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OPTICAL SHARED MEMORY SYSTEM DEMONSTRATION MODEL

University of California

Stephen T. Kowel, N. Matloff, C. Eldering, P. Brinkley, T. Schubert, M. Landgraf, R. Gosula

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APPROVED: Robert L. Kaminski

ROBERT L. KAMINSKI
Project Engineer

APPROVED: Raymond P. Urtz Jr

RAYMOND P. URTZ, JR.
Technical Director
Directorate of Command & Control

FOR THE COMMANDER: Igor G. Plonisch

IGOR G. PLONISCH
Directorate of Plans & Programs

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Stephen T. Kowel, N. Matloff, C. Eldering, P. Brinkley,
T. Schubert, M. Landgraf, R. Gosula

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California
Department of Electrical Engineering and Computer Science
Davis CA 95616

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13. ABSTRACT *(Maximum 200 words)*
This report discusses work performed on developing a system in which it is possible to optically read a VLSI memory into another VLSI device. Work was concentrated in the areas of: liquid crystal imaging of horizontal fields in integrated circuits, thin solid film integrated circuit structures for modulating light, simulation of system performance for a number of optically interconnect architectures, and construction of a working demonstration prototype. The construction of a prototype demonstrated that it is possible to image a memory device using the horizontal fields above the integrated circuit. The liquid crystal approach and the thin solid film approach offer possibilities for the construction of a Single Transmitter Multiple Receiver (STMR) System and a Single Transmitter Single Receiver (STSR) System. Both systems offer advantages over electrically interconnect systems and in certain cases will provide a large speedup in computation.

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Optically Shared Memory Demonstration

Final Report

1. Introduction

During the period of this contract work was performed on developing a system in which it is possible to optically read a VLSI memory into another VLSI device. The end goal of this project is to produce a prototype system which demonstrates the ability to optically interconnect VLSI devices.

Work was performed by a number of faculty members and students in the areas of: liquid crystal imaging of horizontal fields in integrated circuits, thin solid film integrated circuit structures for modulating light , simulation of system performance for a number of optically interconnect architectures, and construction of a working demonstration prototype. A paper discussing the approaches to fixed optical interconnects was presented at the 1989 SPIE International Symposium on Optical and Optoelectronic Applied Science and Engineering. This paper also provides the results of simulations showing the speedup advantages for an optically interconnected system. A paper which discusses the use of polymeric electro-optic materials and devices for optical interconnects has been published in a special issue of *Applied Optics* on optical interconnects (*Applied Optics*, vol. 29, no. 8, March 1990). High resolution imaging of the voltage states of a VLSI device using horizontal field modulated nematic liquid crystals was demonstrated and a publication has been submitted to *IEEE Electron Device Letters*. All of the above mentioned publications are included in the Appendix of this report.

Construction of a prototype system was initially delayed due to contractual problems and later due to a delay in the arrival of the optical microscope which is to serve as the basis of the optical system. The detector is a CCD camera which will be used to image the memory which is covered with nematic liquid crystals. As discussed in the attached paper, we have shown that it is possible to image the memory device using the horizontal fields above the integrated circuit. Using the optical system it will be possible to determine the ultimate optical resolution of the liquid crystal and determine if it is possible to image a single memory cell.

The rest of this report includes a summary of the project and a discussion of the design of the prototype system. The papers in the Appendix provide a complete analysis of the system design and function.

2. Project Summary

In less than 25 years the principal challenge in the field of electronics has gone from the integrating dozens of transistors to form logic devices to the challenge of integrating dozens to thousands of processors to form computing systems. The types of concurrent computing systems being built today vary from shared memory multiprocessors, in which several complex processors work on portions of data obtained from a shared memory, to special-purpose systolic architectures in which a large set of cells having simple computational abilities are interconnected. For any of these concurrent systems to achieve significant computing advantages over single processor machines, it is necessary to match the communications network capability to the computational speed of of the processors. Although concurrent computing systems will require an increase in the density of interconnects between integrated circuits, pin limitations of VLSI devices will prohibit the interconnection of large numbers (>1000) of nodes. Optical interconnects offer the possibility of interconnecting many internal nodes of one integrated circuit with the internal nodes of one or more receiving devices. While a variety of optical interconnection schemes for Si devices have been proposed,[1-6] many mimic electrical interconnects in the sense that electrical signals need to be brought to the edge of the device for conversion to an optical signal, through the use of a light emitting or laser diode array bonded to the edge of the chip. Even if such light emitters can be built directly on a Si integrated circuit, it is unlikely that the density of transmitters will be high enough for this interconnection scheme to show a significant numerical advantage over pin interconnections. We have proposed the use of thin film electro-optic materials and devices formed on the surface of Si integrated circuits as a means of modulating an external light source with voltage information from the internal nodes of the device. Illuminating the integrated circuit with an external light source will yield reflected and diffracted light containing the voltage state information of the internal nodes. This information can be imaged onto one or more Si receiving arrays which serve as memories or data processing arrays. For the case of the single transmitter and multiple receivers, a unidirectional optical bus can be formed. For the single transmitter and single receiver, it will be possible to develop a bidirectional optical bus.

In order to realize fixed, free space optical interconnects three parts of the communication system must be developed: the light source and modulator, the imaging system, and the receiving system. The p-n junctions in Si integrated circuits have been shown to exhibit good quantum efficiency in the near infrared,[7] thus construction of optical receivers in Si devices appears feasible. Recent demonstrations of the optical broadcast of global clock signals to VLSI devices with integrated detectors [8] indicates that reception of optical signals in VLSI devices is possible. Imaging can be performed using lenses or holographic optical elements.[9,10,11] Development of holographic interconnects appears promising, as diffraction efficiencies (total received power/total hologram illumination power) of greater than 20% between one source and 5 detectors has been demonstrated.[12]

Development of a light source and modulator compatible with Si integrated circuits is the most difficult of the problems to be solved. Placing light sources on the surface of Si devices is difficult because of the incompatibility of the materials used for light sources with Si. Even if light sources can be integrated into Si VLSI devices, a large density of transmitters will lead to very high electrical power densities at internal nodes of the chip. Electrically addressable spatial light modulators (SLMs) which are compatible with integrated circuits would allow for the placement of the light source external to the chip and utilize modulators which are placed on the surface of the chip for modulation of the incident light. By developing materials and structures which can be placed on the surface of an integrated circuit and modulated by electric fields at the surface, it will be possible to illuminate the integrated circuit and subsequently broadcast an image containing all of the voltage state information in the device. Modulators based on III-V materials have been fabricated [13, 14] but such devices are not directly compatible with Si integrated circuits. Inorganic materials such as $Ba_{0.5}Sr_{0.5}Nb_2O_6$ and PLZT have been found to exhibit large electro-optic coefficients [15, 16] (5600 and 100 pm/V respectively) and although some of these materials are compatible with Si integrated circuit devices, the large relative dielectric constants limit the switching speed of devices built from these materials.

Two promising solutions for developing IC compatible SLMs are the use of ferroelectric liquid crystals or polymeric electro-optic films. Nematic liquid crystals were used to image the voltage states in integrated circuits.[17,18] It may now be possible to use ferroelectric liquid crystals which have a theoretically predicted[19] time response of 10 - 50 ns and a corresponding change in refractive index of 0.1-0.15. Polymeric electro-optic films are a possible solution since they exhibit an electro-optic effect which is primarily electronic in nature and does not fall off in the GHz region. Polymeric electro-optic materials have already been produced [20] with electro-optic coefficients of 12.8 pm/V, which is comparable with inorganic materials [21] such as $LiNbO_3$. Their topographic adhesion and low temperature processing make them inherently compatible with integrated circuits. Although the electro-optic coefficients on the order of 100 pm/V may be obtained in these materials, the induced birefringence would still be insufficient to effectively modulate light effectively in a film only 1-10 μm thick. Resonant structures such as Fabry-Perot etalons can be used to increase the effective path length of the light in the film to obtain greatly increased modulation. In addition the low dielectric constants of these materials will yield structures with relatively low capacitances.

A computing system utilizing fixed interchip interconnects has been proposed in which memory information would be broadcast optically from one memory array to a number of receiving arrays.[22, 23] This system, entitled **OPTIMUL** (OPTical Interconnect for MULtiprocessors) has the potential of eliminating memory contention in multiprocessor systems because it would allow the entire contents of a shared memory to be read simultaneously by a number of remote processors. We refer to this system, as the Single Transmitter Multiple Receiver (STMR) configuration. This system will require imaging optics capable of producing multiple copies of the broadcast image. The fly's eye lens can be used to produce multiple copies of the broadcast image. The amount of incident optical power required to generate photocurrents in the range of 100-200 nA is on the order of Watts/cm^2, thus it would be desirable to use a incoherent, broadband optical source. This configuration thus lends itself to use with a liquid crystal type modulator which requires polarized light for illumination, but poses few constraints on the monochromaticity, collimation, or coherency of the incident light.

The approach thus taken is a two-fold approach which includes work in both liquid crystal covered devices as well as thin solid film systems. For the liquid crystal work integrated circuit devices were coated with nematic liquid crystals. The paper included in the appendix of this report gives the details and shows that adequate modulation can be obtained using liquid crystals. The use of ferroelectric liquid crystals will necessitate further experimentation to determine how to best align the liquid crystals. The thin film approach guarantees sufficient speed but modulating structures need to be improved to obtain sufficient (1-10%) modulation. We have demonstrated a thin film Fabry-Perot modulator based on the linear electro-optic effect. This shows that thin polymeric films can be incorporated into optical structures which are inherently compatible with integrated circuits.

3. Conclusions and Future Work

It has been shown that the liquid crystal approach and the thin solid film approach offer possibilities for the construction of single transmitter multiple receiver (STMR) system and a single transmitter single receiver (STSR) system respectively. From a computing speed perspective, it has been shown that both systems offer advantages over electrically interconnect systems and in certain cases will provide a large speedup in computation.

An existing microscope at UCD has been used to study the modulation of the liquid crystal on the surface of an integrated circuit, as shown in the attached paper. Under the tasks outlined for the current contract, a new microscope system has been purchased and will be modified for studying the possibility of resolving individual memory cells. It will be possible to modify the optical system of the microscope to provide distribution of the memory information to multiple receivers, thus demonstrating reception at multiple locations. An existing CCD camera will be used for reception and will be multiplexed between the two locations for demonstration purposes.

Looking towards a continuation of this effort, a preliminary design for a dual-photodiode receiving array has been finished. This chip will be fabricated using the MOSIS integrated circuit prototype system, and will consist of an array of balanced receivers (the receiver is described in the attached papers) and a number of test structures for both liquid crystal and thin solid film modulation. Using this chips is should be possible to demonstrate a point-to-point interconnect using Si integrated circuit devices. It will also be feasible to study the optical power requirements (optical light budget) for a point-to-point system. If suitable optics (e.g. fly's eye lens) are developed it will be possible to demonstrate a single transmitter multiple receiver (STMR) system.

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Appendices

PUBLICATIONS PRODUCED DURING THE CONTRACT:

Fixed Optical Interconnects for Concurrent Computing Systems (in *Proceedings of the 1989 International Symposium on Optical and Optoelectronic Applied Science and Engineering*, SPIE vol. 1151, Optical Information Processing Systems and Architectures)

Electro-Optic Polymer Materials and Devices for Global Optical Interconnects (*Applied Optics*, vol. 29, no. 8, 10 March 1990)

High Resolution Imaging of a VLSI Memory Device Using Horizontal Field Modulated Nematic Liquid Crystals (submitted to *IEEE Electron Device Letters*).

