

# Practical realization of massively parallel fiber-free-space optical interconnects

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We propose a novel approach to realizing massively parallel optical interconnects based on commercially available multifiber ribbons with MT-type connectors and custom-designed planar-integrated free-space components. It combines the advantages of fiber optics, that is, a long range and convenient and flexible installation, with those of (planar-integrated) free-space optics, that is, a wide range of implementable functions and a high potential for integration and parallelization. For the interface between fibers and free-space optical systems a low-cost practical solution is presented. It consists of using a metal connector plate that was manufactured on a computer-controlled milling machine. Channel densities are of the order of  $100/\text{mm}^2$  between optoelectronic VLSI chips and the free-space optical systems and  $1/\text{mm}^2$  between the free-space optical systems and MT-type fiber connectors. Experiments in combination with specially designed planar-integrated test systems prove that multiple one-to-one and one-to-many interconnects can be established with not more than 10% uniformity error. © 2001 Optical Society of America

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## 1. Introduction

During the past three decades optics has evolved as a strong competitor to electronics among the technologies used to set up communication networks.<sup>1</sup> For long-distance data transmission such as in wide-area networks and metropolitan-area networks, optics has clearly proved superior to electronics. Copper cables have therefore been widely replaced by glass fiber cables. The most important advantages of the latter are lower energy loss, absence of electrical interference, and much higher bandwidth, including the possibility of multiwavelength operation.

In state-of-the-art local-area networks, both optical and electrical hardware can usually be found, the former to connect hubs with one another and the latter to link hubs with individual participants. Optics has not completely replaced electronics, because, for bridging the "last mile" from a hub to a home, low cost is a dominating criterion, and reliable optical

links are still much more expensive than electrical ones.

In the field of short-distance communication, which ranges from the computer-to-computer level to interchip and intrachip levels, optics is still rarely used.<sup>2</sup> On the one hand this situation can be attributed to physical reasons: Optical interconnects require optoelectronic conversions, which lead to additional expenses that are outweighed by the advantages mentioned above only if the interconnection distance surpasses a certain critical value. This threshold has been steadily decreasing, but it is currently still of the order of meters. On the other hand, there is no mature optical technology to support parallel interconnection of a large number of densely packed channels, which is a standard task in the field of short-distance communication. So far, commercial optical links support only a rather limited number of parallel channels.

Infineon's Paroli system,<sup>3</sup> for example, uses multifiber ribbon cables together with standardized MT-type plugs to interconnect as many as 12 parallel channels optically. The end face of a MT plug thereby covers an area of roughly  $20 \text{ mm}^2$ , yielding a channel density of  $<1/\text{mm}^2$ , which is much too low for direct interconnection of VLSI chips, which will soon have hundreds or thousands of parallel input-output (I/O) channels with densities of the order of hundreds per square millimeter.<sup>4</sup>

Handling such interconnection tasks requires new

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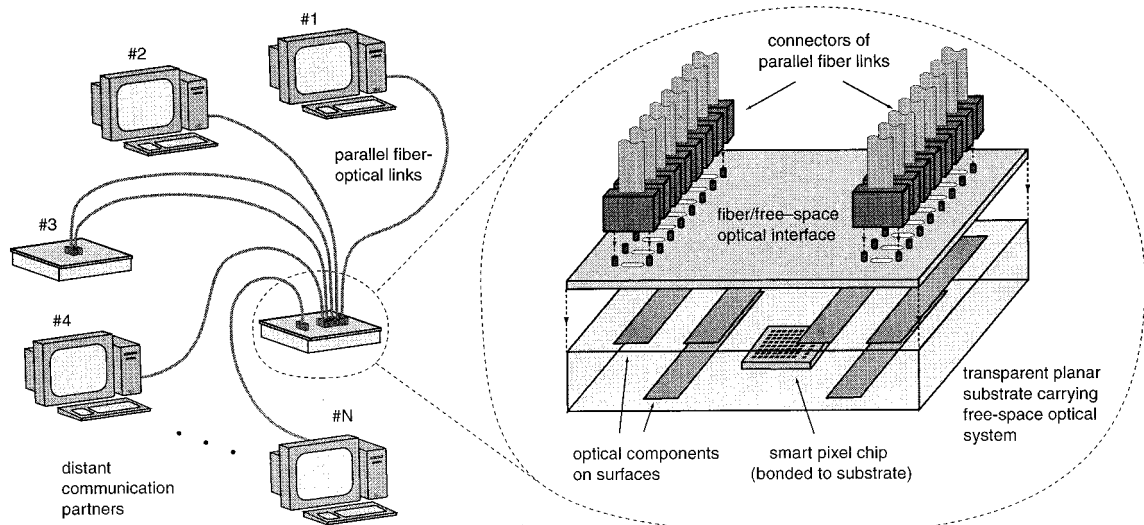


