OPTICAL SIGNAL PROCESSING

edited by

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KLUWER ACADEMIC PUBLISHERS

Distributors for North America:
Kluwer Academic Publishers
101 Philip Drive
Assinippi Park
Norwell, Massachusetts 02061 USA

Distributors for all other countries:
Kluwer Academic Publishers Group
Distribution Centre
Post Office Box 322
3300 AH Dordrecht, THE NETHERLANDS

Library of Congress Cataloging-in-Publication Data

Optical signal processing / by editors, M. A. Fiddy, M. Nieto
-Vesperinas.
p. cm.--(The Kluwer international series in engineering and
computer science ; SECS 153)
ISBN 0-7923-9215-9
1. Optical data processing. 2. Signal processing. I. Fiddy, M.
A. II. Nieto-Vesperinas, M. III. Series.
TA1632.0674 1991
621.36'7--dc20 91-26732
CIP

Printed on acid-free paper.

Printed in the United States of America

THE KLUWER INTERNATIONAL SERIES
IN ENGINEERING AND COMPUTER SCIENCE

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Guest Editors: M. A. Fiddy and M. Nieto-Vesperinas

Multidimensional Systems and Signal Processing 2, 355 (1991)

Editorial

It gives me great pleasure to credit Dr. M.A. Fiddy and Dr. M. Nieto-Vesperinas for organizing the first Special Issue for this journal. In a relatively short span of time, they were able to procure contributions from researchers active in the area of optics and have them reviewed and processed for the readers to enjoy a very timely issue. It is indeed satisfying to see the links between optics and multidimensional processing underscored in this Special Issue. The exchange of information between scientists of different but related backgrounds, which this will promote, serves very well one of the key objectives of this journal. I am sure that Drs. Fiddy and Nieto-Vesperinas will welcome comments from readers on their worthwhile effort.

N.K. Bose
Editor-in-Chief

Multidimensional Systems and Signal Processing 2, 357–358 (1991)

Introduction

Special issue on Optical Signal Processing

At the suggestion of the Editor-in-Chief, Dr. N.K. Bose, we invited various researchers to contribute to a special issue which focused on the use of optical hardware and methods to solve multidimensional signal processing tasks. This special issue contains papers which span a range of applications of optics to signal processing. Optics here refers to the imposition of information on a two dimensional wavefront and the modulation of this information by the optical processor. The intrinsic parallelism of optics suggests very high computational throughputs provided the information to be processed can be read onto and read from the propagating wavefront sufficiently rapidly. The *first paper*, by Fiddy, entitled "Multidimensional Processing: Nonlinear Optics and Computing," describes some of the background to the use of optics in this context. It is primarily written for the nonspecialist in optical processing and reviews some of the potential advantages and prospects for optical processing and computing. This tutorial paper discusses both the needs of computing and the developing optical hardware and materials required. The *second paper*, by John Caulfield, takes a very fundamental look at the "in principle" advantages one can expect from an optical processing system. It is entitled "Space-time Complexity in Optical Computing" and describes how the spatial and temporal complexity of the computing hardware is related to the complexity of the problem. In particular, the possibility of performing a "fan-in" of data optically leads to computational advantages not realizable by nonoptical means.

One of the earliest demonstrations of optical computing was the use of the simple convex lens to perform a Fourier transformation. Much has been written about Fourier optical correlators and in many ways they represent a mature branch of optical computing. In practice, the robustness of such Fourier optical techniques is still limited because of sensitivity to variations in scale and rotation of the feature to be recognized, with respect to its appearance in an input image. The paper by Mendlovic et al., entitled "Composite Reference Image for Joint Transform Correlator," shows how a complex reference image and a composite Fourier planse filter can improve the selectivity of a real time optical correlator of this kind.

