Optical Computing Hardware

Edited by

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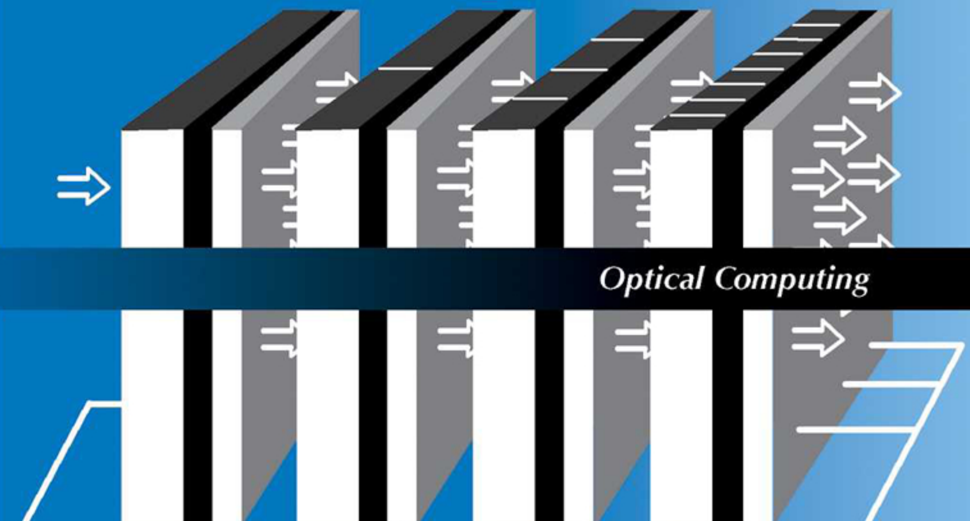

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Contents

Chapter 1: Architectural Considerations for Optical Computing and Photonic Switching

T. J. Cloonan

Chapter 2: Self-Electro-Optic Effect Devices for Optical Information Processing

Anthony L. Lentine

Chapter 3: Vertical-to-Surface Transmission Electrophotonic Devices

Kenichi Kasahara

Chapter 4: Microlaser Devices for Optical Computing

J. L. Jewell and G. R. Olbright

Chapter 5: Physics of Planar Microlenses

Masahiro Oikawa and Kenjiro Hamanaka

Chapter 6: Diffractive Optical Elements for Optical Computers

Jürgen Jahns

Chapter 7: Diffractive Microlenses Fabricated by Electron-Beam Lithography

Teruhiro Shiono

Chapter 8: Parallel Optical Interconnections

D. E. Smith, M. J. Murdocca, and T. W. Stone

Chapter 9: Multiple Beamsplitters

Norbert Streibl

Chapter 10: Photorefractive Optical Interconnects

Arthur E. Chiou

Chapter 11: Three-Dimensional Optical Storage Memory by Means of Two-Photon Interaction

A. S. Dvornikov, S. Esener, and P. M. Rentzepis

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Numbers in parentheses indicate the pages on which the authors' contributions begin.

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Preface

The speed of today's high-performance electronic computers is increasingly limited by the number and bandwidth of the interconnections and by data storage and retrieval rates rather than by processing power. Optics, with its inherent parallelism and three-dimensional interconnection capabilities, can offer interesting solutions to help alleviate these limitations. Applying optics to computing is an emerging technology and many significant advances have been made during the past couple of years in the development of optical computing hardware. The goal of this volume is to review the progress and describe their status.

The selection of the topics for the different chapters was influenced by the two application areas on which we focus in this volume: high-performance computing and high-throughput photonic switching. These two applications require the use of fast logic device arrays, for which only semiconductor-based devices are currently available. Devices for other areas of optical computing such as neural networks, which do not require high-speed operations, are not included in this volume.

The volume starts with a chapter giving a system overview and contains ten other chapters that describe the recent research in optoelectronic devices, micro-optics, optical interconnections, and optical memory.

System overview: Chapter 1 defines the requirements on hardware from a system perspective, i.e., it provides the reader with an overview of the various parts required to build an optical computer: devices, interconnections, packaging, architectures. An example of a free-space optical photonic switching system is presented.