Fig. 1. Optical communication network with massively parallel fiber-free-space optical interconnects.

ideas.<sup>5</sup> Some solutions focus on the design of connector types that can carry a large number of fibers and support high packaging densities, for example, connectors in which fiber ends are arranged in two-dimensional array geometries<sup>6</sup>; other approaches to interconnection deal with waveguide structures upon printed-circuit boards<sup>7</sup> or waveguide architectures that connect chips with fibers.<sup>8</sup> The problem is that such devices are rather complex and require sophisticated fabrication techniques. Therefore they will not easily be able to compete with electronic interconnects in either performance or price.

We follow a different approach by combining fiber optics with planar-integrated free-space optics.<sup>9</sup> Interconnecting thousands of channels in parallel is quite straightforward with appropriate free-space optical hardware (cf. Ref. 10 and references therein). The interconnection schemes can thereby vary almost arbitrarily; important basic operations for signal processing such as fan-out, fan-in, and filtering have been demonstrated.<sup>11,12</sup> Planar integration makes such optical systems compatible with VLSI electronics, both in dimensions and in design and fabrication technology. Fabrication complexity is thereby almost independent of system complexity, so the realization of a sophisticated high-performance optical setup affects only the design component.<sup>13</sup>

The idea is to tap this functionality and compatibility potential by use of planar-integrated free-space optical systems as adaptors between VLSI chips and commercial fiber systems. The fibers ensure that the communication network can be set up flexibly and with a reasonably long range (several meters). The planar-optical system adapts the low channel density of the fiber interconnects to the high channel density on the VLSI chips; in addition, one can use it to carry out fan-out, fan-in, or filtering operations. For the interface between fibers and the planar-optical system that is a key component of this approach, a practical solution is presented in this paper.

In Section 2 we outline the technological framework for our interconnect platform. Section 3 deals with realization of the interface between optical fibers and planar-integrated free-space systems. For a prototype of the interface, special test systems have been designed and fabricated in planar-integrated form, as is discussed in Section 4. Experimental results are given in Section 5. Section 6 concludes our paper and indicates a potential application for the proposed approach.

## 2. Technological Framework

Our approach to realizing interconnects combines guided-wave optics and integrated free-space optics to exploit the advantages of the two concepts optimally. Figure 1 shows a typical interconnection setup. A component with large communication demand, for example, a smart-pixel-based VLSI chip with a large two-dimensional I/O array<sup>14,15</sup> or an optomechanical micromirror array,<sup>16</sup> is bonded to a transparent planar substrate, which carries an integrated free-space optical system. Distant communication partners are connected to this planar substrate via conventional parallel fiber links and a custom-designed fiber-free-space optical interface.

The free-space optical system is designed and fabricated according to the concept of planar integration,<sup>13</sup> which means that it is folded into the planar substrate in such a way that functional optical components are located at the surfaces. These components can be realized through surface structuring<sup>17,18</sup> or manipulation of refractive indices.<sup>19,20</sup> Optical signals travel along zigzag paths (cf. Figs. 6 and 7 below) and are kept inside the substrate through reflective surface coatings. Inasmuch as the optical system is designed and fabricated as a whole by use of advanced lithographic techniques, it is, unlike discrete optomechanic setups, perfectly adjusted, compact, and robust and (potentially) can be produced at low cost.

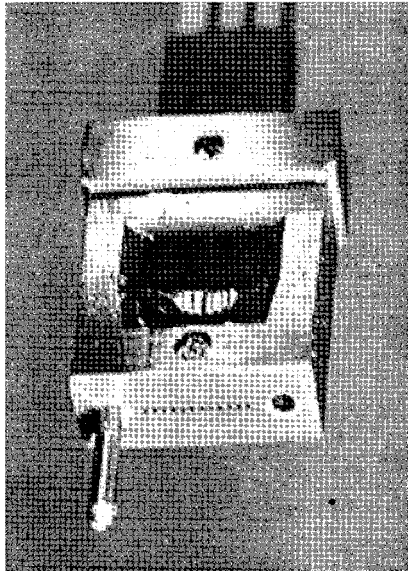


Fig. 2. MT connector with a 0.7-mm steel rod inserted into one of the guiding holes.