The paper by Pantelic considers a specific operation that is computationally intensive but which can be performed relatively straightforwardly using optical hardware. The paper is on "Optical Computation of Sector and Radon Transforms using a Pinhole Array." An optical system is described which computed the sector transform in a fully parallel fashion. Sector transforms are useful for noise insensitive pattern recognition but are computationally time consuming. A large number of optical computing applications are described in the paper by Kitayama and Ito. This paper on "Optical Signal Processing using Photorefractive Effect," outlines many novel applications such as logic operations, optical storage and neural networks which can be performed optically. Their work focuses on the use of the photorefractive materials which have aroused a great deal of interest in the optical processing community over the last ten years. These materials have a refractive index which changes as a function of the illuminating intensity and thus permits information to be stored, modulated or amplified in near real time. Many novel applications in optical signal processing are proposed and demonstrated.

Finally the paper by Navarro and Tabernero entitled "Gaussian Wavelet Transform: Two Alternative Fast Implementations for Images," describes methods for the efficient encoding of image information in a way that is based on human visual models. Schemes for multiresolution image coding are described and such complex procedures for the efficient compression of data are good candidates for parallel optical processing, as and when that hardware advances to the required degree of sophistication.

While this special issue in no way encompasses the entire field of optical computing, it does provide an insight into some of the issues of optical processing and presents some of the latest developments in this fast moving field.

M.A. Fiddy and M. Nieto-Vesperinas

Multidimensional Systems and Signal Processing, 2, 359–372 (1991)

Multidimensional Processing: Nonlinear Optics and Computing

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Received December 30, 1990, Accepted March 20, 1991

Abstract. The purpose of this paper is to overview some of the trends and directions in computing, as performed by optical hardware, resulting from the demands made by multidimensional signal processing. Optical information processing or optical computing is a vast field and some of the more significant issues are discussed here. We discuss future developments and architectural consequences for such potentially highly parallel and interconnected processing systems. Particular emphasis is placed on energy and speed considerations, associated with the use of nonlinear optical materials in optical systems and devices.

1. Introduction

In this paper, we discuss computing and complexity in computing, with optical hardware implementations in mind. The demand for new and continually improved computing capabilities increases constantly. Optics is frequently presented as providing a technology for new types of highly parallel and complex computing architectures. Some very general issues concerning complexity and the potential advantages of optical computing are addressed in the accompanying paper by Caulfield. We review the advantages and disadvantages of optical processing and describe the requirements for optical components used in switching and beam modulation. Finally, trends in the development of the subject will be considered, including the increasing attention being paid to new classes of nonlinear optical materials. This brief paper is by no means complete, but reflects a personal view of some of the key issues in the subject. There are many excellent reviews and books written on the subject, just a few of which are cited here, [Horner 1987; Mandel, Smith and Wherrett 1987; Neff 1987; Goutzoulis 1988; Feitelson 1988; Arrathoon 1989; Wherrett and Tooley 1989; Arsenault, Szoplik and Macukow 1989; Reynolds 1989; Caulfield and Gheen 1989; Berra 1989; Optics News 1986; Opt. Eng. 1986; see also special issues in Opt. Eng. 1989; OSA Technical Digest Series 1989; Opt. Eng. 1990; App. Opt. 1990; Int. J. Optoelectronics 1990].

Optical processing research can be broadly divided into two areas. In one area, attention is focused on optical components that improve the speed and performance of existing computing hardware. The increasing speed requirement combined with demands for smaller scale integration and higher interconnect complexity makes developments in optical technology seem natural and evolutionary. The activity is stimulated to improve and build on existing digital electronic computing concepts. As a result, one can expect more powerful and versatile computing resources developed in a way that advances in technology will be transparent to the user. The other area is focused on carrying out those tasks that are peculiarly suited to optics and which electronics does poorly. It is in the domain of both high speed and high parallelism that the latter is focused. Special purpose hardware that falls into this category might perform two-dimensional correlations or convolutions, solve optimization problems perhaps based on learning principles attributed to artificial neural network models, or simple two-dimensional correlation and Fourier-based computations. This second area suggests the idea of wavefront based computing, which may no longer be based on binary computations but include multivalued, fuzzy or analog signal representations; in analysis, continuum modelling has many advantages over discrete modelling. In each area, and perhaps spanning both, practical necessities lead to a philosophy of combining the best features of optical and electronic hardware through the development of so-called hybrid systems.