Optoelectronic devices: The self-electro-optic effect device (SEED), the vertical-to-surface transmission electrophotonic device (VSTEP), and vertical-cavity surface-emitting microlasers (VCSEL) are presented in Chapters 2, 3, and 4. The chapters explain the basic principles of the devices and their operation either as logic devices or for optical interconnection applications.

Micro-optics: Chapter 5 describes the planar optical microlens as an example of a refractive microlens of the gradient-index type. Diffractive optical elements are also discussed. Chapter 6 explains fundamentals and a few applications of diffractive optics for interconnections and integrated microoptic packaging. Chapter 7 features an advanced way of fabricating diffractive optics by means of direct electron-beam lithography.

Optical interconnections: The large temporal and spatial bandwidth of optical signals is one of the major assets of optics for computing applications. Parallel optical interconnections based on multistage interconnection networks and architectural considerations for optical computing are described in Chapter 8. A specific interconnection application, i.e., the generation of two-dimensional spot arrays, is presented in Chapter 9. Chapter 10 discusses the use of reconfigurable interconnects based on the use of photorefractive materials and holographic storage.

Optical memory: Chapter 11 describes a technique for writing and reading optically in parallel from a three-dimensional matrix by means of two-photon interaction in photochromic organic materials.

Although optical digital computing is not yet a mature technology, the development of hardware components may be useful to other, more near-term applications, such as optical interconnections for VLSI systems or optoelectronic sensors. It is important to note that optoelectronics and micro-optics are built on the same technology base as electronics. For example, the use of lithography and etching techniques has become as common in the manufacturing of microlenses as it is for the fabrication of gallium arsenide optoelectronic devices. The technological compatibility between optoelectronics, micro-optics, and electronics may be one key to making optical technology more acceptable to computer manufacturers than it has been in the past.

Another important consideration that concerns the practicability or manufacturability of computing systems that use optics is optoelectronic integration and packaging. Without suitable means of building optoelectronic systems in a compact and reliable way, it will be hard to introduce optics as a technology of the future. The difficulty of the task becomes obvious from the requirements that optical systems have to satisfy in terms of alignment precision. To overcome this difficulty, packaging considerations must be included as part of the hardware design.

Based on these thoughts, the chapters for this volume were selected. We hope that the reader will find this book a useful source for information and reference.

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Jürgen Jahns and Sing H. Lee

Chapter 1

Architectural Considerations for Optical Computing and Photonic Switching

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1. High-Performance Processing Systems of the Future

Research into the use of free-space digital optics for interconnections and packaging during the past two decades has produced many promising results by combining and coordinating the efforts of researchers, scientists, and engineers from a wide variety of backgrounds. These many backgrounds include classical optics, lens design, diffractive optics, holography, optomechanics, laser design, device physics, semiconductor device fabrication, high-speed electronics design, advanced electronics packaging, thermodynamics and thermal packaging, digital logic design, and system architectures.

The driving force behind this coordinated research effort comes from the demanding requirements being created by the system engineers of today who are designing the processing systems of tomorrow. In particular, the future requirements for two specific types of processing systems are beginning to greatly outpace the evolving capabilities of the standard interconnection and packaging tech-

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nologies that will be available to implement these future systems. These two rapidly growing processing systems are (1) high-performance computing systems and (2) high-throughput telecommunication switching systems.

These two different types of processing systems exhibit many similarities. For example, computing systems are beginning to rely more heavily on parallel processing techniques to provide their functionality. As a result, interconnection networks are oftentimes used to provide the connections between the multiple processors and between processors and shared memories [Fig. 1(a)]. At the same time, telecommunication networks are beginning to be used more frequently to carry packet-oriented data, and the nodes in the self-routing packet-switching networks are being designed with more functionality to route these packets. As a result, the packet-switching networks are beginning to resemble parallel processing systems with small processors (nodes) connected by links [Fig. 1(b)]. In addition, as the data rates in both computing systems and telecommunication systems continually increase, designers are adding registers within the data paths to provide global synchronization of the data signals on different data paths. As a result, both systems are beginning to resemble the simple pipelined processor model shown in Fig. 1(c), where stages of combinational logic are sandwiched between synchronizing latches yielding a long pipeline of processing logic. Nevertheless, some basic differences still exist between computing systems and telecommunication systems, and these basic differences are outlined in the following sections.