In free-space optics, signal paths can cross one another without interference, and many signals are usually routed by the same optical component. This situation is different from that of guided-wave optics, in which every (spatial) optical channel usually requires its own individual hardware. Therefore optical channels can be packed more densely in free-space systems. A planar-integrated imaging system that produces 2500 one-to-one interconnects on an area of  $6.25 \text{ mm}^2$  (Ref. 21) may serve as an example.

Depending on the application, the free-space optical system in Fig. 1 can implement one-to-one, one-to-many, or many-to-one interconnections as well as combinations of these operations, as has been demonstrated.<sup>11,12</sup> In addition, it serves as an adaptor between the VLSI chip with densely packed optical I/Os and the fiber connectors, which have a much lower channel density. Our approach provides a great deal of flexibility because of the variety of functions that the planar-integrated system can implement and because individual communication partners can conveniently be disconnected and the network rearranged. This approach has an advantage over interconnect approaches that use monolithic two-dimensional fiber connectors that are operated in direct contact with VLSI chips.

We chose commercially available parallel fiber links, namely, fiber ribbon cables with MT connectors, to connect the distant communication partners with the planar substrate. The MT connector was invented by NTT some 10 years ago in connection with the company's fiber-to-the-home activities<sup>22</sup> and has since been adopted as international standard *IEC 60874-16* by the International Electrotechnical Commission.<sup>23</sup> An MT connector as shown in Fig. 2 can house as many as 12 single-mode or multimode fibers spaced  $250 \mu\text{m}$  apart in a rectangular ferrule. Cylindrical rods with 0.7-mm diameters that fit pre-

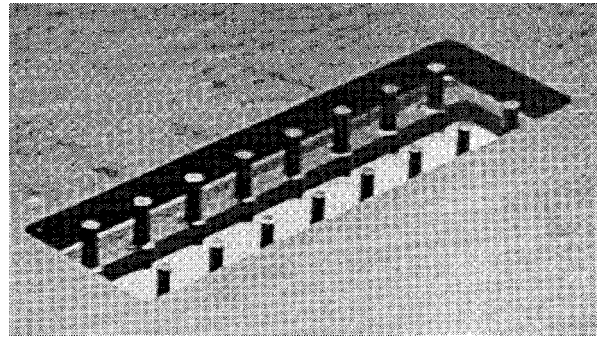


Fig. 3. Aperture and 0.7-mm docking rods milled from a 3-mm-thick metal plate.

cisely into two 4.6-mm-spaced guiding holes on both sides of the fiber array ensure exact positioning when the ferrules are connected.

MT connectors that were fabricated by means of the Lithographie Galvanik Abformung (LIGA) technique and injection molding<sup>24</sup> have been shown to possess the high submicrometer positioning accuracy required for fiber interconnects. These properties open the possibility for low-cost mass production and make MT-based fiber ribbons the parallel optical link of choice for many applications and also for commercial systems such as the Infineon Paroli system. An important reason for us to use MT connectors is furthermore the comparatively small footprint of the MT ferrule ( $<20 \text{ mm}^2$ ), which leads to a higher channel density than with all other established fiber connectors.

In Section 3 we describe the mechanical device that we use to keep the MT connectors fixed in well-defined positions relative to the planar optical substrate.

### 3. Fiber-Free-Space Optical Interface

Our intention is to achieve the highest possible connectivity on the fiber side of a fiber-free-space interface. To this end an orthogonal approach has to be chosen; that is, the MT connectors have to be attached in such a way that the fibers are standing perpendicularly to the surface of the planar optical substrate and the connectors occupy the minimum possible area. Furthermore, design and fabrication of the interface must ensure low mechanical tolerances but should not be too complex or cost intensive.

We satisfy these goals by fabricating the interface in one piece from a 3-mm-thick plate of an aluminum alloy. With a computer numerical control (CNC) machine, an aperture and docking rods with 0.7-mm diameter and 2-mm height are milled from the bulk material, as shown in Fig. 3. In accordance with the MT standard, the rods have a spacing of 4.6 mm across the aperture. With 3-mm spacing along the aperture, attached MT ferrules are almost in physical contact with one another (see Fig. 4).