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Fixed Optical Interconnects for Concurrent Computing Systems

C.A. Eldering, S.T. Kowel, P. Brinkley, N. Matloff, T. Schubert, R. Gosula
Department of Electrical Engineering and Computer Science
University of California, Davis
Davis, CA 95616

ABSTRACT

Concurrent computing systems are effective only if the data rates to and from processing elements are sufficient to keep the processing elements occupied. The inherent parallelism of optics makes it a natural candidate for information transfer while the existing technology of silicon very large scale integrated (VLSI) circuits is the most suitable for performing computational tasks. In this paper we present the use of fixed optical interconnects for information transfer in electronic based concurrent computing systems. This capability is based on the development of electrically addressable spatial light modulators (SLM's) fabricated as part of integrated circuit devices.

1. INTRODUCTION

In less than 25 years the principal challenge in the field of electronics has gone from the integrating dozens of transistors to form logic devices to the challenge of integrating dozens to thousands of processors to form computing systems. The types of concurrent computing systems being built today vary from shared memory multiprocessors, in which several complex processors work on portions of data obtained from a shared memory, to special-purpose systolic architectures in which a large set of cells having simple computational abilities are interconnected. For any of these concurrent systems to achieve significant computing advantages over single processor machines, it is necessary to match the communications network capability to the computational speed of of the processors. Although concurrent computing systems will require an increase in the density of interconnects between integrated circuits, pin limitations of VLSI devices will prohibit the interconnection of large numbers (>1000) of nodes. Optical interconnects offer the possibility of interconnecting many internal nodes of one integrated circuit with the internal nodes of one or more receiving devices. While a variety of optical interconnection schemes for Si devices have been proposed,[1-6] many mimic electrical interconnects in the sense that electrical signals need to be brought to the edge of the device for conversion to an optical signal, through the use of a light emitting or laser diode array bonded to the edge of the chip. Even if such light emitters can be built directly on a Si integrated circuit, it is unlikely that the density of transmitters will be high enough for this interconnection scheme to show a significant numerical advantage over pin interconnections. We propose the use of thin film electro-optic materials and devices formed on the surface of Si integrated circuits as a means of modulating an external light source with voltage information from the internal nodes of the device. Illuminating the integrated circuit with an external light source will yield reflected and diffracted light containing the voltage state information of the internal nodes. This information can be imaged onto one or more Si receiving arrays which serve as memories or data processing arrays. For the case of the single transmitter and multiple receivers, a unidirectional optical bus can be formed. For the single transmitter and single receiver, it will be possible to develop a bidirectional optical bus. Preliminary results of the performance simulations of two types of optically interconnected systems are presented. These simulations show that a highly parallel optical channel will provide a greater degree of speedup as a function of the number of processors than is presently achieved in multiprocessor systems.

1.1 Communication issues in concurrent computing systems

Communications limitations in concurrent computing systems are attested to by the various contention problems suffered by multiprocessor systems since their inception.[7] These problems have prevented the realization of the ideal linear increase in speed as a function of the number of processors and although solutions have been sought,[8-10] contention for system resources (shared memory, shared memory bus, system wide software, processor bus) still limits system performance. In massively parallel systems with with simple processing elements the communications requirements are such that if restricted to electrical interconnects, wafer-scale and hybrid wafer-scale technologies will be necessary to provide the necessary degree of interconnection.[11] Traditional VLSI packaging technology is limited to on the order of 500 pins per device[12] and thus offers few possibilities for the interconnection of thousands of internal nodes.

1.2 Free space optical interconnects for data transfer

Optical interconnect schemes can be classified as inter- or intra-chip, and the configuration can be classified as fixed or dynamically reconfigurable. While intrachip interconnects offer some speed and fanout advantages, they do not address the pin limitation problem. While dynamic (reconfigurable) interconnects would be the most desirable for the implementation of a number of matrix and signal processing operations,[13] such systems require the development of novel materials for dynamic holograms. Fixed interconnects provide a high density of interconnects and offer the possibility of interconnection from one transmitter to multiple receivers, without requiring a holographic system that can be electrically or optically switched. In addition, if the data is electronically processed and then optically broadcast to a subsequent receiver (as in a cascade or ring network) it will be possible to achieve reconfiguration of the interconnect electronically. Fixed, free space, optical interconnects thus offer the most benefit in terms of system performance and only require one suitable material/device for conversion of the voltage information to optical information. It should be noted that even if switching speeds for these materials or devices are on the order of 100 ns, the transmission of data arrays will result in a very high bandwidth compared to an electrical bus which in which 16-64 bits are transmitted at once. As an example, an array of 1000 elements transmitted in 100 ns to one receiver results in an effective data transfer rate of 100GBits/s. This represents the minimum density for which optical interconnects offer a clear advantage. The effective data rate to the receiving array is orders of magnitudes higher than could be achieved with electrical interconnects.

In order to realize fixed, free space optical interconnects three parts of the communication system must be developed: the light source and modulator, the imaging system, and the receiving system. The p-n junctions in Si integrated circuits have been shown to exhibit good quantum efficiency in the near infrared,[14] thus construction of optical receivers in Si devices appears feasible. Recent demonstrations of the optical broadcast of global clock signals to VLSI devices with integrated detectors [15] indicates that reception of optical signals in VLSI devices is possible. Imaging can be performed using lenses or holographic optical elements.[16,17,18] Development of holographic interconnects appears promising, as diffraction efficiencies (total received power/total hologram illumination power) of greater than 20% between one source and 5 detectors has been demonstrated.[19]

Development of a light source and modulator compatible with Si integrated circuits is the most difficult of the problems to be solved. Placing light sources on the surface of Si devices is difficult because of the incompatibility of the materials used for light sources with Si. Even if light sources can be integrated into Si VLSI devices, a large density of transmitters will lead to very high electrical power densities at internal nodes of the chip. Electrically addressable *spatial light modulators* (SLMs) which are compatible with integrated circuits would allow for the placement of the light source external to the chip and utilize modulators which are placed on the surface of the chip for modulation of the incident light. By developing materials and structures which can be placed on the surface of an integrated circuit and modulated by electric fields at the surface, it will be possible to illuminate the integrated circuit and subsequently broadcast an image containing all of the voltage state information in the device. Modulators based on III-V materials have been fabricated [20, 21] but such devices are not directly compatible with Si integrated circuits. Inorganic materials such as $Ba_{0.5}Sr_{0.5}Nb_2O_6$ and PLZT have been found to exhibit large electro-optic coefficients [22, 23] (5600 and 100 pm/V respectively) and although some of these materials are compatible with Si integrated circuit devices, the large relative dielectric constants limit the switching speed of devices built from these materials.

Two promising solutions for developing IC compatible SLMs are the use of ferroelectric liquid crystals or polymeric electro-optic films. Nematic liquid crystals were used to image the voltage states in integrated circuits.[24,25] It may now be possible to use ferroelectric liquid crystals which have a theoretically predicted[26] time response of 10 - 50 ns and a corresponding change in refractive index of 0.1-0.15. Polymeric electro-optic films are a possible solution since they exhibit an electro-optic effect which is primarily electronic in nature and does not fall off in the GHz region. Polymeric electro-optic materials have already been produced [27] with electro-optic coefficients of 12.8 pm/V, which is comparable with inorganic materials [28] such as $LiNbO_3$. Their topographic adhesion and low temperature processing make them inherently compatible with integrated circuits. Although the electro-optic coefficients on the order of 100 pm/V may be obtained in these materials, the induced birefringence would still be insufficient to effectively modulate light effectively in a film only 1-10 μm thick. As will be discussed, resonant structures such as Fabry-Perot etalons can be used to increase the effective path length of the light in the film to obtain greatly increased modulation. In addition the low dielectric constants of these materials will yield structures with relatively low capacitances.

A computing system utilizing fixed interchip interconnects has been proposed in which memory information would be broadcast optically from one memory array to a number of receiving arrays.[29, 30] This system, entitled **OPTIMUL** (OPTical Interconnect for MULtiprocessors) has the potential of eliminating memory contention in multiprocessor systems because it would allow the entire contents of a shared memory to be read simultaneously by a number of remote processors. In this paper we refer to this system, illustrated in Figure 1a, as the Single Transmitter Multiple Receiver (STMR) configuration. This system will require imaging optics capable of producing multiple copies of the broadcast image. The fly's eye lens can be used to produce multiple copies of the broadcast image. As will be shown, the amount of incident optical power required to generate photocurrents in the range of 100-200 nA is on the order of Watts/cm^2, thus it would be desirable to use a incoherent, broadband optical source. This configuration thus lends itself to use with a liquid crystal type modulator which requires polarized light for illumination, but poses few constraints on the monochromaticity, collimation, or coherency of the incident light.

Another possible configuration is the Single Transmitter Single Receiver (STSR) configuration as illustrated in Figure 1b. In this configuration a single transmitting array is coupled to a single receiving array by means of either a simple lens or holographic optical element. The advantage of this configuration is that if a collimated beam is used as a source of illumination and the modulating elements are good specular reflectors, the reflected beam can be collected quite efficiently. If the aperture of the reflecting elements and spacing between them is much greater than the wavelength of the incident light the diffraction from the array is minimal and a lens placed a few cm above the device can collect greater than 75% of the reflected light. If etalon structures are used as surface thin film modulators, it is necessary to illuminate them with quasi-monochromatic light at a specific angle to obtain modulation of the reflected beam. Depending on the finesse of the structure there is also a requirement on the coherency of the light. The STSR configuration appears to be best suited for use with surface modulators requiring well collimated monochromatic sources. This interconnect can be made to be bidirectional, if sources and detectors can be integrated on the same device. It is also possible to form cascading or ring networks in which data is rebroadcast from the receiving device. If the data is electronically rearranged before transmission to the subsequent device it will be possible to use the ring as a reconfigurable interconnect.

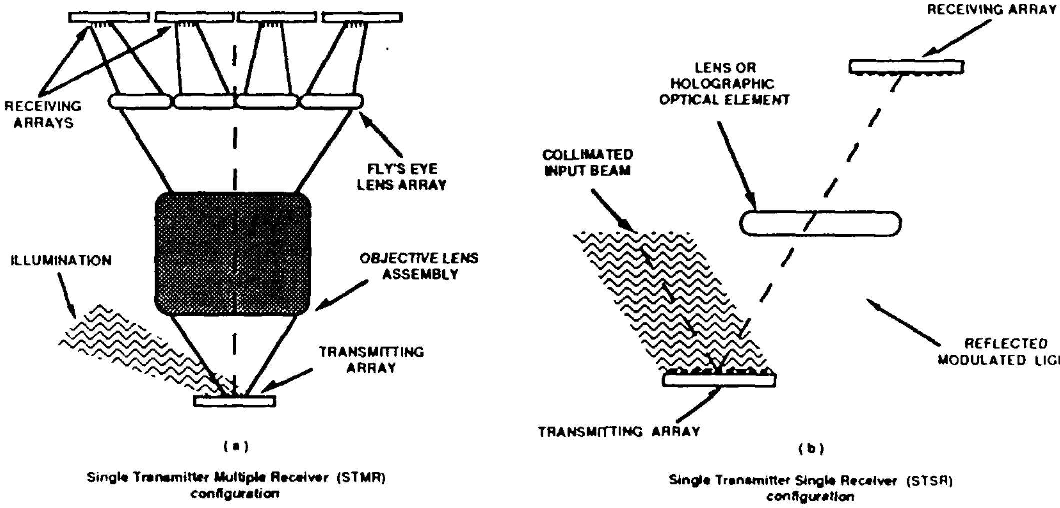

Figure 1. Single and multiple receiver configurations for optical interconnects between VLSI devices.