2. Computing and Work

If one asks the questions, what is computing, it could be summarized as the transfer and manipulation of information, e.g., of strings of bits of information having some logical meaning. Each component or basic element of a computing system usually has one of two states and computation arises from a sequence of state changes. It is a process that requires some energy to be expended. This can be illustrated through the example of the original mechanical computer of Babbage, developed in the 1840s. One could ask the question whether or not this computer could run backwards. Clearly it could not as there must be friction present in order for it to operate reliably. As a result, it's operation requires energy and will generate heat. Modern computers also generate heat, somewhere of the order of 10^8 kT per logic operation, such as an AND or an ADD on single bytes. One would like to operate at lower energies and also at higher speeds; operating on smaller physical scales can assist with these goals, but there will always exist fundamental physical limitations on the minimum dimensions and energies required. Much work has been done to identify exactly where this energy for computation is needed. For example, in a binary processor, binary digits can be materialized as magnetic domains; there is no heat dissipation if the domain is left alone and energy is required only if the state is to be changed.

We can speculate what the lowest energy might be to represent a binary state. A particle spin-state, for example, might suffice and this could perhaps be altered without dissipation of energy. If one considers an electron in a potential well, its probability of escape is $\approx \exp(-\Delta E/kT)$ where $\Delta E \approx kT = 4 \times 10^{-21} J$. This represents a possible limitation on the minimum energy required in computing where bound or unbound electrons distinguish one *state* from another. However, according to Heisenberg's uncertainty principle, if $\Delta E \Delta t \leq h/2\pi$ then quantum mechanical tunnelling may take place, leading to a loss of information. Based on thermal considerations, it is generally accepted that to erase a bit of information requires dissipation of energy $kTln2$, (Landauer's principle). One can compare the energy requirements of different devices used in computing. Today's electronic devices require $\approx 10^6$ kT to switch states, and integrated circuits require $\approx 10^{10}$ kT which is of the order of 10^{11} operations/sec/W, if we define an operation as a bit change. A typical mainframe such as a VAX requires 3 $kW \approx 10^{24}$ kT/sec or 350 instructions/sec/W, where an instruction is defined as a single accept and execute step; this translates to $\approx 10^{-4}$ J/bit.

The situation in optics is quite different. Let us assume we require ≥ 10 photons to distinguish an on-state from an off-state. This corresponds to $\approx 10^{-17} J$ and if assume that we need ≥ 100 photons detected for 10 bits, this is $\approx 10^{-16} J$. If one imagines 1000 by 1000 elements measuring at 10 bit accuracy, then this would require $10^{-10} J$ of energy on this basis. One can now compare this requirement with the digital electronic energy requirements of $\approx 10^6$kt/bit for a device to switch or a total of $10^{-8} J$. Optics thus has an energy advantage, in principle. Moreover, one can project that analog optical processors offer about 100:1 decrease in processor volume along with at least a 10:1 decrease in power requirements over their digital electronic counterparts.

Speed considerations are also important. A transistor may switch at ≈ 5 ps, a logic gate at ≈ 120 ps, a chip may have a clock cycle of ≈ 1 ns and a system a clock cycle of ≈ 5 ns. The difference between the speed capability of a component and the system is a factor of 1000. The reason for this is electromagnetic interference, connection complexity and impedance matching effects. In optics, these delaying factors can be reduced since one can accomplish a high degree of interconnectivity by refractive or diffractive elements. For example, one can regard a simple convex lens, focusing a plane wave to a spot, as similar to a high density fan-in element taking light from an extended array of locations to an isolated site, via free space. This potentially high degree of interconnectivity can be achieved with no interference or cross-talk between connections, provided the propagation medium is linear. If one wanted signals to mix or interfere, they could be propagated through a nonlinear optical medium.

