Chapter 6 | Optical Backplanes, Board and Chip Interconnects

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6.1. Introduction

The present chapter is intended to give some insight into the rapidly advancing field of research into optical interconnects within data processing systems. This topic is dealt with in a huge number of publications at conferences, in scientific journals and their special issues, as well as book chapters, good access to which is obtained through [1–14]. Given the extremely dynamic environment, it becomes clear that we cannot attempt to provide a complete overview but rather have to restrict ourselves to several examples from current research, which the readers hopefully will find representative. We start off by looking into recent developments in the 10 Gbit/s data rate regime at the intersystem level. These are high-speed 850-nm vertical-cavity surface-emitting lasers, parallel optical links, and new-generation silica as well as plastic optical multimode fibers. Within a single box environment we follow down the usual hierarchy from optical backplanes to intraboard to inter- and perhaps even intrachip levels. For all these categories we attempt to list available technology options and give practical examples from ongoing project work.

The overwhelming majority of digital data inside and between even peak performance computer systems is nowadays carried by electrical signals traveling on metallic lines. Besides the fact that high-speed electronic rather than photonic data transmission has historically been the first available

FIBER OPTIC DATA COMMUNICATION:
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technique, clearly there are a number of advantages that speak in its favor. In the computer environment the most important ones are ease of implementation and handling, low cost, and high reliability. However, with the exponentially increasing performance of electronic processing systems, more and more drawbacks of the conventional approach become apparent. The pronounced waveguide dispersion characteristics of electrical lines correspond to a relatively small bandwidth–distance product so that at higher clock rates it is an increasingly difficult task to bridge the required distances even within a single box. Electromagnetic cross-talk is forcing circuit designers to increase the width of data buses rather than the bus frequency. Susceptibility to electromagnetic interference requires proper shielding and grounding, which can turn thin wires into bulky copper strands, thus limiting the overall interconnect density. Finally signaling rates in the hundreds of megahertz regime make impedance matching a necessity, which is not easy to achieve in practice and only works over a very limited frequency range. Apart from the clock rate's driving force, novel distributed or parallel computing approaches fuel the need for high bandwidth linking of individual data processing subsystems. Bearing these challenges in mind it is widely recognized that the consequences of an apparent electrical signaling bottleneck are experienced at shorter and shorter link lengths and that optical interconnects hybridly integrated with electronics have attractive solutions at hand or are at least potentially able to offer them.

It has become customary to classify optical interconnects into distinct, albeit overlapping, categories. Some of those are illustrated in Fig. 6.1, ranging from the longest to the shortest transmission distance:

- Rack-to-rack, also called frame-to-frame;
- Board-to-board;
- Multi-chip module (MCM)-to-MCM or intraboard;
- Chip-to-chip on a single MCM;
- Intra- or on-chip.

On the frame-to-frame level, it is a relatively easy task to replace space-consuming and performance-limited copper cables with lightweight fibers. Single-channel or space-parallel optical transceiver modules are already commercially available at reasonable cost. Board-to-board interconnection within a rack can be accomplished via edge connections to optical waveguides placed on a hybrid electrical/optical backplane or via free-space transmission. Within a printed circuit board, routed fiber circuits or integrated

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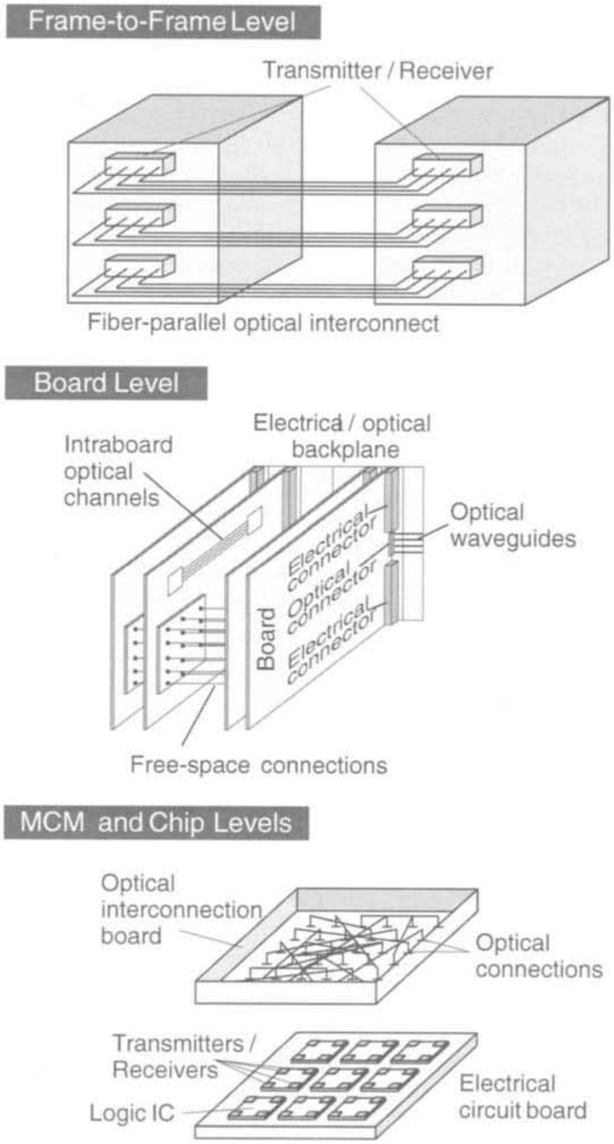

Fig. 6.1 Major optical interconnect categories.