2. INTEGRATED CIRCUIT COMPATIBLE SPATIAL LIGHT MODULATORS

2.1 Ferroelectric liquid crystal approach

To realize integrated circuit compatible spatial light modulators, a fast electro-optic material with a large electro-optic coefficient is needed. Current SLMs using liquid crystals offer high contrast ratios but low speed (e.g. 100 µsec response times). These devices use nematic or cholesteric liquid crystals that align along the direction of an applied field due to interaction between the molecular anisotropy and the applied field. These molecules are large and have a high viscosity that limits their speed. Recently, ferroelectric liquid crystals have been used in electro-optic devices. Using surface stabilized ferroelectric liquid crystal (SSFLC) devices, bistable operation has been demonstrated with microsecond and submicrosecond response times. The bounding surfaces have been treated such that the ferroelectric liquid crystals have a macroscopic electric dipole that interacts with the applied field to provide polarity sensitive response and a larger torque on the individual molecules compared with traditional liquid crystals,[31] hence these ferroelectric liquid crystals have faster response times than nematic and cholesteric liquid crystals. Currently response times of 500 ns - 20 µs are being reported in the literature [31-34] With continued materials improvement it is probable that the theoretical time response limit (~ 50 ns) will be reached as it has been with nematic liquid crystals. The contrast ratios of a single SSFLC cell have been reported[33] to be 1000:1, and a matrix SSFLC device demonstrated a contrast ratio of 200:1.

One of the attractive features of the SSFLC structure is that the system is bistable.[35, 36] Once switched to either state, the voltage may be removed and the ferroelectric liquid crystals remain for hours in the switched state. The structure is similar to CMOS devices, since the FLC devices consume power only during switching. The power consumption of the device is then dependent upon the frequency of switching and the power to switch states. Warmer temperatures do not detract from the performance since the viscosity of the liquid crystal decreases with increasing temperature and the optical rise time is proportional to the viscosity. The temperature cannot be increased arbitrarily since the ferroelectric property of the liquid crystal exists within a narrow temperature range.

2.2 Polymeric electro-optic film approach

The production of molecules having large hyperpolarizabilities [37, 38] has resulted in the development of electro-optic organic crystals.[39] Optically nonlinear chromophores were subsequently used to form mixtures with polymers which could be poled to form noncentrosymmetric materials which have the mechanical and chemical robustness of plastic and exhibit a large, permanent linear electro-optic effect. [40] Parallel plate poling may be used to produce a permanent ordering, although our group has shown that corona onset poling at elevated temperatures (COPET) produces a higher degree of order with greater long term stability.[41,42] We have also employed the Langmuir/Blodgett technique to produce noncentrosymmetric films in which second harmonic generation [43,44] and the linear electro-optic effect [45] can be observed.

2.2.1 Electro-optic thin film etalons

If polymeric films 1 µm thick having electro-optic coefficients of 10 pm/V are deposited on an integrated circuit, local electric fields of 10^6 V/m will produce changes in the index of refraction of $\Delta n = 10^{-5}$. If the film has an index of 1.52 the electrically induced phase shift of 0.9 µm wavelength light making a single pass through the film will be 0.12 mrad. If the phase modulation is converted to amplitude modulation (by interferometric means or through the use of polarization modulation converted to amplitude modulation) the resulting amplitude modulation will be less than 0.02 % of the incident beam. Resonant structures such as Fabry-Perot etalons,[46,47] Gires-Tournois etalons [48] or modulated multilayer dielectric reflectors [49] will be necessary to produce sufficient modulation (1-10%) using the range of voltages (2-7 V) available at electrodes on the surface of VLSI circuits. We have fabricated Fabry-Perot etalons from thin films of poled polymer/dye mixtures between thin film metal mirrors to observe and characterize the electro-optic effect.[50] These results indicate that it will be possible to develop architectures in which the electro-optic effect is greatly enhanced by the resonant cavity.

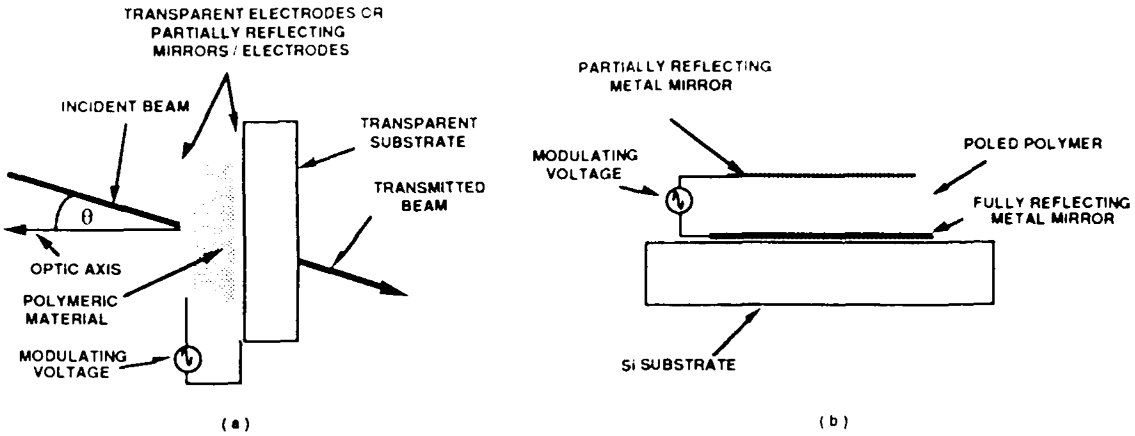

Figure 2. Transmission mode modulator/etalon and reflection mode etalon.

To show how a resonator increases the modulation of light for an electro-optic material, we consider a longitudinal electro-optic modulator constructed from an electro-optic thin film, as shown in Figure 2. The material is considered to be uniaxial and oriented such that the optic axis is in the direction of the film surface normal. For normal incidence the half-wave voltage which produces a phase shift of π radians is given by [51]

$$V_\pi = \frac{\lambda}{2n_o^3 r_{13}} \tag{1}$$

where n_o is the ordinary index of refraction, r_{13} is the electro-optic coefficient, and λ is the wavelength of the incident light. The longitudinal modulator produces phase modulation of the incident light; an appropriate interferometric setup is necessary to convert the phase modulation to amplitude modulation. For a material with r_{13} = 10 pm/V, n_o = 1.52 and λ = 0.9 μm the half wave voltage for normal incidence is 12.81 kV. If the modulation is converted to amplitude modulation, we can define an amplitude modulation depth as

$$\Delta = \pi \frac{V_m}{V_\pi} \tag{2}$$

where V_m is the modulating voltage. A simple optical resonator, the Fabry-Perot etalon, can be constructed if the transparent electrodes shown in Figure 2 are fabricated as partially reflecting mirrors. In the case of a Fabry-Perot modulator the modulation depth is increased to

$$\Delta_{(FP)} = N \frac{V_m}{V_\pi} \tag{3}$$

where N is the finesse of the cavity. The cavity can be tuned to obtain maximum modulation by electrical bias, wavelength tuning, or rotation. The resulting modulation is direct amplitude and thus no external polarizers are necessary. In addition, the modulation depth is increased by a factor of N/π. Thus if a modulation voltage of 100 volts is necessary to produce 10% modulation of the light in the case of a longitudinal phase modulator, a Fabry-Perot modulator having a finesse on the order 30 will directly amplitude modulate 10% of the light with a modulating voltage of 10 volts. Thus we see that the Fabry-Perot etalon increases effective modulation and converts phase modulation to amplitude modulation.

2.2.2 Experimental results

Polymeric Fabry-Perot etalons were used to demonstrate the ability to interconnect two points optically, as shown in Figure 3. The optical source used was a HeNe laser and polarizer which provided an incident power of 2.1 mW. The modulator was a Fabry-Perot etalon fabricated using sputter deposited Au mirrors and a spun-cast azo-dye / poly(methyl methacrylate) (PMMA) mixture, 2 μm thick, which was heated to 127 °C and poled using an electric field of 5 (10^7) V/m. The devices had areas of $1 cm^2$ and capacitances of 1.5 - 2.0 nF. The finesse of the structures was approximately 12. Fabrication and characteristics of these devices are discussed elsewhere.[50] Transverse magnetic polarization was used, as this provides coupling to the largest component of the electro-optic tensor of the poled polymer film. The approximate electro-optic coefficient of the polymeric material used in this experiment (at an angle of incidence of 33°) was r_{eff} = 0.5 pm/V. An AM signal consisting of a 1 MHz carrier, 10 volts peak-to-peak, modulated with a 1 kHz square-wave tone was applied across the etalon, which was angle tuned to an angle of 33° to obtain maximum modulation of the optical beam. The receiver was a reverse-biased Si photodiode which generated photocurrent into a 50 Ω load. Figure 4 shows the transmitted and recovered audio signal. The transmission of information on a 1 MHz carrier shows the ability to modulate these devices at frequencies above the audio range.

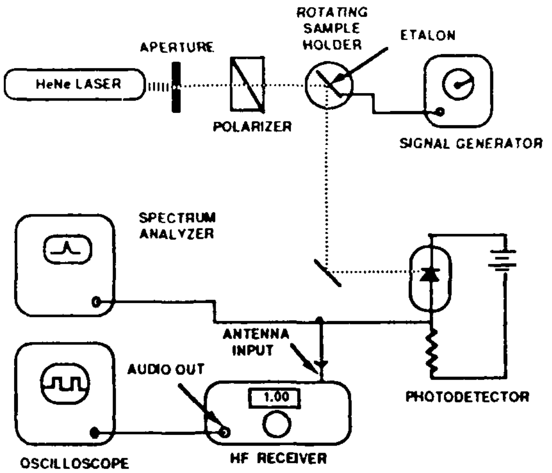

Figure 3. Experimental setup for demonstration of optical interconnection using a thin film etalon.

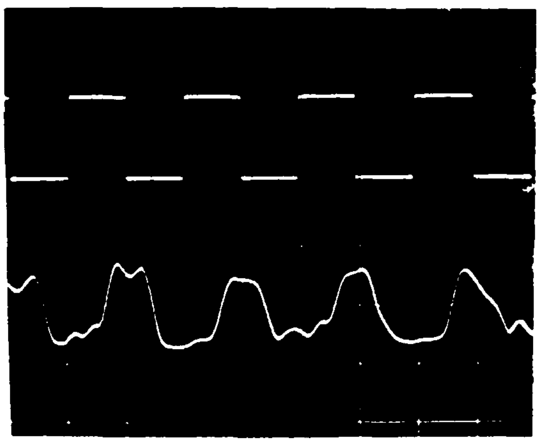

Figure 4. Photo of received signal. Scale of vertical axis is 2 V/div and horizontal axis is 500 μs/div.

3. SYSTEM REQUIREMENTS AND LIGHT BUDGET

If a modulator and light source are developed using either the liquid crystal or polymeric thin film etalon approach, it is possible that only partial modulation of the reflected/diffracted beam will be obtained. While this represents a loss of the incident optical power, it is still possible to transfer data using a differential detection system. A dual-detector can be formed by placing two reverse-biased photodiodes in series; the unmodulated portion of the signal generates a DC photocurrent which is excluded from the detection circuitry. Such receivers have been proposed and constructed for coherent fiber optic communications systems.[52] A differential detection/reception scheme is shown in Figure 5.

In order to determine the photocurrent I_{ph} generated at a receiving cell it is necessary to consider the efficiency of modulation, diffraction losses and imaging system losses (C_d and C_i respectively), and the detector responsivity R. An expression relating the generated photocurrent per receiving cell as a function of the incident illuminated power density P_0 is

$$I_{ph} = \frac{P_0 \, A \, C_d \, C_i \, m \, R}{n_r} \tag{4}$$

where A is the area of the receiving cell and n_r is the number of receiving arrays, and m is the modulation efficiency. Figure 6 illustrates calculations for both the STMR and STSR configurations.