The information carrying capacity of optical fields is usually expressed in terms of numbers of channels passing through a given area. It has been shown [Ozaktas and Goodman 1990] that optical channels can be regarded as solid wires with a minimum cross section of $\lambda^2/2\tau$, where λ is the optical wavelength. A consequence of this analysis is that any number of independent wavefields are permitted to overlap in real (image) space or in Fourier space, but not in both. Also, one can deduce from a degrees of freedom argument, that the size or volume of an optical processor is linear in the total communication length. This follows from the fact that a diffraction limited spot does not increase in size on cascading several systems together; i.e., the effective cross-section of each optical channel is independent of length. Hence, with increasing system size, the communication volume required for establishing optical interconnections will grow more slowly than that required for establishing conductor-guided interconnections, [Ozaktas and Goodman 1990].

3. Computing Architectures

Conventional digital electronic processing relies on a serial processing architecture which leads to an input-output bottle neck. This bottle-neck manifests itself in fundamental limitations on computing speed since all processing has to be performed by passing information through a single cpu. Obviously present day systems exploit parallel or multiprocessor architectures, [Hwang 1987], and these are referred to as fine-grained or coarse-grained processors, operating either in a single instruction multiple tasks or multi-instruction multiple-task modes, which alleviates the bottleneck to some extent.

Recently there has been interest in so called artificial neural processing architectures, [Khanna 1990]. These architectures are very loosely based on a simple model for the brain and assume a high degree of interconnectivity between sets of simple processing elements such as two-state switches. The power of this kind of computing resides in the connection strengths between processing elements. These connection weights can be modified and so the performance of the network can be influenced by a learning rather than algorithmic rule. The expectation is that such a network will be able to more easily solve recognition and optimization problems of the kind that are currently difficult to solve by conventional processing means, [Soffer, et al. 1986; Caulfield, Kinser and Rogers 1989; Owechko 1989; Psaltis 1990].

A system consisting of many processing elements, each one of which makes a weighted connected to all others, is referred to as a fully connected architecture. If a fully connected parallel processing hardware were available, there are several problems that could be programmed to be solved on it, [e.g., Abbiss, Brames, Byrne and Fiddy 1990; Steriti, Coleman and Fiddy 1990]. Since the key requirement is a highly interconnected set of simple processors, this kind of architecture has been of considerable interest to the optics community, since it looks likely that optical hardware could more easily provide the large parallel systems necessary. Optically, a *processing element* may take the form of a bistable optical switch which either transmits or does not transmit light, according to the light level incident on it. It is still early days in hardware development of neural computers, but there have been many proposed optical architectures which look promising, once the necessary optical components become available, [Caulfield, Kinser and Rogers 1989].

If one accepts that there could be advantages in processing information with photons rather than electrons, one has to identify classes of materials with the performance required for this technology to be competitive. Higher speeds, higher interconnectivities and lower overall energy requirements are motivating conditions for this approach, [Feldman, et al. 1988]. However, electronics will continue to miniaturize further, with associated reductions in processing speeds and energy requirements. The fundamental limitations associated with free space optical interconnections, resulting from the constant radiance theorem [Goodman 1985] and recently discussed in the context of tubes of information by Ozaktas and Goodman [1990], make it unlikely that the physical dimensions of optical components will be much different to those used in digital electronic devices. Diffraction limitations will ultimately restrict the density of cross-talk-free interconnects that can be experimentally realized. The advantages optics can offer will have to be found in the ease of generating high density but nonwired interconnects and the prospects for low energy operation.