The planar substrate with the free-space optical system has to be precisely aligned and fixed to the back side of the metal plate, as can be achieved with

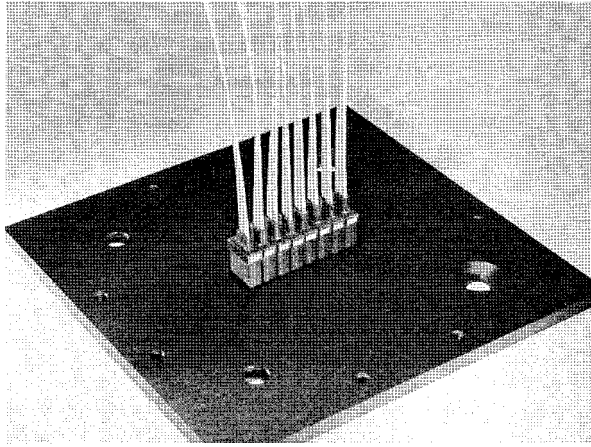


Fig. 4. Fiber-free-space optical interface with eight MT connectors attached.

an autocollimation-type procedure.<sup>25</sup> The procedure involves lenses that are integrated at certain positions on the top side of the planar-optical substrate and docking positions for MT connectors at the corresponding positions of the metal plate (see Fig. 5). The lenses image a plane P located at a distance  $d$  below the bottom surface of the optical substrate onto itself. Thus, if the plate with an attached connector is precisely adjusted, an optical signal emerging from the input fiber will be coupled into the output fiber, which is point symmetric with respect to the optical axis. If the plate is moved from this position the intensity of this signal, measured at the end of the output fiber, will quickly decrease, making precise active alignment possible. To eliminate both shift and rotational misalignments requires two such autocollimation-type systems. After the optimal position has been found, the planar-optical substrate and the metal plate can be cemented together.

With modern CNC machines a (nominal) fabrication accuracy in the micrometer range is no problem.

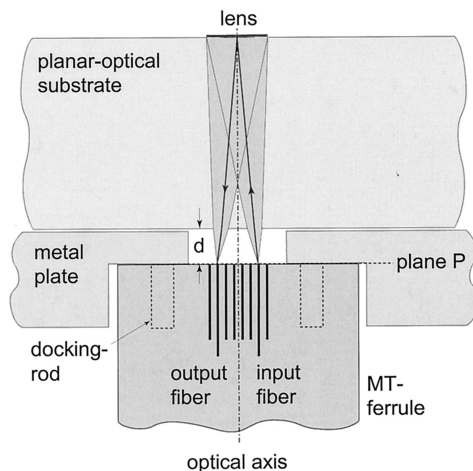


Fig. 5. Autocollimation-type setup for aligning the planar-optical substrate and the metal plate.

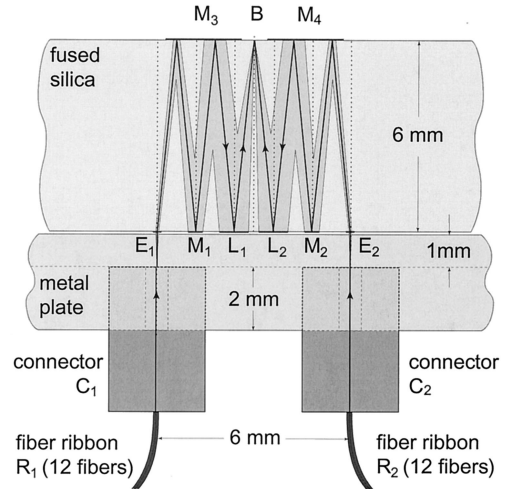


Fig. 6. Schematic cross section of planar-integrated optical test system I.

This degree of precision is good enough for most planar-integrated optical systems and is sufficient for coupling signals into multimode fibers. Therefore we can expect the accuracy of the milled metal plate to be good enough for our approach to interconnection. To verify this assumption experimentally, we designed planar-integrated test systems, which we discuss in Section 4.

#### 4. Planar-Optical Test Systems

We designed two planar-integrated systems to test whether optical signals can reliably be coupled from fiber ribbons onto detectors of a VLSI chip that is bonded to the planar-optical substrate and whether it is possible to process optical signals emerging from a fiber ribbon in a free-space system, route them through the planar substrate, and couple them into a second fiber ribbon with good uniformity.