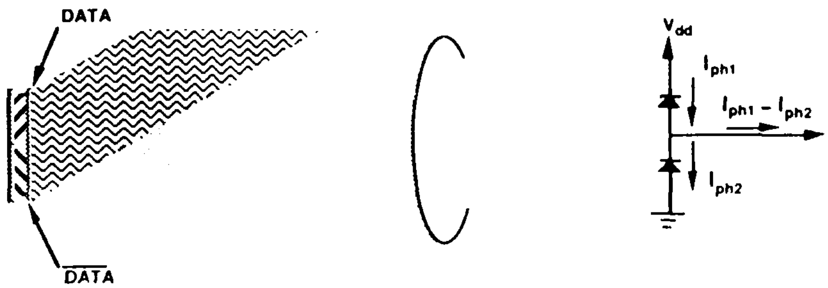

Figure 5. Differential detection scheme.

We note that in the STMR configuration a high degree of modulation (90%) is assumed. In addition, the transmitter area is assumed to be 10^3 μm^2. These values are reasonable is a liquid crystal system is used as the modulator. The diffraction loss factor for this system is assumed to be 0.34, and can be calculated if the source is assumed to be a uniform emitter and the lens has f # = 1.5. From this calculation it can be seen that incident illumination of 10 W/cm^2 will be necessary to generate currents on the order of 100 nA per receiving cell in a system of 64 receiving arrays. This current can then be integrated to recover the transmitted data value.

If we consider the use of etalon structures to form a STSR configuration a much larger transmitter area of 10^4 μm^2 is assumed since the modulation efficiency of the etalons will be much lower than for the liquid crystal systems. In addition, the requirement for quasi-monochromatic and collimated illumination implies that the source power density will be in the range of mW/cm^2 . From the calculation shown we see that with an incident power densities of 100 mW/cm^2 and a modulation efficiency of 10% it is possible to generate photocurrents on the order of 200 nA per receiving cell.

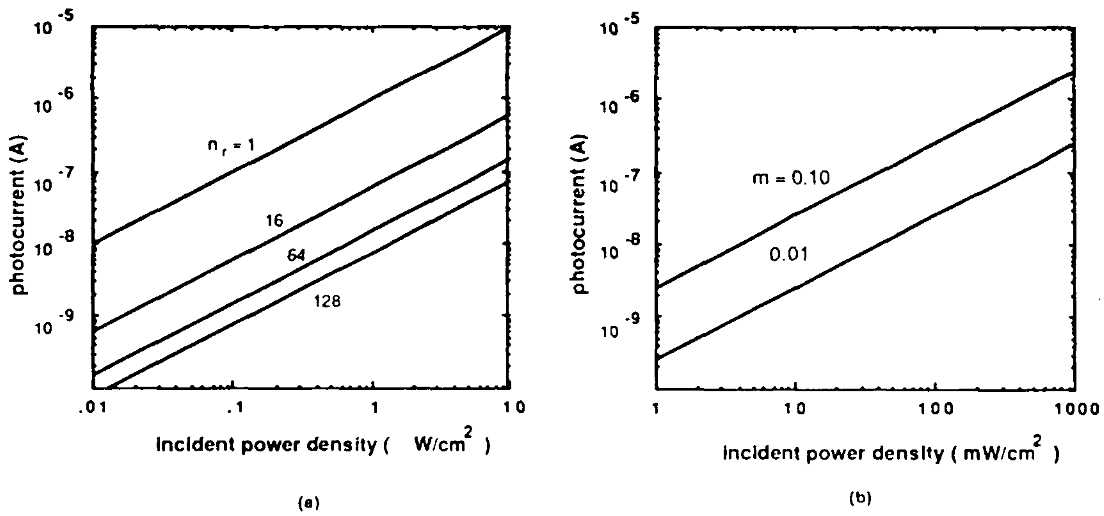

Figure 6. Generated photocurrent as a function of incident optical power for STMR and STSR configurations.

4. POTENTIAL ADVANTAGES OF OPTICALLY INTERCONNECTED SYSTEMS

4.1 Optically shared memory using a STMR configuration

Simulation were performed to compare the electrical single bus and crossbar networks to the STMR configuration. The simulation determined the effect of different connection networks on a simple problem of adding 256 numbers executing on a 16 processor system. This problem requires 84% reads and 16% writes to memory and thus serves as a reasonable benchmark. The results, shown in Table 1, compare the contention cost to access shared memory for single bus, crossbar and the STMR optical configuration. The STMR system uses a shared bus to perform writes to shared memory. It should be noted that in this simulation there is no transmission cost associated with the crossbar. This greatly underestimates the true costs of a crossbar and thus implies performance closer to the ideal performance than can actually be achieved. Nevertheless, the STMR configuration shows almost ideal performance (ideal being no contention cost for shared memory) indicating that there is a significant advantage over the crossbar interconnect.

4.2 Optically interconnected ring network using STSR configuration

A ring network of processors optically interconnected using the STSR configuration was simulated. Each processor in the ring was assumed to provide the power of a VAX 8600 processor. The size of the problem was varied from 16K to 256K integer arrays (1 integer = 32 bits) on systems consisting of 2 to 128 processors. The transfer time for the data array (processor to processor) was 500 ns. The data transfer rate used for the conventional electronic ring was 50 Mbits/s. The results for sorting a 128K integer array are shown in Figure 8. The results show that the optically interconnected system achieves a performance level which is much closer to ideal than the conventional electronically interconnected system. We note that in this simulation a relatively large data array (4 MBits) and long transfer time (500 ns) was assumed. Systems fabricated using etalon technology may not initially achieve this density of interconnects but the overall data transfer rate (8 TBits/sec) is still reasonable for an optical interconnect technology.

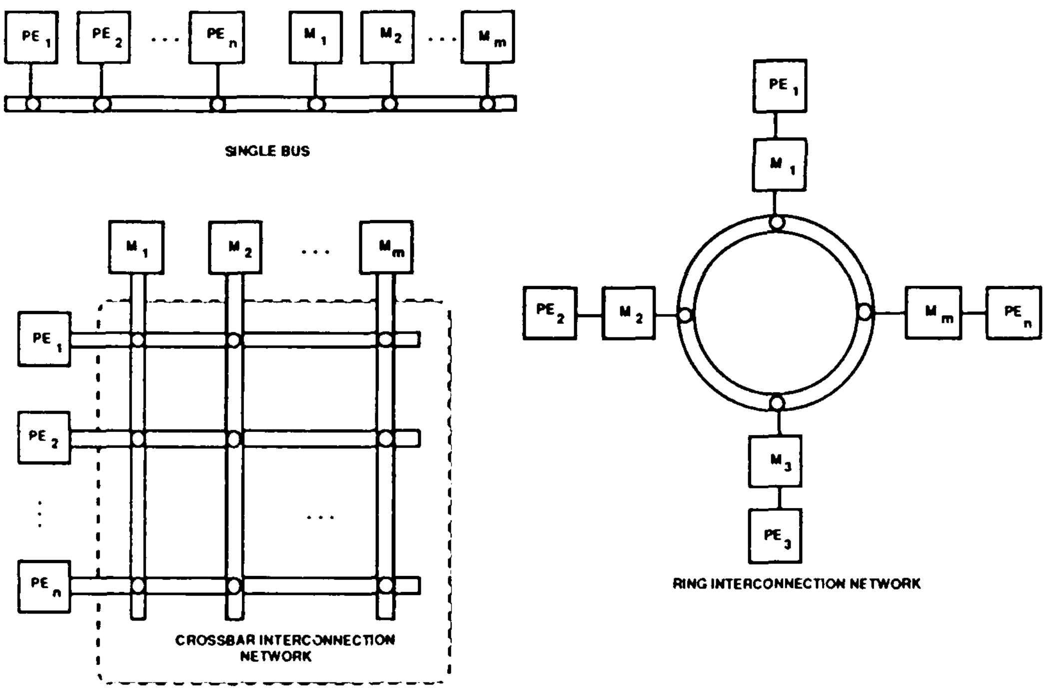

Figure 7. Connection networks.

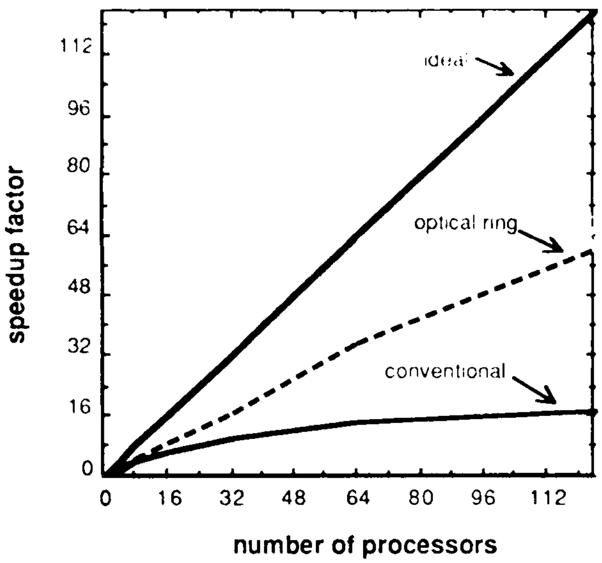

Table 1
Comparison of Connection Networks

Connection Network	Ratio - to - Ideal
STMR (OPTIMUL)	1.07
Crossbar	1.37
Single Bus	2.15

Figure 8. Speedup as a function of the number of processors.

5. CONCLUSIONS

Of the existing possible approaches to developing optical interconnects for Si VLSI circuits the use of ferroelectric liquid crystals and polymeric etalons appear to be realizable in the near future. Ferroelectric liquid crystals offer switching speeds as low as 50 ns and a high degree of birefringence but surface structures and preparation techniques need to be developed to produce effective modulators on the surface of integrated circuits. Polymeric electro-optic thin films, if incorporated into etalon structures, can be used to produce surface spatial light modulators which will be limited in speed only by the structure capacitance. Since it is likely that only partial modulation of the reflected and diffracted light will be obtained with either of these techniques, it will be necessary to use a differential form of detection to recover the transmitted signal. The benefit in developing optical interconnects of this nature will be the ability to transmit large amounts of data from the internal nodes of integrated circuits. The capability can be used to meet the high bandwidth requirements of concurrent computing systems which cannot be met adequately by purely electronic means.

6. ACKNOWLEDGEMENTS

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Electrooptic polymer materials and devices for global optical interconnects

Charles A. Eldering, Stephen T. Kowel, M. A. Mortazavi, and P. F. Brinkley

Global optical interconnects can provide high data rate parallel communication capability through access to the internal nodes of very large scale integrated circuits. Topographic arrays of polymeric electrooptic multilayer devices such as etalons or multilayer mirrors broadcast the data stored on the surface of the chip. Differential detection of this image permits interconnection without the need for high contrast ratios. An experimental demonstration of a point-to-point interconnection using a Fabry-Perot etalon with a polymeric thin film spacer is presented.

I. Introduction

A. General

Free-space optical interconnects offer an attractive alternative to electrical interchip and intrachip linkage because they allow for the interconnection of many thousands of internal circuit nodes. A computing system utilizing fixed interconnects has been proposed in which memory information is broadcast optically from one memory array to a number of receiving arrays.[1,2] This system, optical interconnect for multiprocessors (OPTIMUL), has the potential of eliminating memory contention for reads in multiprocessor systems because it allows the entire contents of a shared memory to be read simultaneously by a number of remote processors. We consider the more basic problem of free-space point-to-point optical interconnects which link the internal nodes of a single transmitting device to the corresponding nodes of a receiving device. Ultimately, if a very large density of interconnects can be achieved, large amounts (>1 Mbyte) of memory information could be optically broadcast to multiple locations.

We discuss the basic requirements of the optical communication link between two integrated circuits and show that polymer materials and devices offer a solution to the problem of developing spatial light modulators physically integrated with semiconductor devices. The fundamental properties of polymeric nonlinear optical materials are reviewed, and the use of polymer-based etalons as modulating structures is presented. The use of differential transmission and reception alleviates the necessity for full modulation of the optical signal. A simplified analysis of a unidirectional channel is used to calculate the generated photocurrent in the receiving device as a function of the input optical power. This calculation demonstrates that current polymer materials can provide adequate performance if utilized with a multiple-pass structure. Finally, we describe an experimental point-to-point optical interconnect using a thin film Fabry-Perot etalon.