4. Spatial Light Modulators

A major bottleneck in optical processing has been that of imparting the required information onto the optical beams. Sources and light modulators have their own intrinsic limitations in terms of speeds, resolutions and efficiencies, and at present these spatial light modulators constitute a weak link in any optical computing architecture. There are many mechanisms that can be exploited for this purpose, such as electro-optic, magneto-optic, acousto-optic, photorefractive, mechanical (e.g., deformable mirrors) etc., [special issue of App. Opt. 1989; Neff, Athale and Lee 1990].

Perhaps the two most commonly available SLMs are liquid crystal based or magneto-optic. Commercially available SLMs such as liquid crystal based *light valves*, tend to have 2 to 100 ms response times, 20 to 100:1 contrast ratios and 16 to 30 line pairs/mm resolution. Both optical and electronic addressing is possible. Magneto-optic devices tend to have response times in the tens of nanosecond range and frame rates ranging from 350 to 1000 Hz, with high contrast ratios (10,000:1) but low resolutions of the order of 10 line pairs/mm. The magneto-optic pixelated devices are binary in character and nonvolatile, with up to 256 by 256 pixels available, [special issue of App. Opt. 1989].

Newer mechanisms for SLMs suitable for digital optical computing are being developed. For example, in so-called SEED (self-electro-optic-effect) devices, excitonic absorption in a layer of quantum wells can be controlled by an applied voltage. These offer 2 ns switching speeds and 5:1 contrast ratios, and arrays of 32 $\times$ 64 elements or 50 line pairs/mm resolutions, [Miller et al. 1985]. The symmetric or S-SEED switches state if about 1 pJ of light is incident on it; they cost $\approx$ \$14k per array. Such multiple quantum well materials also provide potentially low threshold lasers and hence modulating sources. Their low threshold of operation arises because as the volume of the gain medium is reduced the material losses are reduced and as the reflectivity of cavity mirrors is increased, the cavity loss reduces further.

New materials are appearing routinely, which may make significant improvements to the SLM situation. We cite, for example, erasable dye polymers and polymers which can be addressed in the infrared and undergo phase changes [e.g., Roland 1990]. New components such as arrays of surface-emitting microlasers can be used for computational purposes, either for logical functions or interconnections.

5. Computing Needs

There are some areas of computing into which optics is already providing improvements. We cite for example communications, e.g., via fiber optics. The research bit rate limit today is around 350 Gbits/sec with a colliding pulse mode-locked laser and predictions of 1 Tbit/sec by the year 2000. Currently, up to 1 Gbit/sec communications between chips has been reported (MIT Lincoln Laboratories) and guided wave or free space interconnects promise further improvements; see for example the use of overhead holograms relaying clock pulses across VLSI chips, [Goodman et al. 1984; Kostuk, Goodman and Hesselink 1985]. Problems with wire interconnects arise when their length is limited to approximately that of the wavelength of the signal and at higher frequencies, shorter interconnect lengths are required. Currently, computer speeds are limited by interconnect times (100 ps) rather than switching times of devices (10 ps for GaAs devices). Optics should help overcome clock skew problems, ground loop isolation, cross-talk (which increases at higher frequencies), losses and impedance matching problems. Also, 3-D transmission is possible with optics between arbitrary locations on boards.

Another computing need is data storage. Magnetic media are capable of 0.15 Mbits/sq.mm or 100 MBbits/sq.in. with IBM having announced 1 Gbit/sq.in.; the storage capacity for magnetic media appears to double every 2.5 years. For optical storage, such as magneto-optic or phase change storage, 645 Mbit/5.25 in. disk is virtually the entry level storage density, with further increases in density expected. An advantage of optical disk storage is the fact that the recording head need not be too close to the storage medium, minimizing problems of head crashes, etc.

A number of materials have been proposed for optical storage and/or reconfigurable interconnects and the more promising ones are shown in Table 1.