A cross section of system I is depicted in Fig. 6. Two MT connectors are attached to the metal plate described in Section 3 at docking positions that are 6 mm apart. Optical signals emerging from the fibers are symmetrically imaged into window B by means of two identical imaging systems consisting of lenses  $E_1$  and  $L_1$  and  $E_2$  and  $L_2$ , respectively, as well as plane mirrors  $M_1$ – $M_4$ . Window B is the assumed location of an optoelectronic VLSI chip on the top side of the 6-mm-thick planar-optical substrate. For the pitch of the optical I/Os on the chip we assume a value of  $62.5 \mu\text{m}$ , which is typical for currently available hardware.<sup>15</sup> Hence, as the fiber spacing in a MT connector is  $250 \mu\text{m}$ , the magnification of the imaging systems needs to be  $m = -0.25$  to permit interconnection of each fiber with one I/O on the chip, which requires a ratio of 4:1 for object and image distances. Therefore lenses  $L_1$  and  $L_2$  have to provide the main focusing power. Lenses  $E_1$  and  $E_2$  deflect the beams that enter the planar-optical substrate and ensure object-side telecentricity. This property is important because it makes the setup tolerant of slight variations of distance  $d$ .

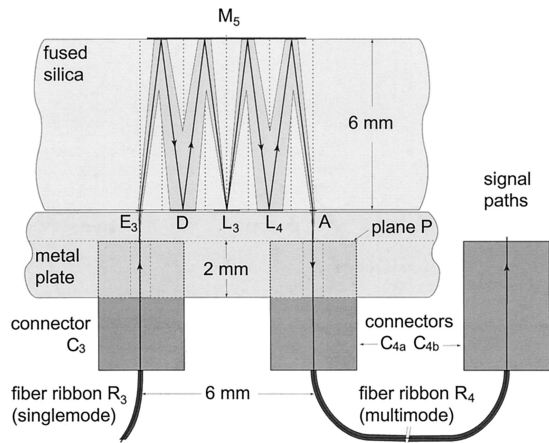


Fig. 7. Schematic cross section of planar-integrated optical test system II.

Under ideal conditions, two signals, which originate from the corresponding fibers of the left and the right MT connectors, will be perfectly superimposed in window B. A mutual displacement of these two signals can be caused only by mechanical deviations of the metal plate or the planar-optical substrate from their respective scheduled geometries; it cannot be caused by a relative misalignment of the optical substrate and the metal plate, because that would shift both images in the same way. We point out that the mechanical tolerances for the metal plate are relaxed, as errors are also subject to the magnification of  $m = -0.25$  in the geometry of Fig. 6.

Figure 7 shows a cross section of test system II. Again, two MT connectors are attached to the metal plate described in Section 3 at docking positions that are 6 mm apart. Here, however, a single optical signal is coupled into the free-space optical system and deflected onto diffractive element D, which splits it into 10 parts with equal intensities. These 10 replicas are routed farther through the system via a light-pipe setup formed by lenses  $L_3$  and  $L_4$  and coupled into the fibers of the second MT connector. As in test system I, coupling lenses  $E_3$  and A ensure telecentricity on the connector side.

Note that we use a single-mode fiber for the input because good performance of diffractive fan-out element D requires an approximately pointlike signal source. Element D was designed as a one-dimensional phase-only Fourier-type array illuminator<sup>26</sup> by use of an iterative Fourier-transform algorithm (IFTA).<sup>27,28</sup> The lenses in both test systems are discrete phase-level Fresnel zone plates.<sup>29</sup> The systems were fabricated by means of two-mask binary photolithography and reactive ion etching upon a fused-silica substrate. As a reflective coating we use a thin layer of aluminum, which was evaporated. Figure 8 is a picture of the planar-optical test module after it was aligned and fixed to the metal plate by the method described in Section 3. The

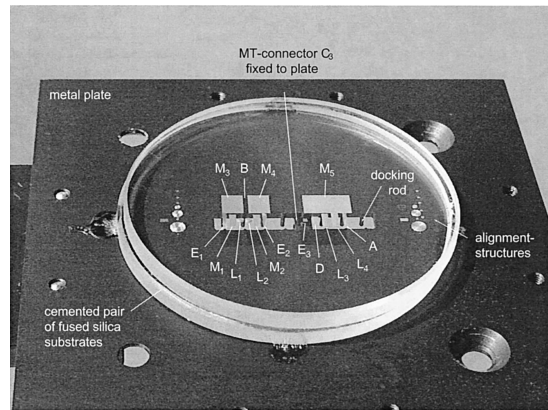


Fig. 8. Experimental setup with test systems I (left) and II (right). See Figs. 6 and 7 for schematic cross sections.

optical module is composed of two 3-mm-thick substrates that were cemented together.