B. Background

The growing complexity and density of Si very large scale integrated (VLSI) circuits are providing greater electronic computing power but at the same time place greater requirements on interchip and intrachip communication capabilities. In particular, pin limitations (number of pins available and attendant clock skew due to long routing distances) place constraints on the data transfer between devices. Although it has been claimed that excessive IO requirements can be avoided by functionally partitioning circuits,[3] the growing trend toward distributed computing[4-6] indicates that more interchip communication, and not less, will be necessary.[7] An analysis of VLSI packaging technology confirms that even using packaging techniques such as hermetic chip carriers and pin grid arrays, extending the number of electrical connections beyond 400, poses a number of problems in terms of both manufacturing and performance.[8] Intrachip communications are also an important issue in VLSI design,

The authors are with University of California, Davis, Department of Electrical Engineering & Computer Science, and the Organized Research Program on Polymeric Ultrathin Film Systems, Davis, California 95616.

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and although pin limitation problems are avoided by integrating many components of a computing system onto one chip, the routing of interconnects remains a problem. Wafer scale integration[9] may alleviate the routing problem but cannot solve it. Multilevel metallization systems are a partial solution but do not resolve the problem of electrical loading in long interconnects.

Free-space optical interconnects have been recognized as one possible solution to the interconnect problem in electronic computing systems.[10-15] While dynamic (reconfigurable) interconnects would be the most desirable for the implementation of a number of matrix and signal processing operations,[16] such systems require the development of novel materials and devices for dynamic holograms. Fixed interconnects would provide a high density of interconnects and offer the possibility of interconnection from one transmitter to multiple receivers without requiring a holographic material that can be electrically or optically switched. In addition, topographic electrooptic thin film devices could play an important role in reconfigurable systems, eliminating the requirement for emitters such as GaAs laser diodes bonded to either the surface or the edge of the chip.

Optical interconnects require a light source, modulator, imaging system, and receiving system. Reception can be considered the least difficult of the problems to be solved, since the *pn* junctions in Si integrated circuits show good quantum efficiency in the near IR.[17] Optical detection of globally broadcast clock signals has been proposed and demonstrated, proving that detectors can be integrated into VLSI circuits.[18]

Imaging can be performed using lenses or holographic optical elements.[10,19,20] Development of holographic interconnects appears promising as diffraction efficiencies of >20% between one source and five detectors have been demonstrated.[21]

This leaves the light source and modulation of the source from the surface of the chip as critical problems. Placement of III–V sources on the edges of a chip has speed and fanout advantages compared to electrical interconnects but does not allow interconnection of internal nodes or the reduction of space requirements at the edge of the device. To achieve the interconnection of internal nodes, electrically addressable spatial light modulators on the surface of an integrated circuit serve to modulate the incoming light with the electric fields associated with the stored data. Such modulators permit the placement of the light source external to the chip and affect the broadcast of an image containing all the voltage state information on the surface of the device.

Modulators based on III–V materials have been fabricated,[22,23] but such devices are not directly compatible with Si integrated circuits. Inorganic materials such as $Ba_{0.5}Sr_{0.5}Nb_2O_6$ and PZLT have been found to exhibit large electrooptic coefficients[24,25] (30–5600 pm/V), and, although some of these materials are compatible with Si integrated circuit devices, the large relative dielectric constant (due to their ferroelectric nature) limits the switching speed of devices built from these materials. Silicon compatible light modulators based on ferroelectric liquid crystals may be an intermediate solution, since a spatial light modulator having a switching time of <1 μs has been demonstrated.[26] Ultimate switching times for ferroelectric liquid crystals might be as low as 5 ns. Power dissipation may limit the achievable switching times to the range of 500 ns, but such times still permit data rates of 10 Gbit/s for a 20Kbit array transmitted in parallel.

Since polymeric electrooptic materials have already been produced[27] with electrooptic coefficients of 12.8 pm/V, it is clear that they are competitive with inorganic materials[28] such as $LiNbO_3$. Their topographic adhesion and low temperature processing make them inherently compatible with Si integrated circuits. As discussed in Sec. II, the electrooptic effect in these materials is primarily electronic in nature permitting modulation at rates limited only by electrode capacitance. The lack of strong ionic motion in polymeric materials results in relative dielectric constants which are low (ϵ_r = 3–4), and thus the capacitance of structures fabricated from these materials will permit modulation bandwidths in excess of gigahertz for each array element.

Electric fields on the surfaces of integrated circuits can be quite strong, and horizontal fields may be as large as 10^6 V/m in the region between adjacent electrodes. Special structures may be built to create vertical fields of similar strength. However, even with such strong electric fields, electrooptic coefficients of the order of 10–50 pm/V are not sufficient to provide effective modulation of the reflected light in a film which has a thickness of the order of several wavelengths. Thus multiple pass structures such as Fabry-Perot etalons,[29,30] Gires-Tournois etalons,[31] or multilayer dielectric reflectors[32] will be necessary to produce detectable modulation at the voltages (2–7 V) available at electrodes on the surface of VLSI chips. We have fabricated Fabry-Perot etalons from thin films of poled polymer–dye mixtures between thin film metal mirrors to observe and characterize the electrooptic effect.[33] These results indicate that it is possible to develop structures in which the electrooptic effect is greatly enhanced by the effect of the multiple passes in a resonant cavity.

II. Polymer Electrooptic Materials

The synthesis of molecules having large hyperpolarizabilities[34,35] has resulted in the development of organic crystals[36] with electrooptic coefficients as large as 67 pm/V. Optically nonlinear chromophores were subsequently used to form mixtures of polymers and dyes, which could be poled after spin coating to form noncentrosymmetric materials, which have the mechanical and chemical robustness of plastic and exhibit a large permanent linear electrooptic effect.[37] Parallel plate poling may be used to produce a permanent ordering, although our group has shown that corona onset poling at elevated temperatures (COPET) produces a higher degree of order with greater long term stability.[28,29] We have also employed the Langmuir/Blodgett (L/B) technique to produce noncentrosymmetric films in which second harmonic generation[30,31] and the linear electrooptic effect[32] have been observed.

In the organic materials reported here the optical nonlinearity is primarily electronic in nature. This can be proved by determining the contribution of the electronic term in the electrooptic effect (Pockel's effect) by measurements of the second harmonic generation coefficient and low frequency Pockel's coefficient. Using the notation of Wemple and DiDomenico,[33] we note that the electrooptic coefficient can be considered to have three sources. The electrooptic coefficient can be written as

$$r = r^{X} + r^{s} + r^{e}, \tag{1}$$

where r^{X} is the stress free coefficient, r^{s} is the strain free coefficient, and r^{e} is the electronic coefficient. For crystalline substances the stress-free coefficient can be related to the acoustic mode phonons, while the strain free coefficient can be related to the optic mode phonons.

The electronic contribution to the electrooptic effect for organic materials can be calculated from the expression

$$r^{e}_{ijk} = -4 \frac{d^{SHG}_{kji}}{(n_i^2 n_j^2)_{\epsilon}}, \tag{2}$$

where d_{kji} is a second harmonic generation coefficient and n_{ϵ} is the index of refraction at the second harmonic wavelength. By comparing this value for the Pockel's coefficient with the value measured in the audio frequency range, the electronic contribution to the electrooptic effect can be determined. Table I illustrates this calculation for a number of materials. While for the organic materials the ratio of the electronic Pockel's coefficient to the measured Pockel's coefficient is not highly accurate due to inaccuracies in the measurement of the nonlinear coefficients and estimated indices of refraction, it is clear that the electrooptic effect is primarily electronic in nature for these materials, as opposed to a material like $BaTiO_3$, in which the effect is principally ionic. Calculated electronic Pockel's coefficients for two materials we have prepared by corona-onset poling[38] in which the electrooptic effect has not been measured are also presented to illustrate the potential these materials have as electrooptic films.

Table I. Electronic Contribution to the Electrooptic Effect Calculated from Measured Second Harmonic Generation Coefficients

Substance	$d^{(2\omega)}_{ij}$ (pm/V)	Wavelength λ (μm)	n_0	r^{e}_{ij}	$\frac{r^{e}_{ij}}{r_{ij}}$
α-quartz	$d_{11} = 0.4$	1.06	1.55	0.28	0.97
$LiNbO_3$[a]	$d_{33} = 41$	1.06	2.27	7.16	0.23
$LiTaO_3$[a]	$d_{33} = 19$	1.05	2.18	3.32	0.11
$BaTiO_3$[a]	$d_{31} = 17$	1.05	2.46	2.10	0.003
MNA[b]	$d_{11} = 67 \pm 25$	1.06	2	50	0.95 ± 0.5
PMMA/DR1[c]	$d_{33} = 2.51 \pm 0.5$	1.58	1.52	1.93	0.73 ± 0.2
PMMA/DR1[d]	$d_{33} = 4.5$	1.06	1.52	2.997	
DVC-MMA[e]	$d_{33} = 19 \pm 1.9$	1.58	1.58	12.19	0.68 ± 0.2
COUM/PMMA[f]	$d_{33} = 17 \pm 1$	1.06	1.55	12.5	

Notes. Wavelengths shown are of the fundamental beam in SHG experiments. Calculations are made assuming a dispersion-free index of refraction.

[a] Kaminow and Turner.[27] [d] This work.
[b] Lipscomb *et al.*[35] [e] Singer *et al.*[37]
[c] Singer *et al.*[36] [f] Mortazavi *et al.*[38]
[d,f] Spun-cast followed by corona onset poling at elevated temperatures. [d] The chromophore is disperse red 1 azo dye; [f] It is N-(3-methacryloxyalkyl)-7-diethylaminocoumarin-3-carboxamide, a coumarin dye.

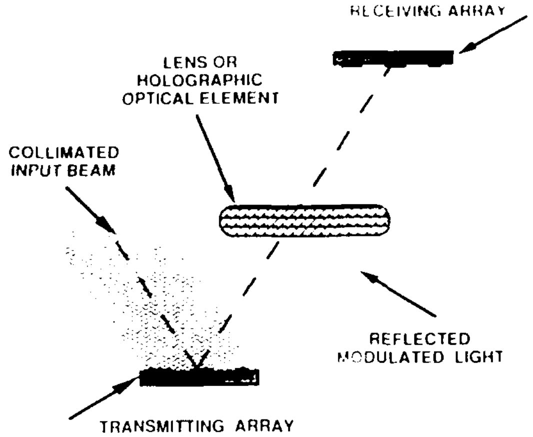

Fig. 1. System diagram for optical interconnection using surface compatible spatial light modulators.

III. System Requirements

Optical interconnection requires a source, modulator, imaging, and reception of the optical signal. Figure 1 illustrates the basic components of an interconnect. We consider the case where electrooptic devices are placed on the surface of the chip, and an external light source provides the optical power to be modulated. The imaging system forms the image of the transmitting array at the surface of the receiving array, which converts the received signal to photocurrent, which can be integrated or used directly as a switching current to recover the transmitted information. We do not consider the imaging system in detail here except to note that if a lens system is used it will be possible to image almost all the collected light onto the surface of the receiver.

