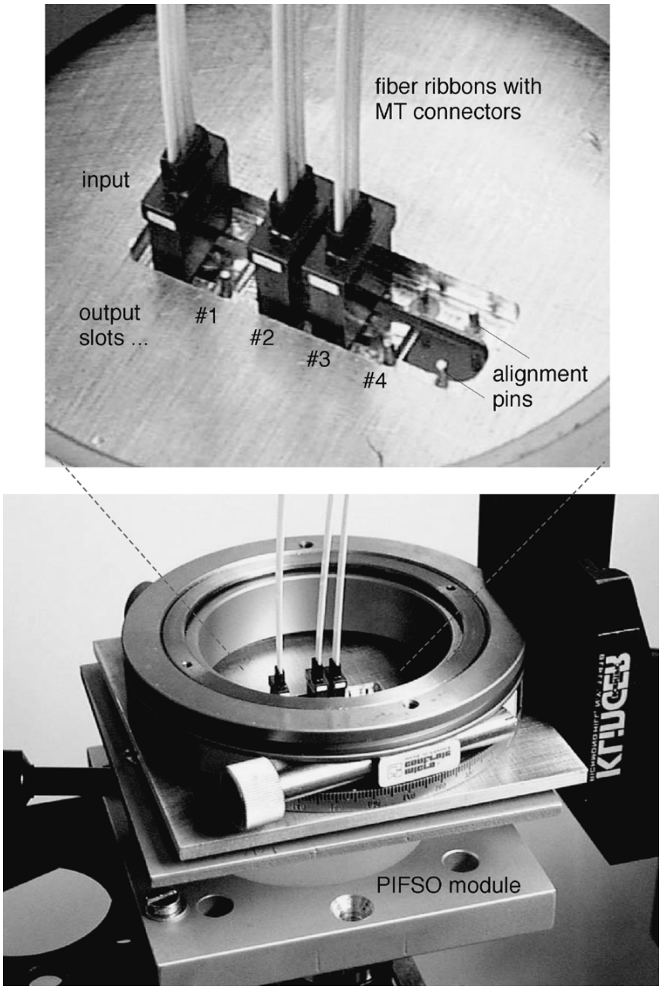

Fig. 8. Setup for the second experiment: quantitative evaluation of the energetic efficiency of the interconnects.

the expense of a considerably higher fabrication effort to make the metal film adhere to the fused silica optical substrate). At the bottom side of the substrate, where no optical elements need to be integrated, a commercial plane dielectric mirror with about 99.9% efficiency is used for reflection. For the experiments, it was attached to the PIFSO substrate with an index matched fluid. Since Fresnel losses contribute only to a small degree to the total loss, we can afford to do without an (expensive) antireflection coating to suppress them.

With these considerations, the required splitting ratios for the four basic cells can be calculated in an iterative procedure: initially, the (unknown) diffraction efficiencies of the $1 \rightarrow 2$ AI gratings are set to 100% so that a first estimation of the losses can be made. Based on that, a first approximation of the splitting ratios is calculated. With an iterative Fourier transform algorithm (IFTA) [13], corresponding AI grating profiles are then generated. Their calculated diffraction efficiencies allow one to calculate more precise estimates of the required splitting ratios and so on. It turns out that after a few iterations, no significant changes occur any more. In our case, the procedure resulted in splitting ratios of 4.22:1, 2.59:1, and 1.17:1 for the first three basic cells (and no splitting in the last cell).

The respective optical system was fabricated on a fused silica substrate with 12-mm thickness and 50.8-mm diameter. The phase functions of lens L_1 and the AI grating were thereby combined in a single DPE in each basic cell. Fig. 5 shows the finished PIFSO system in a mount with which it was connected to a translation stage.

V. EXPERIMENTS

In a first experiment, the metal interface plate for the MT connectors was fixed to a separate mechanical translation stage and aligned with respect to the PIFSO fan-out module (Fig. 6). Instead of fiber ribbons, a beam splitter cube was then placed on top of the plate, which allows one to couple in a (single) optical test beam and to observe the fanned-out beams along the orthogonal direction. The spot images that the PIFSO system generates in the plane of the MT connector faces were captured with a charge-coupled device (CCD) camera. Two examples are shown in Fig. 7. Apparently, there are no visible optical aberrations. However, the intensity of the spots gradually decreases from output 1 to output 4, which means that the losses are slightly higher than estimated theoretically.

In a second experiment, MT-connected fiber ribbons (single-mode with 9-μm-core diameter for the input and multimode with 50-μm-core diameter for the output) were then plugged onto the docking slots of the metal plate (cf. Fig. 8) for a quantitative evaluation of the module. It could be verified that optical signals that are coupled in will be fanned out and coupled back into each fiber ribbon. The measured coupling efficiencies range from -11.4 dB for output 1 to -13.4 dB for output 4.

VI. CONCLUSION

Comparing these results with the interconnection efficiencies of earlier PIFSO-type interconnect demonstrators that are at least an order of magnitude worse, it can be concluded that the design goals for this project, realizing a functioning coupling mechanism between PIFSO and fiber optics and achieving a satisfactory energetic efficiency, have been achieved.

Although the performance described in this paper does not yet meet industrial specifications and can certainly not compete with state-of-the-art fiber connectors and components, it still shows that PIFSO has already moved a significant step ahead of proof-of-principle studies and has come a big step closer to real-world applications.

REFERENCES

[1] D. A. B. Miller, "Physical reasons for optical interconnection," *Int. J. Optoelectron.*, vol. 11, pp. 155–168, 1997.