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channel waveguides can be applied for inter-MCM communication. Data transfer between or even within chips finally might be achieved by optical fiber bundles or an optical overlay providing guided-wave or free-space data transport. In most of these scenarios the demand for high-throughput interconnection can be satisfied only by one- or two-dimensional high-density arrays of optoelectronic components, the surface-normal operation of which usually proves to be extremely beneficial.

6.2. Frame-to-Frame Interconnections

Owing to the benefits addressed before, it is an increasingly common practice to take advantage of optical fibers to implement the data links between a high-performance computer box and its outside world, which might consist of other processing units, a storage farm, or a network server. In this section we thus review some recent achievements in graded-index fiber-based optical interconnects approaching the 10 Gbit/s data rate regime, which in the future are likely to be employed at the frame-to-frame level, replacing 1 Gbit/s or lower speed modules. In particular these advances rely on progress in the fabrication of high-speed vertical-cavity surface-emitting laser arrays and new-generation silica as well as polymer optical multimode fibers.

6.2.1. ONE-DIMENSIONAL VCSEL ARRAY DEVELOPMENT FOR NEXT-GENERATION PARALLEL OPTICAL DATA LINKS

The vertical-cavity surface-emitting laser (VCSEL) [15–15b] is a fine specimen of a novel compound semiconductor device that has been successfully commercialized in the last few years. Operation principles and laser technology are treated in some detail in Vol. 1 Chapters 2 and 16 of this handbook. Among the various VCSEL applications, optical datacom is the primary driving field. Especially Gigabit Ethernet (GbE) and related transceivers for graded-index (GI) multimode fiber (MMF) data transmission have become inexpensive mass products by relying on 850 nm short-wavelength VCSEL technology. Generally speaking, the most attractive features of datacom VCSELs include on-wafer testing capability, mounting technology familiar from the low-cost light-emitting diode market, circularly symmetric beam profiles for ease of light focusing and fiber coupling, high-speed modulation with low bias currents, driving voltages well compatible to silicon VLSI electronics, temperature insensitive

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operation characteristics, and obvious forming of one- or two-dimensional arrays. Transceiver modules are employed for a variety of tasks such as in-building backbone links, interconnection of computer clusters or of telecom gear in central offices. The aggregate data throughput of single-channel modules can easily be increased by using the space-division multiplexing technique described, e.g., in Vol. 1 Chapter 11, where optical signals are transmitted in parallel through a MMF ribbon cable. A useful overview with many references on early fiber ribbon data links has been compiled in [16]. Although significant cost breakthroughs have been achieved with high yield one-dimensional laser [17] and photodetector arrays as well as alignment tolerant packaging approaches [18], a GI MMF ribbon cable is still a relatively expensive component, especially if interchannel skew is to be minimized. Therefore parallel links are currently competitive only for several tens of meter transmission length. State-of-the-art modules operate at 2.5 Gbit/s channel data rate and thus achieve 30 Gbit/s throughput for a 12-channel system [19–21]. Obviously, intensive work toward modules with 10 Gbit/s individual channel data rate has commenced.

Figure 6.2 shows a photograph, bit error rate (BER) characteristics, and an eye diagram of a $1 * 10$ elements VCSEL array that is being developed for these next-generation parallel optical transceivers. The oxide-confined VCSELs are arranged on a 250-μm pitch that is compatible to MT (Mechanical Transfer) -type multifiber connectors [22] and each unit cell of the array contains p- and n-contacts separated by 125 μm. The etched VCSEL mesas are planarized by polyimide to obtain a low parasitic capacitance, coplanar contact layout. With this design, modulation corner frequencies in excess of 12 GHz are achieved [23] which are well-suited for data transmission in the 10 Gbit/s regime. In the given experiment, about 3 μm active diameter lasers with an average threshold current $I_{th} = 340\ \mu A$, emitting in a single transverse and longitudinal mode at 850-nm wavelength, have been driven at identical 1.65 mA bias current and 0.65 V_{pp} modulation voltage [24], yielding a dynamic on-off ratio of 6 dB. Figure 6.2 reveals that the BER curves thus obtained for back-to-back operation almost coincide and that error rates of 10^{-9} are reached with less than -15 dBm optical power incident onto a pin photodiode and transimpedance-amplifier-based fiber pigtailed receiver. Although 10 Gbit/s-compatible prototype VCSEL arrays are available today, the manufacturing of complete interconnect modules still requires some challenges to be addressed. Among those are the realization of high-sensitivity MMF-compatible photoreceiver arrays and the dense hybrid integration of optoelectronic chips with high-speed, probably silicon germanium (SiGe) based electronics [24a].

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