A. Modulation

If we consider a longitudinal electrooptic modulator constructed from a poled electrooptic film (in which the optic axis is normal to the film surface), the halfwave voltage (π-rad phase retardation voltage) will be given by[44]

$$V_{\pi} = \frac{\lambda}{2n_{o}^{3}r_{33}}, \tag{3}$$

where r_{eff} is the effective electrooptic coefficient and n_{eff} is the effective index of refraction as determined by the angle of incidence. Figure 2 illustrates this type of modulator, for which external polarizers are necessary to convert the polarization modulation to amplitude modulation. For a material with r_{13} = 10 pm/V, n_0 = 1.52, and λ = 0.9 μm, the halfwave voltage for normal incidence is 12.81 kV. For the case of non-normal incidence, r_{eff} contains a term proportional to the r_{33} component of the electrooptic tensor. Since the r_{33} component is larger than the r_{13} component by a factor of 3–5, the halfwave voltage will be lower than for the case of normal incidence, but the value is still of the order of 10^3–10^4 V. For modulating voltages which are much less than the halfwave voltage we can define the *modulation efficiency* as

$$m = \frac{V_m}{V_\pi} . \tag{4}$$

where V_m is the applied modulating voltage. Combining Eqs. (3) and (4) yields the modulating efficiency as a function of the index of refraction, electrooptic coefficient, wavelength, and modulating voltage:

$$m = \frac{2n_{eff}^3 r_{eff}}{\lambda} V_m. \tag{5}$$

A Fabry-Perot etalon can be constructed if the transparent electrodes shown in Fig. 2 are replaced by partially reflecting mirrors. In the case of a Fabry-Perot modulator, the halfwave voltage is reduced to

$$V_{\pi(F.P.)} = \frac{\lambda}{2n_{eff}^3 r_{eff}} \frac{\pi}{N} , \tag{6}$$

where N is the finesse of the cavity. This assumes that the cavity can be tuned to obtain maximum modulation. This can be accomplished by electrical bias, wavelength tuning, or angle tuning. The resulting modulation is direct amplitude, and thus no external polarizers are necessary. The modulation efficiency for the Fabry-Perot becomes

$$m = \frac{2n_{eff}^3 r_{eff}}{\lambda} V_m \frac{N}{\pi} . \tag{7}$$

It can be seen that the modulation efficiency is increased by a factor of N/π over what is obtained for the longitudinal modulator. If we assume that the modulation efficiency will need to be in the 1–10% range to construct an optically interconnected system, it is possible to determine the cavity finesse requirements given the electrooptic coefficient r_{eff} of the spacer layer. Figure 3 illustrates the required finesse for 1 and 10% modulation efficiencies assuming a modulating voltage V_m = 5 V, index of refraction n_{eff} = 1.52, and wavelength λ = 0.9 μm.

We have constructed[33] simple etalons using sputter deposited Au mirrors and spun-cast polymer films, achieving a finesse of the order of 10. Using dielectric mirrors and transparent electrodes it should be possible to obtain a finesse in the range of 30–300. With an electrooptic coefficient r_{13} = 10 (for normal incidence, $r_{eff} = r_{13}$) and a finesse of 300, the halfwave voltage

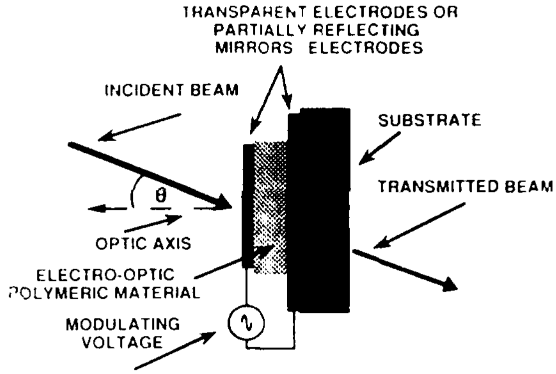

Fig. 2. Configuration for a polymeric longitudinal electrooptic modulator and a Fabry-Perot modulator. For the longitudinal modulator transparent electrodes are used, while for the Fabry-Perot modulator partially reflecting mirrors and electrodes are used. The longitudinal modulator requires external polarizers to convert polarization modulation to amplitude modulation.

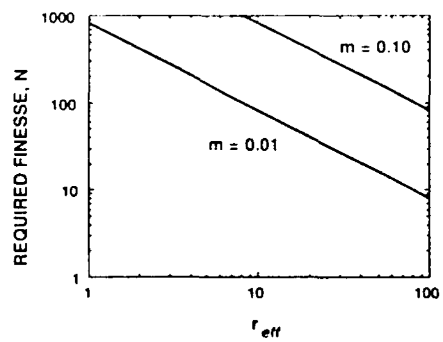

Fig. 3. Required finesse for 1 and 10% modulation efficiencies m as a function of the electrooptic coefficient r_{eff}, assuming a modulating voltage V_m = 5 V, index of refraction n_{eff} = 1.52, and wavelength λ = 0.9 μm.

would be reduced to 134.19 V. From this we conclude that fabrication of high finesse etalons, coupled with modest improvements in materials, will allow the development of devices which can be at least partially modulated with voltages available on the surfaces of integrated circuits.

Reflection mode devices are also possible. The Fabry-Perot device is a suitable modulator since it produces direct amplitude modulation, but to construct a device on top of a Si chip, it is necessary to include the optical properties of the chip surface in designing the back surface mirror. Figure 4 illustrates the Gires-Tournois etalon,[31] which can be used to produce phase modulation. Polarization modulation is also possible if the material in the cavity is sufficiently anisotropic. The idea of using multilayers of electrooptic materials of alternating high–low indices to form a structure whose reflection coefficient can be directly modulated has been proposed[32]; such a structure has the advantage of producing direct amplitude modulation of the reflected beam. Figure 5 shows a

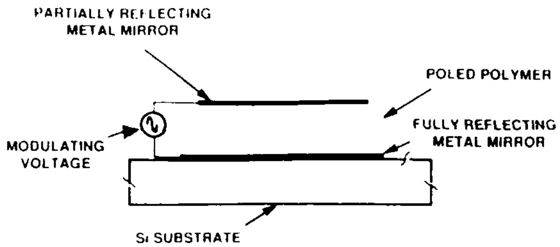

Fig. 4. Gires-Tournois reflection mode etalon.

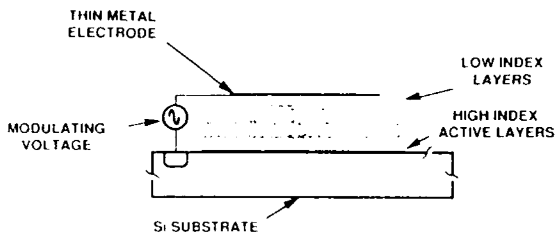

Fig. 5. Modulated multilayer reflecting structure.

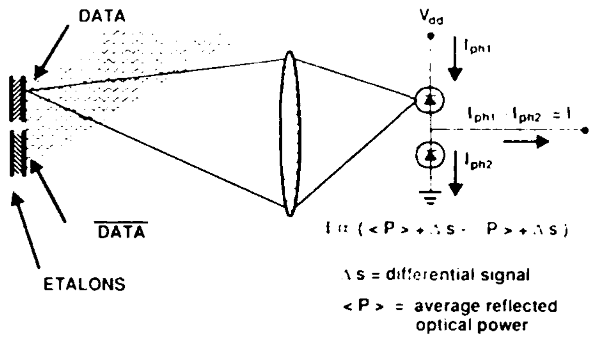

Fig. 6. Differential transmission and reception of data.

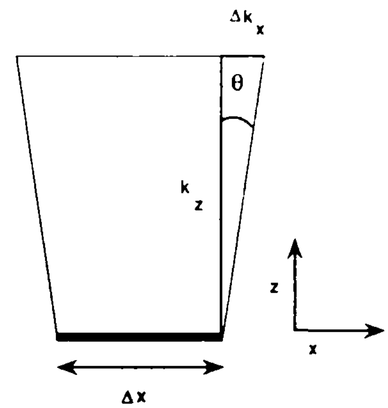

Fig. 7. Calculation of beam spread based on the classical uncertainty principle.

device which could be constructed using spin-on or L/B techniques, provided that materials with sufficiently large differences in indices can be obtained.

In any of these structures the multiple pass effect will serve to reduce the halfwave voltage so that integrated circuit voltages in the 1–10-V range will modulate 1–10% of the reflected beam. Since not all the reflected beam is modulated, it is desirable to transmit either a reference or an antipodal signal along with the data. If the second signal originates from a region which is spatially close to the first transmitter, an additional advantage accrues that variations in the incident beam illumination over the surface of the device will not affect the differentially transmitted signal. Figure 6 illustrates differential transmission of information using the amplitude modulated reflected beams from adjacent transmitters. Detection of differential signals is discussed following considerations of the imaging system.

B. Imaging

The imaging system, in the form of a traditional lens or holographic element, collects a portion of the reflected light and images it onto the corresponding receiver, which converts the optical power to electrical current. We note that for the case of surface IC modulators which range in size from 10×10 to 100×100 μm the diffraction of the reflected beam is small enough that a lens or holographic element with area ≈ 5 cm^2 placed a few centimeters above the device can collect close to 100% of the radiated energy. This can be proved by considering a square radiating aperture of size d, as shown in Fig. 7. The classical uncertainty principle,

$$\Delta k_x \cdot \Delta x \geq {}^1/_2 \tag{8}$$

can be used to obtain the minimum beam angle,[45] which is given by

$$\theta \approx \tan\theta = \frac{\lambda}{4\pi d} \, . \tag{9}$$

Evaluating this expression using $\lambda = 0.9$ μm and $d = 10$ μm shows that the minimum beam angle is $<0.01°$. Based on this, we conclude that, for the case of a specular reflector illuminated by a collimated source, it will be possible to collect at least 75% of the radiated light with a lens or holographic element with an area of 5 cm^2 placed a few centimeters above the device.

C. Reception

Appropriate detection circuitry determines the binary value transmitted and stores this value for subsequent processing. A dual detector can be formed by placing two reverse biased photodiodes in series; the unmodulated portion of the signal generates a dc photocurrent which is not injected into the detection circuitry. Such receivers have been proposed and constructed for coherent fiber optic communications systems.[46] A differential detection/reception scheme is shown in Fig. 6. This effectively deals with the low modulation efficiency and compensates for local variations in sensitivity across the chip.

Error detection and correction need to be considered. Sources of error include misalignment, vibration-induced crosstalk, and photocurrents induced outside the detection regions.

D. Link Budget

Table II illustrates a link budget for an optical interconnect where the transmitter is composed of two adjacent polymeric devices for differential transmission. The area of each transmitter is 100 × 100 μm yielding a total area of 2×10^4 μm^2. For an integrated circuit of 1- × 1-cm area, 1000 transmitters would only occupy 20% of the chip area. The total capacitance for the transmitter pair, using a thickness of 2 μm and relative dielectric constant $\epsilon_r = 4$, is 354 fF. We do not address the issues of drive or receive electronics here but attempt only to show the ability to generate reasonable currents which can be integrated or used directly for switching.

We consider a lens imaging system which has a nominal efficiency of 0.75 for both collection and imaging. With an input power density of 1 W/cm^2 and a modulation efficiency of 0.10, the received optical power is 11.25 μW. Assuming a detector responsivity of 0.45 A/W, the generated signal current is 5.06 μA. It should be noted that the light source is required to have a coherence length of no more than 1 mm even for etalons with finesses approaching 1000; thus a laser is not required for the light source provided a hologram is not used for the imaging.

From this calculation we see that, using a reasonable incident optical power density, switching currents of 5 μA can be generated. While much consideration must be given to the detection circuitry and to issues such as crosstalk and detector noise, it is reasonable to conclude that this current can be integrated to recover the transmitted binary value. The receiver circuitry will determine the time necessary to recover the information; this time can be minimized at the expense of circuit complexity and area. The fact that the receiver need not be placed at the edge of the chip offers great advantages in terms of circuit layout, but complete analysis of the chip function, architecture, and layout is needed to determine the minimum speed of the receiver which would allow effective utilization of the optical interconnect. We note, however, that for an interconnect density of 1000 interconnects/device, a long charge integration time of 100 ns still results in a data transfer rate of 10 Gbits/s. This data rate, coupled with the ability to interconnect internal nodes without routing to the edge of the device, offers a distinct advantage over present electrical interconnects.