High capacity storage is possible in a volume rather than disk media. Also, volume or Bragg diffraction results in high efficiency optical elements. Most volume storage concepts are based on the idea of holographic storage, whereby readout is by addressing the medium with a specific *reconstruction* wave, or read-out is by association. The latter is frequently equated to a neural network content addressable or associative memory, in which partial information acts as the key to read-out the entire data set.

The storage capacity theoretically possible in a volume medium is given by $N = V/\lambda^3$ bits, which results in $N = 10^{12}/cm^3$ assuming $\lambda = 1\ \mu m$. In practice, the number of stored bits is determined by such considerations as desired diffraction efficiency, crosstalk, etc. For example, to obtain equal diffraction efficiency for angularly multiplexed (i.e., reference waves with different incident angles) holograms, an elaborate exposure scheduling technique has to be devised in which successively written holograms take into account the previously written holograms. Calculations suggest that about 100 holograms with 1% diffraction efficiency can be multiplexed in a volume medium. However, increasing the number of multiplexed holograms greatly increases the precision with which the exposure time and laser power must be controlled; typically for 100 holograms the recording energy must be maintained to better than 0.1%.

Given a storage capability in excess of 1000 lines/mm, one can expect to write approximately 0.25 Mbits/sq.mm. (160 MBits/sq.in.) in principle. Thus, a target storage capacity of 10^{12} bits stored would require a disk area of $4 \times 10^6\ mm^2$, which is a total of 4 square meters. However, if volume storage were employed, and an effective resolution capability of $1.25 \times 10^8\ bits/mm^3$ is possible, which it is in principle, this would reduce the required storage volume to $8 \times 10^4\ mm^3$, which is a volume of just 80 cubic centimeters or approximately 4.5 cm-cube. With smaller wavelengths, improved coding and track squeezing, 8 G bits/sq. in. is projected.

Table 1. Materials for storage and interconnects.

Physical effect	Typical materials	Resolution lines/mm	Response time/sec	Sensitivity mJ/cm^2	Diffraction efficiency
Photorefractive	BSO, BGO SBN	≈2000	10^{-3} to 1	100	10%
Thermoplastic	Stabelite ester + PVK	1000	0.1 to 1	0.1	20%
Magneto-optic	GaTbFe	1000	10^{-7}	100	$< 10^{-3}$%
Photo-polymers	Dyes in polymers	>1000	10^{-6}	50	20%
Deformable polymers	Elastomers	1000	10^{-8}	30	7 to 10%
Phase change	InSbTe	1000	10^{-7}	100	—

6. Optical Computing

The subject of optical computing *per se* has been studied since the early 1960s, [Goodman 1989]. Initially processing was carried out through the use of convex lenses which can be shown to perform a Fourier transformation on a wavefront, [Reynolds et al. 1989]. Since the Fourier transform plays such a key role in many signal and image processing applications, the idea of performing this operation in real time directly on an image-bearing wavefront was clearly appealing. Many designs for optical processors, i.e., analog optical computers, based on this simple principle have been considered over the years, but few hardware implementations have been incorporated into systems. Exceptions are optical processors for the processing of synthetic aperture radar images, [Cutrona et al. 1966], and compact optical correlators designed primarily for military use, [Flannery and Horner 1989; Caulfield et al. 1987; Gregory and Kirsch 1988]. One of the factors reducing the impact of optical processors of this type has been the need for a possibly expensive SLM for input of information. Another reason has been the belief that accuracy would invariably be limited to about 4 bits which was not considered satisfactory for many applications, especially if further digital image processing was required. Also, of course, the reducing costs of digital electronic hardware to perform similar functions, did little to stimulate optical solutions.

It is still essentially true today that analog processing, while recognized as being a powerful and an elegant solution to many multidimensional processing problems, is not widely pursued. However, further study of these better established analog optical technologies is finding some encouragement these days, for example through the DARPA TOPS (Transition of Optical Processors to Systems) program. Optical procedures will be developed in this program for channelizers, pulse compressors, real time synthetic aperture radars, null steering, pattern recognition, optical control of phased arrays, precision direction finding and data base management.