## 5. Experiments

With the setup of Fig. 8, we carried out several experiments to determine the mechanical tolerances of the milled metal plate and to test the practical feasibility of our interconnect approach.

Using two fiber ribbons, we coupled  $2 \times 12$  optical signals into test system I and observed window B with a CCD camera. From Fig. 9 one can recognize B between two adjacent mirrors,  $M_3$  and  $M_4$ , as well as some small structures that enable one to conveniently evaluate the performance of the interconnection: On the left there are squares of  $40\text{-}\mu\text{m}$  length with  $20\text{-}\mu\text{m}$  square apertures in the center. The structures at the right are  $20\text{-}\mu\text{m}$  squares. These structures are centered at the target positions, i.e., the positions that the imaged signals are intended to hit. They simulate VLSI detectors that have a typical size of  $20\text{ }\mu\text{m} \times 20\text{ }\mu\text{m}$ .<sup>15</sup> Below them one can

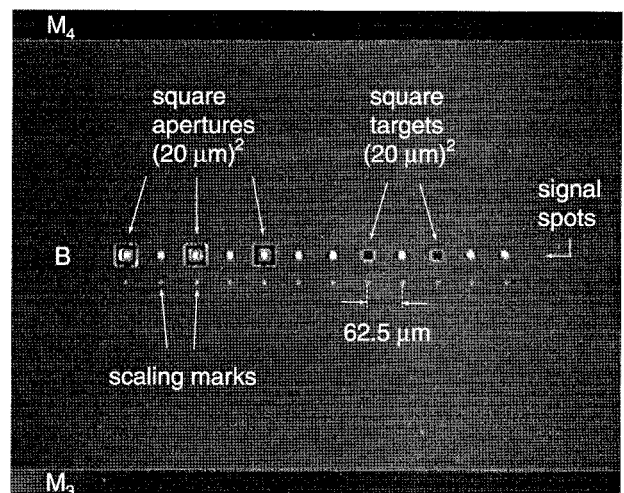


Fig. 9. CCD image of window B with signal spots.

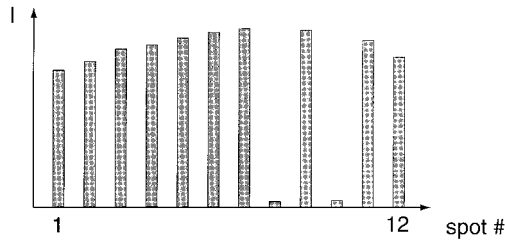


Fig. 10. Evaluation of Fig. 9: Signal intensity integrated over square windows of  $40\text{-}\mu\text{m}$  length centered at the target positions.

see an array of tiny  $5\text{-}\mu\text{m}$  squares, which serve as scaling marks.

In an ideal optical link the signal spots will hit the sensitive areas of the detectors without loss. In our experiment this is equivalent to the situation that the  $20\text{-}\mu\text{m}$  targets fully block the light while the apertures let the light pass completely. The intensity diagram of Fig. 10 shows that such is almost perfectly the case. The walk-off effect toward the edges of the diagram can be attributed to vignetting in the observation optics, and the nonzero intensity at the target locations is (at least in part) due to the CCD dark current. A mutual displacement of the two superimposed images owing to mechanical tolerances becomes obvious only when single-mode fibers are used [cf. Fig. 11, which shows closeups of Fig. 9 for the single-mode (top) and the multimode (bottom) cases]. We can conclude that the observed mechanical tolerances do not impair the functionality of the system.