Table II. Optical Link Budget

Incident power density P_0	1 W/cm^2	30 dBm cm^{-2}
Transmitter area A	2×10^{-4} cm^2	−36.99 dB cm^2
Modulation efficiency m	0.1	−10.00 dB
Diffraction losses C_d	0.75	−1.25 dB
Imaging losses C_i	0.75	−1.25 dB
Received power P_r	11.25 μW	−19.49 dB m
Detector responsivity R	0.45 A/W	
Generated photocurrent I	5.06 μA	

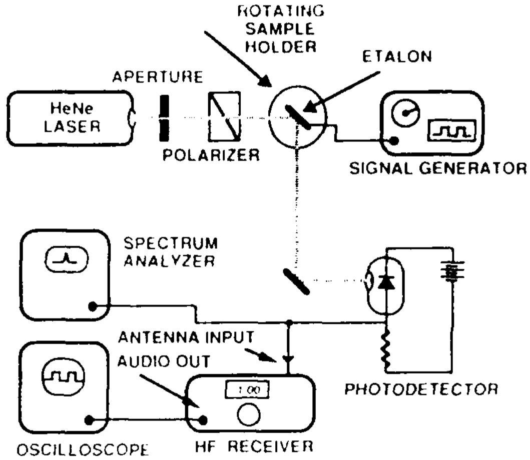

Fig. 8. Experimental setup for the demonstration of signal transmission using a polymeric Fabry Perot etalon.

IV. Demonstration of a Point-to-Point Interconnect

Polymeric Fabry-Perot etalons were used to demonstrate the ability to interconnect two points optically, as shown in Fig. 8. The optical source used was a He–Ne laser and polarizer which provided an incident power of 2.1 mW. The modulator was a Fabry-Perot etalon fabricated on a BK7 glass substrate using sputter deposited Au mirrors and a spun-cast azo dye/polymethyl methacrylate (PMMA) mixture, 2 μm thick, which was heated to 127°C and poled[47] using an electric field of 5×10^7 V/m applied across the gold electrodes. The devices had areas of the order of 1 cm^2 and capacitances in the range of 1.5–2.0 nF. Fabrication and characteristics of these devices are discussed elsewhere.[33] Transverse magnetic polarization was used, as this provides coupling to the largest component of the electrooptic tensor of the poled polymer film. The approximate electrooptic coefficient of the polymeric material used in this experiment (at an angle of incidence of 33°) was $r_{eff} = 0.5$ pm/V. An AM signal consisting of a 1-MHz carrier, 10 V Peak-to-Peak, modulated with a 1-kHz square-wave tone was applied across the etalon, which was angle-tuned to an angle of 33° to obtain maximum modulation of the optical beam. The receiver was a silicon reverse-biased photodiode which generated photocurrent into a 50-Ω load.

Figure 9 shows the received spectra of the optical signal obtained by ac coupling the output from the photodiode circuit to a spectrum analyzer. The observed signal was seen to be independent of frequency up to 1 MHz, the point at which the capacitance of the etalon began to attenuate the modulating signal. Connecting the ac coupled output of the photodiode to the

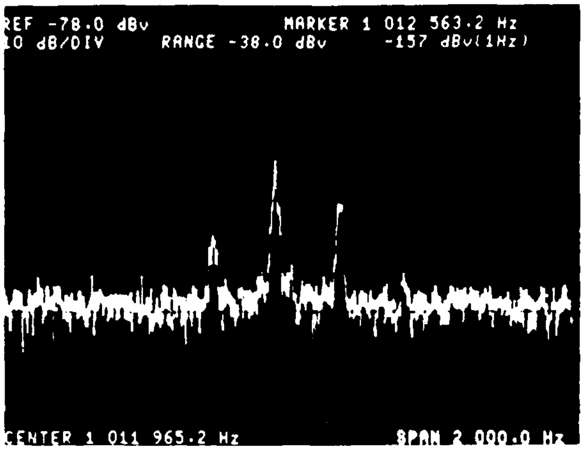

Fig. 9. Received spectra of a signal from the modulated etalon. The signal was a 1-MHz carrier amplitude modulated by a 1-kHz square wave. Sum and difference frequencies of the carrier and fundamental of the square wave are clearly observable.

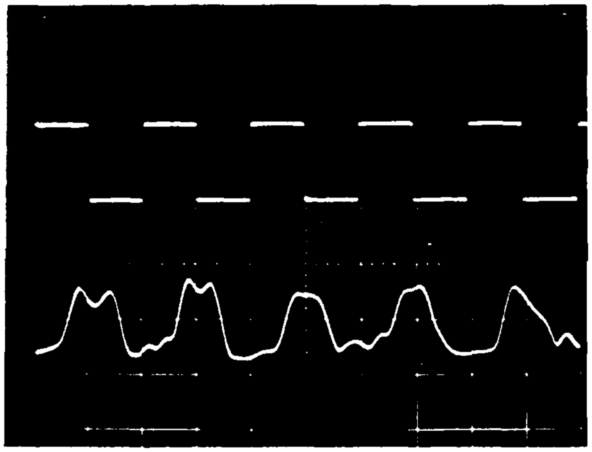

Fig. 10. Oscilloscope photograph of the transmitted (upper trace) and recovered (lower trace) 1-kHz square wave. Vertical scale is 2 V/division, and the horizontal scale is 500 μs/division.

antenna input of a HF radio receiver (ICOM 735) recovered the audio signal. Figure 10 shows the transmitted and recovered audio signal. Repeated experiments offered convincing proof of the robustness of the modulating etalon.

V. Conclusions

We have shown that thin film polymeric electrooptic materials have become competitive with inorganic materials such as $LiNbO_3$ and that the electronic nature of the optical nonlinearity will allow these materials to operate at high modulating frequencies. It will be possible to incorporate these materials into interferometric thin film structures such as Fabry-Perot etalons to obtain halfwave voltages which are much lower than those that can be obtained with single pass longitudinal or transverse electrooptic modulators. Devices fabricated using metal mirrors and parallel plate poled spacer materials were used to demonstrate a free-space optical interconnection between two points. These experiments were very primitive in the sense that lossy metal mirrors and materials having electrooptic coefficients of the order of r_{33} = 1.5 pm/V were used. Nonetheless, it was possible to use such structures for the direct amplitude modulation of an optical beam which could be detected by a simple photodiode. Subsequent development of devices using dielectric mirrors and recently developed corona poled polymeric materials[48] with electrooptic coefficients of the order of 12 pm/V will allow for the construction of prototype Si compatible modulators. This technology appears to be a feasible means of realizing global optical interconnection of 1000, or many more, nodes of Si VLSI circuits. Covering the surface of the chip with an etalon array which senses the electrode fields across the surface to effect modulation promises to provide a flexible, cost-effective, and robust method for optical interconnects. Reconfiguration can be accomplished by data rearrangement within the chip, taking advantage of the large data transmission rates.

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INTERELECTRODE VOLTAGE STATE IMAGING USING HORIZONTAL FIELD MODULATED NEMATIC LIQUID CRYSTALS

by

Marc E. Landgraf, Patrick F. Brinkley, Charles A. Eldering and Stephen T. Kowel*

Department of Electrical Engineering and Computer Science

and

Organized Research Program on Polymeric Ultrathin Film Systems

University of California, Davis

Davis, CA 95616

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*Author to whom correspondence should be addressed

Abstract

We show that the horizontal electric fields between planar electrodes can be used to rotate nematic liquid crystals in the plane of the substrate. The use of horizontal fields for liquid crystal light modulation potentially offers far greater resolution in voltage state imaging than do vertical fields which inherently limit resolution by field meshing. Observation of the orientation of the liquid crystal is performed using electrodes deposited on a glass substrate viewed through a transmission microscope. Imaging of the voltage states on the surface of an integrated circuit using horizontal fields is also demonstrated.

Coating integrated circuits with liquid crystals has been reported as a means of diagnosing electrical and thermal faults in integrated circuits.[1,2,3] Voltage states were optically imaged using vertical electric fields between surface metal electrodes and a glass cover slip electrode which rotated liquid crystals. The resulting change in optical birefringence was made visible by examining the device through crossed polarizers. The use of these vertical fields is indicated in Figure 1, where homeotropically aligned nematic liquid crystals with a negative dielectric anisotropy orient perpendicular to the vertical field between the electrodes and the cover slip. As shown, the electric fields emanating from adjacent electrodes, and thus the regions of liquid crystal alignment mesh together, resulting in a limited resolution of those electrodes.

In this paper, we show that horizontal electric fields between the electrodes may be used to rotate homogeneously aligned nematic liquid crystals. This allows the use of existing electrodes on the integrated circuit, without the need for external electrodes. Because the liquid crystal exhibits positive dielectric anisotropy, the molecule alignment is parallel to the electric field (Figure 2). Thus, horizontal fields align the liquid crystals between electrodes in the plane of the circuit surface, the X-Y plane in Figure 2.

One application of using horizontal fields to rotate liquid crystals in the plane of the circuit surface is in globally optically interconnected systems.[4,5] The transfer of data in such a system would be achieved by imaging the data from the surface of one integrated circuit, the transmitter, onto one or more receiving arrays, which would convert the optical information back into electronic data. With the use of horizontal fields, the imaging of voltage states is done without external electrodes, and the potential for resolution of the imaged electrodes on the surface of the transmitting device is far greater. Resolution with interelectrode horizontal fields is inherently only diffraction limited, whereas with vertical fields the resolution is limited by the meshing above the electrodes.[6]

An electric field between two electrodes causes the liquid crystal director to rotate relative to the input polarization, altering the refractive index as seen by the incoming light. When viewed between crossed polarizers, the output light intensity varies as [7]

$$I = I_0 \sin^2 2\theta \sin^2\left[\frac{\pi \ \delta n \ d}{\lambda}\right]$$

where I = output intensity, I_0 = incident intensity, λ = wavelength of the incident light,
θ = angle between the liquid crystal director and the input polarization,
$\delta n = n_e - n_o$, the liquid crystal optical birefringenc-e, d = thickness of liquid crystal.

As described here, the only intensity variation arises from the angle of rotation of the liquid crystal director, θ. This angle is 0° for no applied field (V = 0V), and 90° when the saturation voltage is reached (V = 5V), given an input polarization in the direction of the Y-axis as shown in Figure 2.

Intensity modulation due to liquid crystal polarization rotation was observed using a transmission microscope with crossed polarizers. The nematic liquid crystal material, Roche RO-TN-623, was spread over a glass substrate with 5μm wide chrome electrodes, separated by 10μm. Without any cover slip over the liquid crystal, electric field induced contrast between electrodes was observed, indicating that the rotation of the molecules is achieved by horizontal, not vertical fields.

Figures 3a and 3b show the metal lines (dark) with and without voltages applied, demonstrating the well defined contrast visible between different orientations of liquid crystal. In the figures shown, a cover slip had been applied to provide uniform thickness, though discernable contrast was noted without the presence of any cover slip.

Using input polarization perpendicular to the initial orientation of the liquid crystal, effects of liquid crystal optic axis rotation in the plane of the electrodes were observed upon application of an electric field. Rotation of the liquid crystal perpendicular to the substrate would not produce contrast in this case.

It was also observed that between closely spaced electrodes (5μm separation) the liquid crystal oriented, without field applied, parallel to the electrodes. However, a cover slip prepared to provide alignment (coated with a thin layer of polyimide and then rubbed) and oriented perpendicular to the electrode direction produced a uniform alignment in the direction of the rub at its surface, the molecules forming a twisted nematic structure through the liquid crystal layer. The occurrence of this twisted nematic configuration was confirmed by rotating the applied cover slip through 90°, and observing the output polarization rotate through the angle of the cover slip rotation. From these experiments it was concluded that horizontal fields can be used for the rotation of liquid crystals having a positive dielectric anisotropy.