[2] International Technology Roadmap for Semiconductors [Online]. Available: http://public.itrs.net/

[3] K. Iga, M. Oikawa, S. Misawa, J. Banno, and Y. Kokubun, "Stacked planar optics: An application of the planar microlens," *Appl. Opt.*, vol. 21, pp. 3456–3460, 1982.

[4] J. Jahns and A. Huang, "Planar integration of free-space optical components," *Appl. Opt.*, vol. 28, pp. 1602–1605, 1989.

[5] M. C. Wu, "Micromachining for optical and optoelectronic systems," *Proc. IEEE*, vol. 85, pp. 1833–1856, Nov. 1997.

[6] *IEEE J. Select. Topics Quantum Electron. (Special Issue on Lasers in Biology and Medicine)*, vol. 9, Mar.–Apr. 2003.

[7] *Proc. SPIE—Micro-Optics VCSEL's, and Photonic Interconnects*, vol. 5453, H. Thienpont, K. D. Choquette, and M. R. Taghizadeh, Eds., 2004.

[8] J. Jahns, "Planar packaging of free-space optical interconnections," *Proc. IEEE*, vol. 82, pp. 1623–1631, Nov. 1994.

[9] D. Fey, W. Erhard, M. Gruber, J. Jahns, H. Bertelt, G. Grimm, L. Hoppe, and S. Sinzinger, "Optical interconnects for neural and reconfigurable VLSI architectures," *Proc. IEEE*, vol. 88, pp. 838–848, June 2000.

[10] M. Gruber, "Multi-chip module with planar-integrated free-space optical vector-matrix-type interconnects," *Appl. Opt.*, vol. 43, pp. 463–470, 2004.

[11] P. Lukowicz, J. Jahns, R. Barbieri, P. Benabes, T. Bierhoff, A. Gauthier, M. Jarczynski, G. A. Russell, J. Schrage, W. Süllau, J. F. Snowdon, M. Wirz, and G. Tröster, "Optoelectronic interconnection technology in the HOLMS system," *IEEE J. Select. Topics Quantum Electron.*, vol. 9, pp. 624–635, Mar.–Apr. 2003.

[12] M. Gruber, E. ElJoudi, S. Sinzinger, and J. Jahns, "Practical realization of massively parallel fiber-free-space optical interconnects," *Appl. Opt.*, vol. 40, pp. 2902–2908, 2001.

[13] H. Aagedal, F. Wyrowski, and M. Schmid, "Paraxial beam splitting and shaping," in *Diffractive Optics for Industrial and Commercial Applications*, J. Turunen and F. Wyrowski, Eds. Berlin, Germany: Akademie-Verlag, 1997, pp. 165–188.

[14] T. Kubota and M. Takeda, "Array illuminator using grating couplers," *Opt. Lett.*, vol. 14, pp. 651–652, 1989.

[15] J. W. Goodman and A. M. Silvestri, "Some effects of Fourier-domain phase quantization," *IBM J. Res. Develop.*, vol. 14, pp. 478–484, 1970.

Matthias Gruber received the M.Sc. degree in physics from the University of Erlangen, Erlangen, Germany, in 1991, and the Ph.D. degree in electrical engineering from the University of Hagen, Hagen, Germany, in 2003.

From 1991 to 1994, he was a Research Assistant at the Institute of Electro-Optical Engineering of the National Chiao Tung University, Hsinchu, Taiwan, working on optical data storage and neural networks. From 1994 to 1996, he was a Member of the Technical Staff of Tamarack Technologies, Inc., Hsinchu, Taiwan, and in charge of optical scanner design. In 1996, he joined the Faculty of Electrical and Information Engineering of the University of Hagen as a Teaching and Research Assistant. In 2003, he was appointed Assistant Professor of Optical Microsystems in the same faculty. He is the author of approximately 50 journal and conference publications and has coauthored the chapter "Planar-Integrated Free-Space Optics" in the book *Micro-Optics* (New York: Springer, 2004). His research interests include diffractive optics, photonic integration, microoptoelectromechanical system (MEMS) design, optical interconnects, optical information processing, and optical metrology.

Dr. Gruber is a Member of the German Society for Applied Optics (DGaO), the Optical Society of America (OSA), and the International Society for Optical Engineers (SPIE).

Ralf Kerssenfischer received the M.Sc. degree in electrical engineering from the University of Hagen, Hagen, Germany, in 2003, with a thesis on the design and experimental characterization of a planar-integrated optical fan-out module for multifiber-terminated (MT)-connected fiber ribbons.

Since graduation, he has left the university to work in the private industry.

Jürgen Jahns (M'87) received the M.Sc. and Ph.D. degrees in physics from the University of Erlangen, Erlangen, Germany, in 1978 and 1982, respectively.

He was with Siemens AG, Munich, Germany, from 1983 to 1986, where he worked on robotics, sensors, and optical fiber communications. From 1986 to 1994, he was a Member of the Technical Staff in the Optical Computing Research Department, AT&T Bell Laboratories, Holmdel, NJ. During that time, he worked on optical interconnections, diffractive optics, and microoptic packaging. Since 1994, he has been a Full Professor of Optical Information Technology at the University of Hagen, Hagen, Germany. He is the author of nearly 250 journal and conference publications and holds 16 international patents. He has contributed several book chapters, co-edited a book *Optical Computing Hardware* (New York: Academic, 1994), coauthored a book *Microoptics* (New York: Wiley-VCH, 2nd ed., 2003), authored a book *Photonik* (Munich, Germany: Oldenbourg, 2000, in German), and co-edited a book *Micro-Optics* (New York: Springer, 2004).

Dr. Jahns is a Member of the German Society for Applied Optics (DGaO), where he leads a technical group on microoptics, as well as a Fellow of the Optical Society of America (OSA).