PART I

Applications and Device Requirements

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"NONLINEAR OPTICAL MATERIALS & DoD DEVICE REQUIREMENTS"

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ABSTRACT

Within the past several years, the development of advanced materials with large second and third order nonlinear ($X2$ and $X3$) effects has generated interest in developing devices to exploit these properties in military systems of the future. This interest has taken many forms, from the funding of basic research aimed at developing enhanced nonlinear optical effects in materials to the deployment of actual mil-spec devices. Two years ago, at this same forum, we delineated a series of materials performance requirements which, if achieved, would allow device developers to take maximum advantage of these nonlinear effects in such disciplines as optical computing, optoelectronic interconnects and sensor protection. In the interim, DoD requirements for advanced materials and devices have continued to accentuate the need for advanced nonlinear optical materials. This paper will discuss some of the most recent trends in nonlinear optical materials research from a device requirements perspective, including an overview of the results of the recent DARPA forum on nonlinear optical materials and a discussion of future directions. As in the previous paper, we will confine ourselves to three challenging areas: nonlinear optical materials for optical computing applications, materials for computer peripherals and internode communications, and materials for sensor protection.

I. Introduction

Within the past several years, the development of advanced materials with large second and third order nonlinear ($X2$ and $X3$) effects has generated interest in developing devices to exploit these properties in military systems of the future. This interest has taken many forms, from the funding of basic research aimed at developing enhanced nonlinear optical effects in materials to the deployment of actual mil-spec devices. Two years ago, at this same forum, we delineated a series of materials performance requirements which, if achieved, would allow device developers to take maximum advantage of these nonlinear effects in such disciplines as optical computing, optoelectronic interconnects and sensor protection. In the interim, DoD requirements for advanced materials and devices have continued to accentuate the need for advanced nonlinear optical materials. This paper will discuss some of the most recent trends in nonlinear optical materials research from a device requirements perspective, including an overview of the results of the recent DARPA forum on nonlinear optical materials and a discussion of future directions[1].

This talk will confine itself to four challenging areas: nonlinear optical materials for internode communications, optical computing applications, memory systems, and materials for sensor protection. The obvious similarities which exist between the first three cases will be extended to the fourth, where it will be shown that the similar types of materials and nonlinear effects can be utilized to overcome a major DoD challenge. For each of these areas, applications currently exist which require the production of large area (several inch diameters), optical quality, high uniformity materialsDDan ability which we currently do not possess. Furthermore, each of these applications stresses a different aspect of the nonlinear optical material, and the goal of this paper is to shed some light on the mapping between device requirements and materials properties.

In developing advanced nonlinear optical materials for DoD applications, we seek to take advantage of the unique properties of the optical medium; namely, the lack of photon interaction in linear media (for communication systems) and the rapid switching potential of photonic devices. The ideal nonlinear optical material (NLOM) for most applications would have a very large nonlinear response, extremely low switching thresholds and rapid switching times. For DoD applications, the NLOM should also be easy and inexpensive to manufacture, mechanically tough, formable into thin films or coatings and have a high damage threshold to laser irradiation, temperature cycling or corrosive or oxidative environments.

At present, no one NLOM satisfies all of these criteria. Candidate materials systems, such as organics, semiconductors, photorefractive materials or phase change materials all accentuate one critical aspect of the ideal NLOM. The challenge exists to capitalize on the unique properties and nonlinear processes of each of these candidate systems, and thereby generate appropriate structures or hybrid device concepts for DoD applications.

Increases in computational throughput have traditionally relied upon advances in VLSI/VHSIC chip performance, reductions in memory access times, improvements in intracomputer communication systems, and the development of novel architectures to exploit them. Optical materials are central to the next generation of computing system advances, as can be seen in the following discussions on internode interconnections in parallel VLSI architectures (Section II), on optical computing systems (Section III), and on memory systems (Section IV). These will be followed by a summary of recent advances in sensor protection schemes (Section V).

II. Opto-electronic Interconnects

As the on-chip performance of VLSI continues to improve via the scale down of the logic elements, the problems associated with transferring the data both within the chip and within the computer become more severe. At present, they are limited by the metallic interconnects. The use of optical carriers to transfer the information within the computer is very appealing, due to the ability to multiplex signals up to gigabit propagation rates and the crosstalk reduction that the conversion to optics presents [2,3]. Accompanying these advances is the transition to multiprocessor computer architectures, where the coordination of information transfer between computing nodes requires more flexible interconnect structures.

A multiprocessor, as the name implies, is a computer system which consists of more than one computing element or central processing unit (CPU). Systems have been demonstrated with as many as 65,236 individual processing elements; obviously the interconnection of this number of processors is a significant contributor to the overall performance of the multiprocessor computer. This section will discuss the application of opto-electronic techniques to optimize interconnect performance and flexibility.