Modulation effects were also observed in light reflected from an integrated circuit surface under the microscope equipped with crossed polarizers. Contrast arising from horizontal electric field modulated liquid crystal rotation was clearly observed between second level (top layer) metal lines on the surface of the device.

The integrated circuit used in this study was an AMD Am9114 NMOS 1K x 4 memory array. The ceramic package was opened and the circuit coated with a layer of nematic liquid crystal 10 μm thick, without any special processing or chemical treatment. A glass cover slip similar to the one used in the transmission experiment was used to provide a uniform thickness and a preferential direction of crystal alignment at the cover slip surface. Second level metal lines on the device measure between 3μm and 8μm wide, 1μm high, with minimum separations of 6μm. Voltages applied to second level metal lines generated visible contrast between lines perpendicular and parallel to the cover slip rub. This demonstrates that the liquid crystals align to surface topography, and form the twisted nematic structure between the circuit surface and the cover slip in regions where cover slip rub and electrode direction are perpendicular.

Contrast ratios of up to 1.9-to-1 were measured, even in the regions where the electrodes were separated by only 6μm. Further, the contrast was noted to be a very sensitive function of the electric field strength since the presence of sub-surface lines with voltages applied visibly altered the brightness in the areas where these lines existed. Figure 4a shows the second level metal lines of 4μm width spaced by 6μm, without any signals applied. Voltages are applied in Figure 4b to show enhanced reflection in five interstitial regions. Constant voltages applied to the electrodes produced only transient contrast, possibly due to surface charging,[1,2] though this is not yet clearly understood. Contrast above the electrodes was attributed to the fringing electric fields and the fact that the reflection coefficient of aluminum is three times greater than that of silicon.

The use of horizontal electric fields in the rotation of liquid crystals on the surface of an integrated circuit circumvents the need for external electrodes by making use of existing electrodes, the second level metal lines on the device. This greatly simplifies the processing needed to prepare an integrated circuit for liquid crystal light modulation. With homogeneously aligned positive dielectric anisotropic nematic liquid crystal, rotation of the molecules is in the plane of the circuit and predominantly limited to alignment between electrodes, increasing the potential resolution over that where molecules are aligned above electrodes. Applications that could benefit from this technique include globally optically interconnected systems and liquid crystal displays, as well as other devices that utilize liquid crystal light modulation.

Further work will involve the evaluation of the field patterns and the removal of the passivation to eliminate possible charging. Characterization of the viewing angle and gray level resolution are under way.

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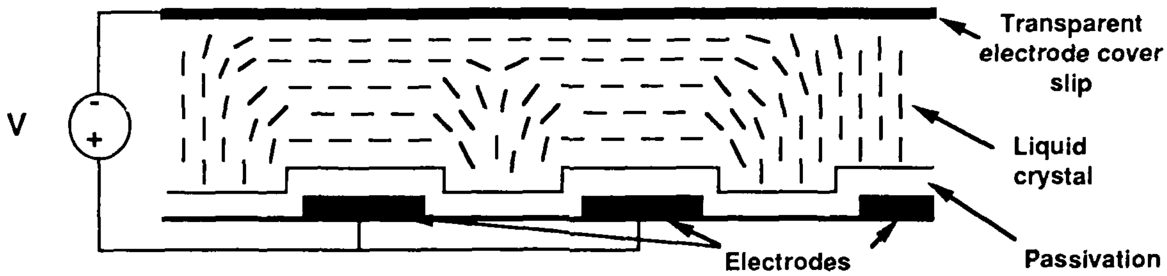

Figure 1. Use of vertical electric fields to align liquid crystals above electrodes. Voltage applied between electrodes and cover slip.

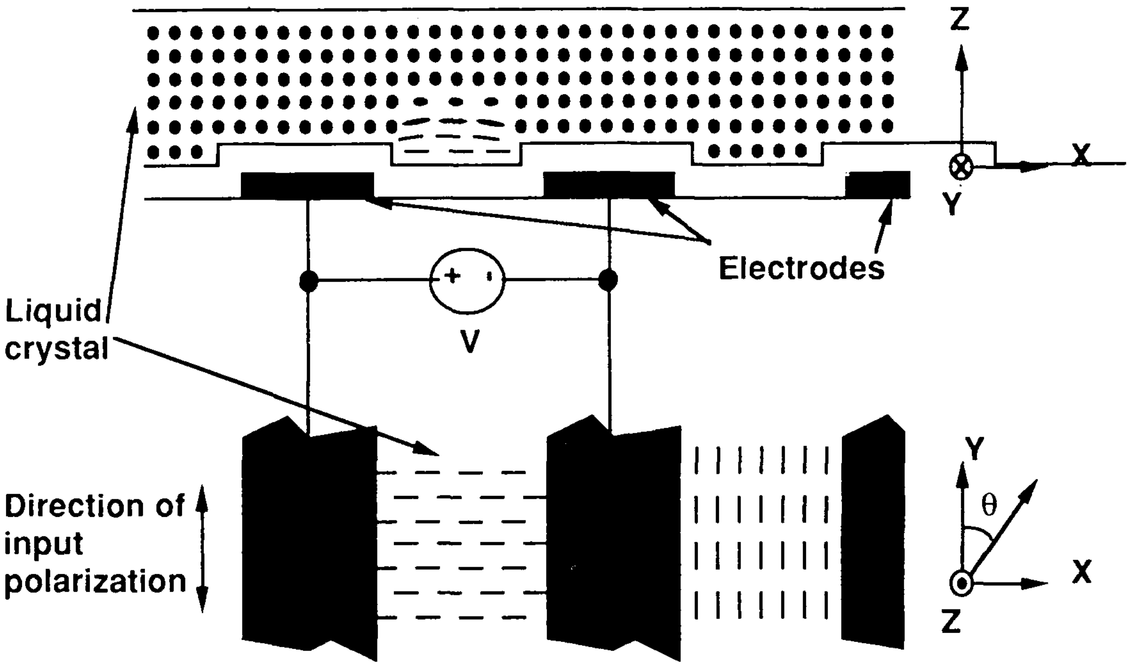

Figure 2. Use of horizontal electric fields to align liquid crystals between electrodes. Voltage applied between first and second electrode.

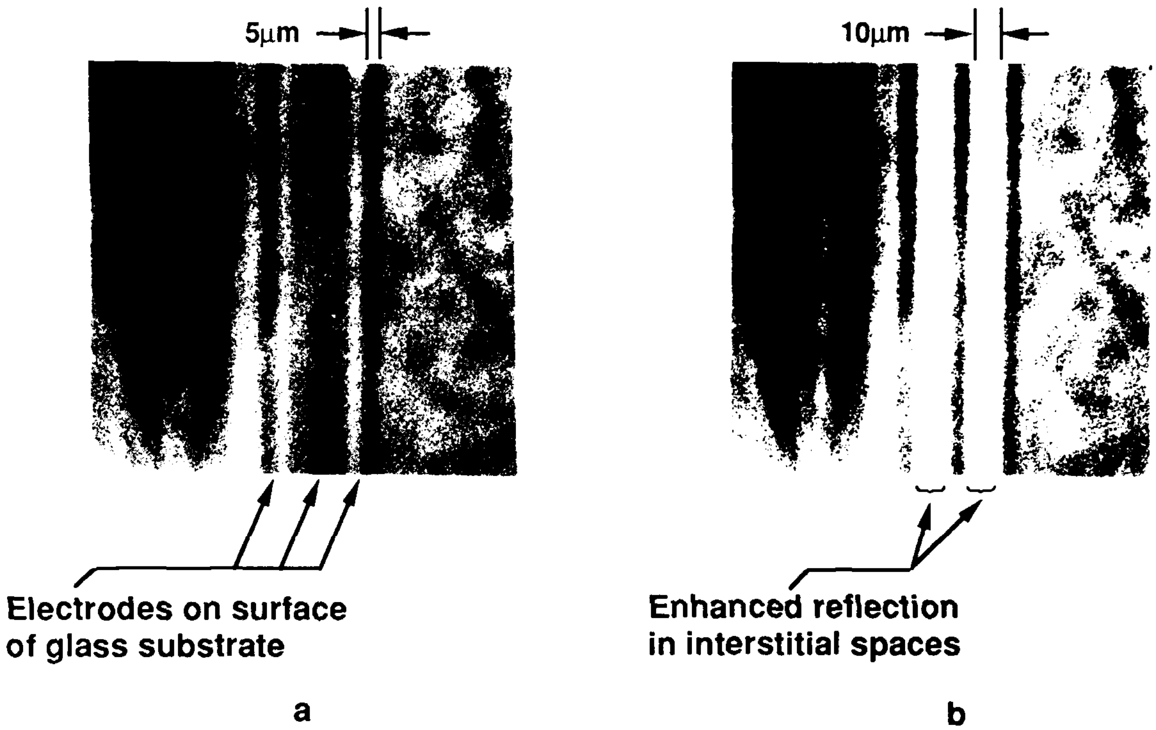

Figure 3. Photomicrograph of electrodes on glass substrate with (a) no voltage applied and (b) voltage applied to produce contrast between three electrodes.

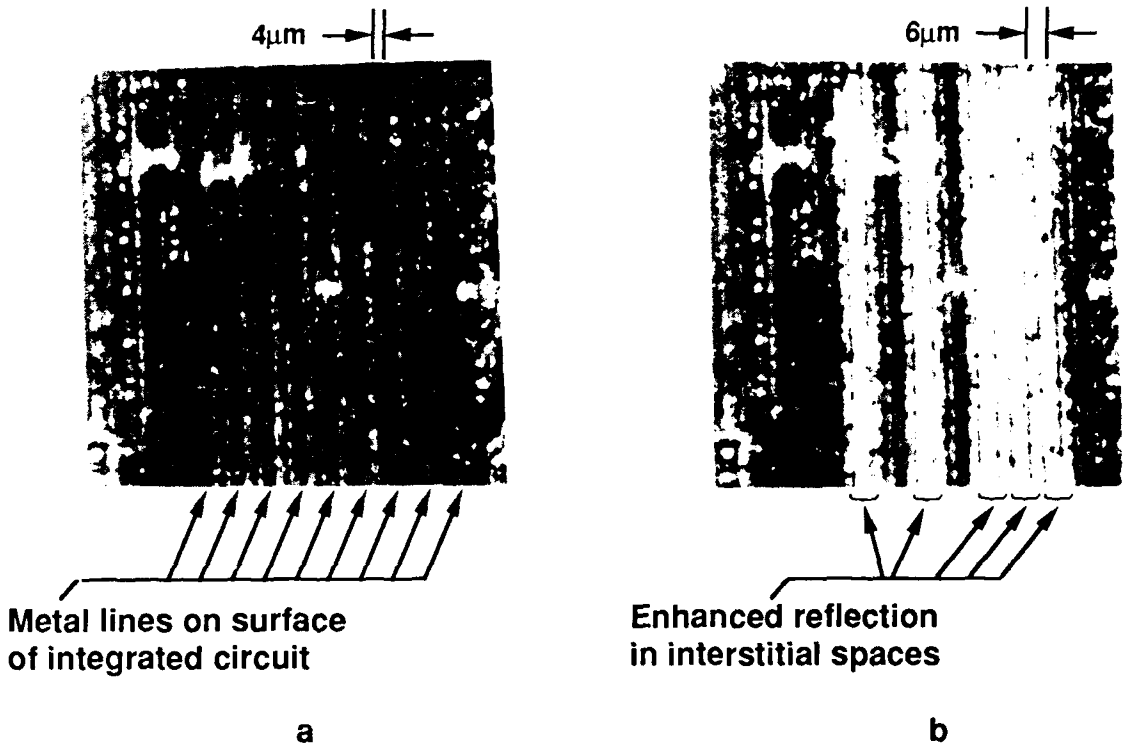

Figure 4. Photomicrograph of integrated circuit surface with (a) no voltage applied and (b) voltage applied to produce contrast in spaces 1, 3, 5, 6, and 7.