The question remains unanswered as to whether digital optical computers can perform better than their digital electronic counterparts. Much has been written specifically on digital optical computing, [Jenkins et al. 1984; Jenkins 1984; Prise, Striebl and Downs 1988; Striebl et al. 1989; Cathey, Wagner and Miceli 1989]. AT&T has announced a functioning prototype digital optical computer, [Huang 1990]. It employs four arrays of S-SEEDS, using only 32 of the 2048 S-SEEDS on each chip; each S-SEED acts as a NOR logic gate. The prototype systems operates at one million cycles per second and has a potential speed of one billion switching operations per second. Hughes Research Labs have developed an acousto-optic [Lee and Vanderlugt 1989] matrix processor referred to as PRIMO (Programmable Real-time Incoherent Matrix Optical Processor), [Owechko and Soffer 1989]. It can perform 10 billion multiplications and additions/s and occupies a small volume. It is currently based on a 256 by 256 SLM and can be used as a Fourier processor and correlator. OptiComp's DOC2 (digital optical computer 2) comprises 64 lasers and exploits acousto-optic devices to impart data onto a beam. This system, in principle, has the potential to operate at one trillion binary operations per second, but is currently limited in performance by the electronic computer which provides instructions to the optical processor. Guilfoyle, founder of OptiComp, predicts the capability of searching 10,000 pages of text a second and running the system on only 200W of power. Our own group has worked in close collaboration with Semetex Corporation on the construction and evaluation of a digital optical processor based on the Semetex magneto-optic Sight-Mod. Using cascaded Sight-Mods, with binary data sets input to each, one can interpret the multivalued output levels directly in terms of Boolean operations between these data sets. Performance is currently limited by the fact that the processor is driven by a serial computer, but the optical branch, with just two cascaded 256 by 256 SLMs, is capable of 12.2 million operations per second.

This general question about whether optical processors can out perform electronic processors is the focus of the accompanying paper by Caulfield [1991]. In that paper he argues that if one breaks the solution of a problem down into its time and space complexity, i.e., the number of clock cycles and the number of cpus necesary to compute a solution, then an optical processor has an intrinsic advantage. This advantage lies in the fact that the processor implicitly performs a fan-in or a fan-out by optical means, a process which normally would expend computational time or effort, but which happens in real time, through the use of bulk refractive optics, in an optical processor.

7. Nonlinear Optical Materials

One of the factors that rejuvenated work in optical processing in the late 1970s was the discovery of materials with large third order susceptibilities. These materials provided a mechanism for faster and lower power switching of light by light, in parallel configurations. There are certain fundamental bounds on the peformance of any such bistable switching element, based on a Fabry Perot etalon structure containing a nonlinear medium between its reflecting surfaces. These limits were first suggested by Smith [1982]. Constraints on performance involve limitations in heat dissipation that might be anticipated (e.g., 100 W/cm^2, the thermal transfer limit), a quantum (tunneling) limit and a thermal limit (electron confined in potential box). Theses various considerations lead to an expected optimal performance around 0.1 μW/bit being possible, in principle, for switching at 0.1 ps. This specification exceeds that of all current optical devices, (see also [Smith 1982; Keyes 1985]). It is instructive to note that the human neuron performs with switching times of tens of ms and power requirements of nW per bit.

All optical materials exhibit some degree of nonlinearity in the sense that their refractive index is a function of an externally applied voltage or is a function if the incident light intensity. Materials with a refractive index dependent on the light intensity are known as Kerr media or χ^3 media and all materials fall into this category. Those whose index is a function of the light amplitude or an externally applied voltage are known as Pockel's media, (e.g., [Hopf and Stegeman 1986]). We consider here only the role of Kerr-type media for optical switching, but do so for illustrative purposes and in no way mean to dismiss the importance of χ^2 media. Table 2 illustrates the range of values possible for these nonlinear media.