Opto-electronic interconnections in multiprocessor architectures can typically be grouped according to the degree of connectivity between the individual computing elements. As seen in Figure 1, the lowest degree of interconnection is in fixed point-to-point communications, such as the use of fiber optics or other guided wave structures to connect nearest neighbor computing elements.

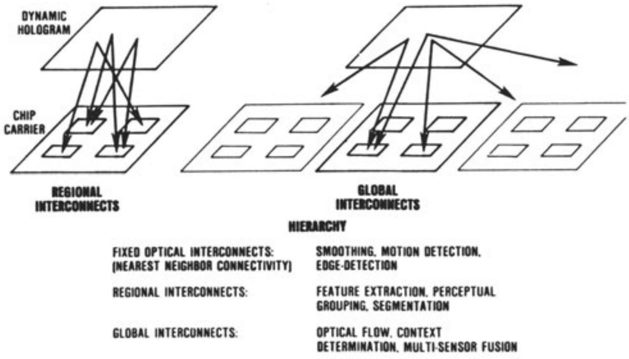

Figure 1
Types of Optical Interconnects

The next level of connectivity in computer architectures, regional interconnects, allows the concept of dynamic reconfiguration to be implemented. Regional interconnects can be thought of as "one-to-many" connections within a multiprocessor, allowing one computing node to be connected to a subset of the remaining computing elements (see Figure 1). Regional interconnects allow the architecture to be adapted to support such advanced processing requirements as feature extraction and segmentation, both of which are critical to advanced target recognition and discrimination algorithms.

The highest level of connectivity is represented by global interconnects, which allow every element of the computing network to be connected to every other. This type of interconnect, also known as the crossbar interconnect, has recently been demonstrated optically in 64-node (8-by-8) structures by researchers at Optivision, Rockwell and BDM. To be really useful, however, these crossbar devices need to support interconnections of 256-by-256 systems at switching rates faster than the individual clock speeds of the underlying electronics. DoD system level performance requirements provide additional constraints, such as the reduction of switching powers per pixel to levels of 50 µW, access to low-cost, high uniformity (1/10) and large area (packages of comparable size to ICs, or approximately 10 cm^2), and total power budgets of less than 50 mW. While these are obviously optimal long term requirements, they are typical of the space of performance and system level tradeoffs viewed by DoD device designers when seeking to incorporate new technologies in next generation systems (see Table I).

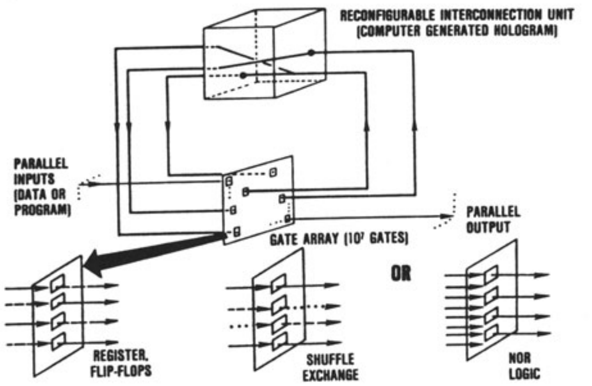

Figure 2
Reconfigurable Interconnection Networks

While reconfiguration is currently beyond the ability of computer designers, one hope for providing this flexibility is the development of 2-dimensional dynamic "masks" in the interconnect structure. Again, the major impediment to implementing these concepts is in the lack of suitable high quality, low threshold, large area optically nonlinear materials. Such masks could consist of large area active optical elements operating in conjunction with passive optical networks (see Figure 2) such as the recently demonstrated folded perfect shuffle [4]. The perfect shuffle is a type of crossbar interconnect which draws its name from an analogy with a complete mixing (shuffling) in a deck of cards. As seen in figure 3, the folded perfect shuffle takes a square input array and proceeds with the operations of magnify/mask, divide-by-rows/interlace-by-columns, and divide-by-columns/interlace-by-rows to generate the output. A typical 16-node (4-by-4) output is shown in figure 3, an output format which is compatible with the input. This allows the perfect shuffle to be implemented in feedback loops or cascaded to achieve multiple interconnect levels.