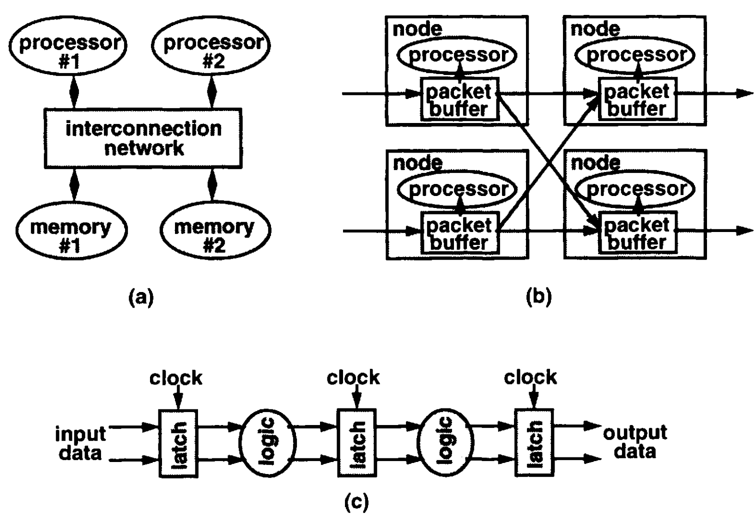

Figure 1. Typical processing systems: (a) parallel computer, (b) packet-switching network, and (c) pipelined processor.

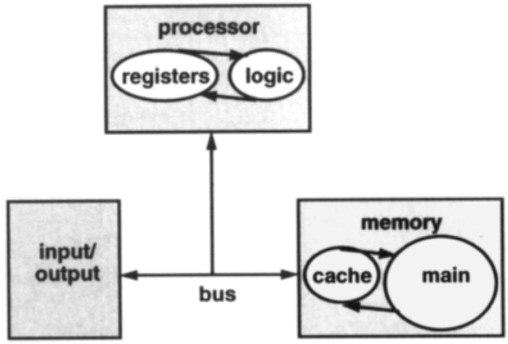

Figure 2. Fundamental components in computing systems.

1.1 Fundamental Components in Computing Systems

In general, any computing system must contain at least three fundamental components: a processing element, a memory, and an input/output interface (Fig. 2). The processing element typically contains combinational logic to implement the desired arithmetic operations, and it also contains registers to store intermediate results. Since data are often repeatedly routed between the registers and the combinational logic in a manner reminiscent of classical finite state machines, feedback loops are generally an inherent part of computing systems (Stone 1980). The registers in the processing element are usually filled with data that were initially stored in the memory, and the results of mathematical operations can then be stored in the memory for future access or for retrieval by the system user. The memory is often divided into two functional units to improve the average processing rate. A small cache memory with a very fast access time holds data that are accessed quite frequently, while a larger main memory with slower access times holds most of the other data. The input/output interface within the system provides a means for the user to communicate with the computing system, and it also provides a means for the system to send pertinent information regarding the internal system status to the user.

1.2 Fundamental Components in Telecommunication Systems

A telecommunication system can be divided into two distinct subsystems: the transmission facility and the switching system. The transmission facility provides a physical connection for signals to be transported over relatively long distances (ranging from hundreds of meters to thousands of kilometers depending on the particular application). This physical connection can be provided by metallic cables, microwave towers, or optical fibers. The transmission facility must also provide the hardware needed to amplify and regenerate the transmitted signals as

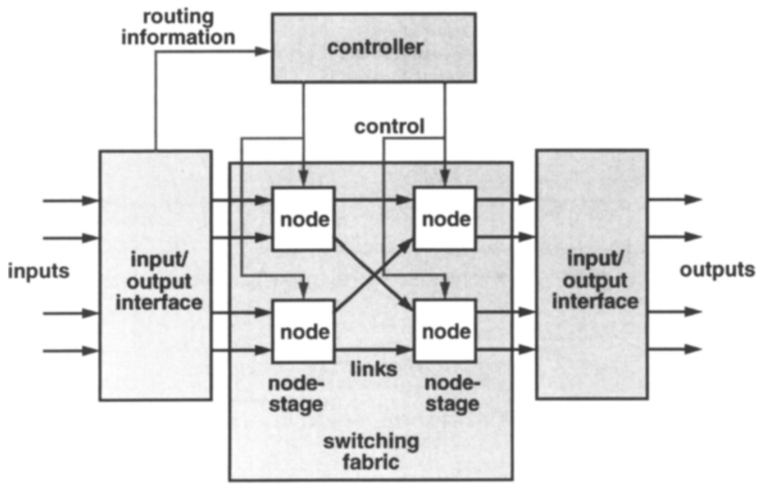

Figure 3. Fundamental components in switching networks.