In experiments with test system II, only the input MT connector was initially attached; the output area was observed with a CCD camera. A single optical

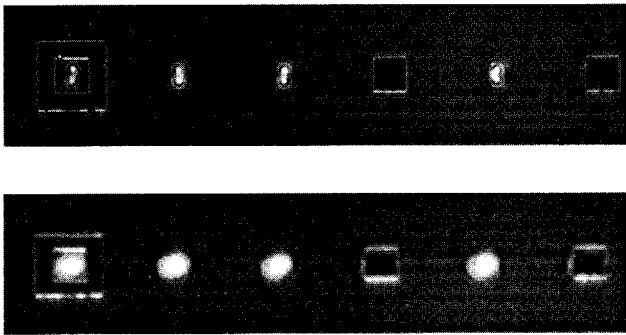


Fig. 11. Closeups of window B showing signal spots obtained with single-mode (top) and multimode (bottom) fiber ribbons.

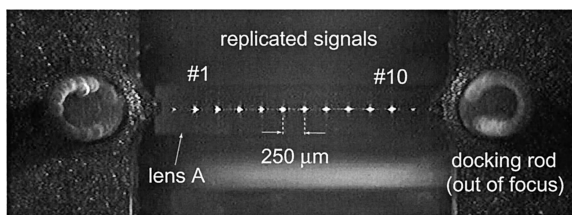


Fig. 12. CCD image showing the docking position for connector  $C_{4a}$  in test system II and the 10 replicated signals.

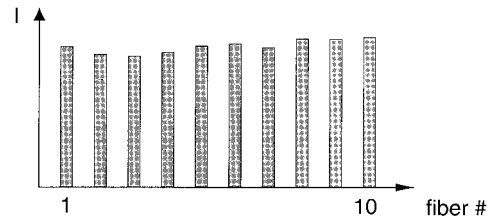
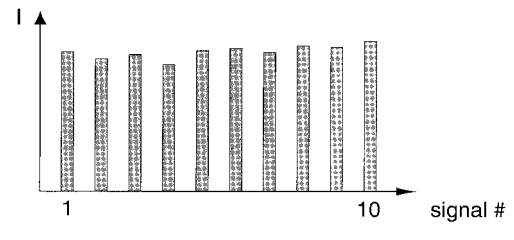


Fig. 13. Intensity of the signals before they are coupled into the fibers of connector  $C_{4a}$  (top) and after being coupled out of connector  $C_{4b}$  (bottom).

signal was coupled in and fanned out by the free-space system that generated the 10 replica signals that can be seen in Fig. 12. We point out that the weak spots on both sides of the  $1 \times 10$  spot array are due to an imperfect Fourier-type array illuminator design and are not completely avoidable.

Then the output MT connector was attached such that the 10 signals could be coupled into fibers. Figure 13 depicts the intensities that were measured at the interface between the free-space system and the fibers before the MT connector was attached and the intensities at the end of the output fiber ribbon after it was connected. Obviously, the signals can be coupled homogeneously from the free-space system into the fibers; uniformity errors are less than 10%.

In terms of overall energy efficiency our test module performs rather poorly, with total losses of more than 90%. This poor performance is, however, not a fundamental drawback of our approach but is rather due to budget constraints. We used aluminum as the reflective coating because it is cheap and easy to handle; its reflectivity, however, is less than 90%. With optimized dielectric coatings the reflectivity could easily be brought to almost 100%. The planar-optical system was not equipped with an antireflection coating either; such a coating could reduce losses when signals are coupled in and out of the free-space optical system.

## 6. Conclusions

We have proposed a novel approach to realizing massively parallel hybrid fiber-free-space optical interconnects. A key component of this approach, which combines the advantages of both disciplines, is the interface between MT-type fiber ribbon connectors and planar-integrated free-space optical systems. We have designed and fabricated a prototype of such an interface. Experiments in combination with specially designed planar-integrated test systems have proved the practicality of our interconnect concept.

The next steps are to quantify coupling losses and to devise appropriate measures to minimize them.

The proposed approach is interesting for applications that require interconnection networks with high bandwidths, an example of which is supercomputer architectures of the symmetric multiprocessor type, which consist of a cluster of standard processors that are linked via a bus and communicate by means of a shared memory. A powerful optoelectronic bus for symmetric multiprocessors can be implemented by integration of the arbitration and the control logic as well as of data buffers for all participants on a single smart-pixel optoelectronic VLSI chip and use of parallel fiber-optical links for interconnection.<sup>30</sup> Because in a VLSI chip parasitic capacitance, cross talk, and impedance problems are insignificant compared with macroscopic implementations, high bandwidth and low latency can be achieved. For interconnecting the optical fibers with the optoelectronic VLSI-bus chip, our approach is ideal.

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