These materials could be used in devices like the nonlinear Fabry Perot etalon or a Fredkin gate, [Shamir et al. 1986]. The mechanisms responsible for the nonlinearity depend upon the size and material properties of the medium. Mechanisms include thermal effects, which might be low, electrostrictive forces and local field effects, real transitions, i.e., absorption and resonance phenomena and virtual transitions (no losses) such as electronic nonlinearities, which can be very fast. Nonlinear polarizability effects could be as fast as a femtosecond, while the large χ^3 associated with fluorescein doped Boric acid glass may take 10 seconds.

Table 2. Examples of values of χ^3.

$$D = \epsilon_0 E + P = \epsilon_0(1 + \chi) E = \epsilon_0 n^2 E$$

$$P = \epsilon_0 \{\chi^1 E + \chi^2 E^2 + \chi^3 E^3 \ldots)$$

We consider only third order nonlinearities here, hence

$$n = n_0 + n_2 |E|^2 \text{ and } n_2 \text{ in m}^2/\text{W} \approx (4\pi)^2\ 10^{-7}\ \chi^3/3 \text{ in esu, i.e., 1 esu} \approx 1 \text{ cm}^2/\text{kW}$$

χ^3 esu	
10^1	fluorescein doped Boric acid glass [Tompkin, Malcuit and Boyd 1990]
10^0	fluorescein absorbed to gold spheres InSb at 77 °K
10^{-1}	Hg_{1-x} CD_xTe (at resonance)
10^{-2}	microparticles and quantum confinement: close to resonance [Hache, Ricard and Flytzanis 1986]
10^{-3}	thermal results with colloidal gold [Lai, Leon, Lin and Fiddy submitted] and electrostriction theory for coated particles [Neeves and Birnboim 1989]
10^{-4}	various thermal effects
10^{-5}	chinese tea [Zhang et al. 1989]
10^{-6}	vanadium pentoxide rods
10^{-7}	gold microparticles in glass; Fermi smearing theory [Bloemer, Haus and Ashley 1990] 0.5 μm glass particles in water [Smith et al. 1981]
10^{-8}	colloidal gold and nanocrystals in glass
10^{-9}	0.2 μm latex spheres; quantum confinement: theory
10^{-10}	Ge, Si, GaAs induced polarization
10^{-11}	
10^{-12}	CS_2 molecular reorientation
10^{-13}	most liquids and glasses

In an etalon, as the incident optical field increases in intensity, the refractive index of the medium between the mirrors increases, shifting the transmission peaks of the etalon to other wavelengths. The speed of the device is determined by the build up time of the resonator; thus one can reduce the response time by reducing the length of the cavity, but then this, of course, requires that more power be used to induce the same refractive index change. Such a nonlinear etalon can function as a simple Boolean logic gate and, because of local field effects leading to bistable behavior, can function as a latching device also.

The Fredkin gate was originally described by Bennett [1973], who argued that dissipation in such a system could be arbitrarily low if computations were carried out in a thermodynamically reversible fashion. The basic Fredkin gate consists of a simple Mach-Zehnder interferometer, in which two incident information bearing waves are split to each pass both ways around the interferometer. In one arm of the interferometer, there is a nonlinear optical medium whose properties can be controlled by a third beam, not passing around the interferometer path. When the third beam is on, the two input beams are reversed at the output. Milburn [1989] argued that this architecture might allow switching in a reversible and error free way, provided a lossless nonlinearity was used to produce intensity dependent phase shifts in one arm of the interferometer, and provided only one photon was used at a time. This latter requirement clearly makes the device impractical since an extremely large χ^3 would be required. However, with realistic χ^3, and larger photon numbers, classical field fluctuations lead to phase fluctuations and some degree of error, but maybe an acceptable performance; see also R.W. Keyes [1989].