they are distorted and attenuated by the propagation along the imperfect channel. The actual routing of the signals along the desired path is accomplished by the switching system, which receives signals from multiple transmission links and steers the signals to the desired output transmission link based on control signals sent to the switching system. A typical multistage interconnection network that could be used in a switching system is shown in Fig. 3. This system is comprised of four fundamental components: a controller, a pair of input/output interfaces, a set of nodes, and a set of connecting links. The input/output interfaces provide conditioning of the signals (such as bit synchronization, extraction of routing information, etc.) between the transmission facility and the switching network. Extracted routing information is sent to the controller, which determines the network path through which the signals must be routed. The controller then sends commands to the nodes, indicating how they should steer the signals, and the node hardware must actively guide the signals as directed. The links between adjacent node stages provide the passive connections that carry the signals from stage to stage. Thus, unlike the data in a computing system, the data in a switching system only flows through the stages in a feed-forward fashion, which tends to ease some of the system-level requirements within the switching system.

1.3 Interconnection and Packaging Problems in Processing Systems

High-performance computing systems and high-throughput telecommunication systems will share many common attributes in the future. For example, both of these processing systems will undoubtedly require very high data rates (50 Mbps to 1 Gbps) to be passed on the signal traces between functional units. (A functional unit can be defined as an integrated circuit chip, a multichip module, a printed circuit board, a card shelf, or an entire electronic frame.) High-performance computer systems will require these data rates as the speeds of processors and cache memories are continually increased. High-throughput telecommunication systems will require these data rates as future communication networks begin to carry high-definition video signals, video-conferencing signals, CAD/CAM and medical imaging information, and high-speed computer data signals in addition to the voice traffic they transport today. [In anticipation of these changes, new transmission line formats such as the Synchronous Digital Hierarchy (SDH) and Synchronous Optical Network (SONET) are already being standardized and developed to carry these higher data rates (Davidson and Muller 1991).] Future computing and telecommunication systems will also attempt to capitalize on the high degrees of integration that will become possible within the different functional units as the gate count within integrated circuit chips continues to increase. Empirical formulas, such as Rent's rule, give an indication of the number of pinouts that may be required as the gate count within an integrated circuit chip increases. According to Rent's rule, the number of pinouts P required for an integrated circuit chip with G logic gates is described by:

$$P = k(G)^{1/c}, \tag{1}$$

where k is a constant that depends on the amount of sharing (multiplexing) on chip pinouts ($k = 2.5$ for high-performance applications and 0.5 for low-performance applications) and c is another constant whose values are typically between 1.5 and 3.0 ($c = 1.79$ is typical for high-performance systems) (Rymaszewski and Tummala 1989). Typical pinout requirements for high-performance processing systems are plotted as a function of the gate count in integrated circuit chips in Fig. 4. Since the gate count of VLSI circuit chips is rapidly moving from

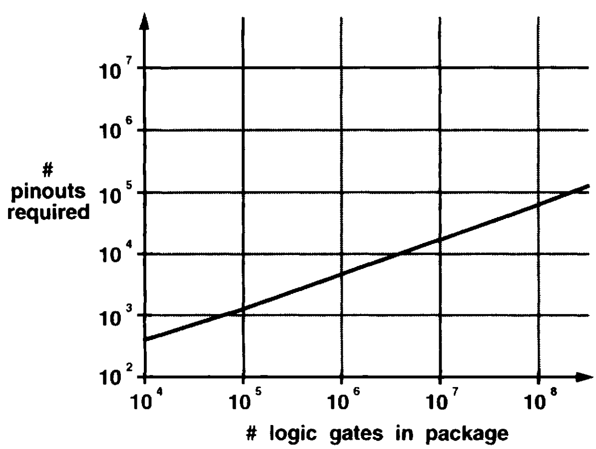

Figure 4. Pinout requirements for device packages in high-performance processing systems ($k = 2.5$, $c = 1.79$).