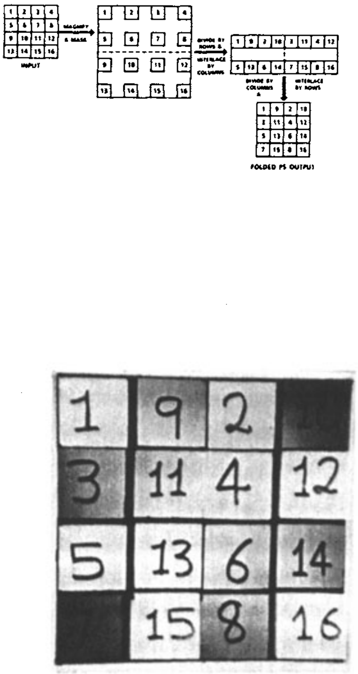

Figure 3
The Folded Perfect Shuffle
(after reference 4)

The perfect shuffle serves a passive information routing function. By combining shuffle exchange interconnects with active optical elements such as the compare and exchange operation [5], the reconfigurable network depicted in figure 2 can be implemented. The compare and exchange (see figure 4) is a fundamental operation which allows computers to compare two values and switch their placement depending on which is greater in value. This operation is the central element in the algorithms for sorting and extracting information from databases and from the knowledge bases of systems used in artificial intelligence applications. In the optical implementation of the compare and exchange operation [6], the latching properties of optical bistable devices are used to control the switching of the output. While these materials and devices are sufficient for laboratory demonstrations, widespread application within DoD systems requires a greater availability and low cost production of optically bistable materials.

III. Optical Computing Architectures

Nonlinear optical materials play a central role in all envisioned optical computing architectures . Photorefractive materials form the basis of many spatial light modulators (SLM's), which are the central active element of most optical computing systems. In SLM's, as in most novel devices, the goal is to simultaneously optimize as many of the critical parameters as possible to meet the desired performance requirements. Very often, individual performance parameters can be traded–off to achieve the overall system level performance. The desired DoD performance requirements for SLMs are to optimize resolution (to > $(10^3)^2$ elements in a square array), frame rate (to > 1 kHz operation), and uniformity (to < 3 % variation across 10^6 pixels) without loss of contrast (at > 30 dB dynamic range). At present, the uniformity, reproducibility and cost of the NLOM utilized in SLMs are the limiting factor in their performance [7]. This section will focus on the relationships between materials properties and SLM performance.

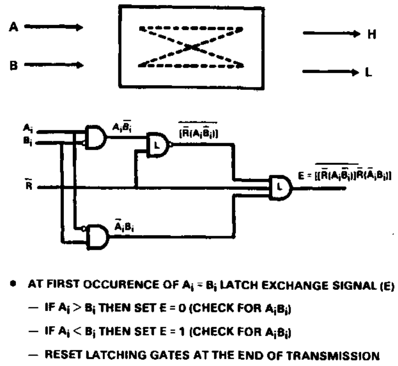

Figure 4
Optical Compare and Exchange Operation
(after reference 5)

There is no unique mapping between device requirements and materials properties. For SLMs, a large electro-optic effect (of order 10^2 – 10^4 x 10^{-12} m/V) is obviously desirable since it directly influences the device operating voltages and optical transfer functions. Beyond these parameters, however, the operating envelope of the device is a complex relationship of materials properties and manufacturing techniques and the specific application of the SLM. For most applications, the dynamic range and contrast of the SLM (dominated by the crystallographic symmetry groups of the underlying NLOM) should be optimized while keeping the pixel sensitivity and response times as low as possible (a function of the mobility–lifetime product). In high signal situations with relatively low processing speed requirements, a balance can be struck between the dynamic range and the sensitivity, allowing manufacturing parameters to be slightly eased. Manufacturing characteristics, such as the residual birefringence and resistivity of the NLOM and the resulting optical quality and flatness of the material, dictate the storage and framing rates and the overall uniformity of the SLM.

	INTERCONNECTS		MODULATORS	
	SHORT TERM	LONG TERM	SHORT TERM	LONG TERM
SWITCHING RATES:	10 MHz[1 2]	1 GHz	1 kHz	1 MHz
INPUT SWITCHING POWERS/PIXEL:	500 μW	50 μW	500 μW	50 μW
BIASING POWERS/TOTAL:	1 W	50 mW	1 W	50 mW
UNIFORMITY/OPTICAL QUALITY:	λ /10	λ /10	λ /10	λ /10
AREA:	4 cm^2	10cm^2	10 cm^2	100 cm^2
HIGH DIFFRACTION EFFICIENCIES:				

NOTES:
1. RECONFIGURATION AFTER COMPLETION OF 10's OF OPS/BIT
2. SWITCHING WITHIN CLOCK CYCLE
3. MEDIA PERFORMING I/O AND MEMORY SWITCHING (DEPENDENT ON CHOICE OF ARCHITECTURE)
4. SWITCHING WILL BE ALMOST EVERY FRAME
5. MATERIAL MAY HAVE TO BE MUCH LARGER

Table I
DoD Requirements for Interconnects and Modulators

Other opto–electronic interconnect structures seek to utilize nonlinear optical materials in different ways. The picosecond and sub–picosecond response times of third order materials make four–wave mixing of interest as a switching media for broadcasting to large numbers of processing elements (a variant of global interconnection) in computing systems. Yet the lack of uniformity of response (order of