11:28:39 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 02/28/91

Active

Project #: E-21-F06 Cost share #: Rev #: 5
Center # : R6212-0A0 Center shr #: OCA file #:
Work type : RES
Contract#: N00014-86-K-0626 Mod #: A00002 Document : CONT
Prime #: Contract entity: GTRC

Subprojects ? : N
Main project #:

Project unit: ELEC ENGR Unit code: 02.010.118
Project director(s):
RHODES W T ELEC ENGR (404)894-2929

Sponsor/division names: NAVY / OFC OF NAVAL RESEARCH
Sponsor/division codes: 103 / 025

Award period: 860701 to 910930 (performance) 911130 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	460,800.00
Funded	0.00	460,800.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: Y

Title: RESEARCH ON OPTICAL COMPUTING ALGORITHMS & ARCHITECTURE

PROJECT ADMINISTRATION DATA

OCA contact: E. Faith Gleason 894-4820

Sponsor technical contact	Sponsor issuing office
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Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): Y
Defense priority rating : GOVT supplemental sheet
Equipment title vests with: Sponsor GIT X
IF IN PROPOSAL BUDGET OR WITH PRIOE APPROVAL
Administrative comments -
MOD #A00002 PROVIDES A NO-COST EXTENSION TO SEPTEMBER 30, 1991.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 07/20/93

roject No. E-21-F06 Center No. R6212-0A0

roject Director RHODES W T School/Lab ELEC ENGR

ponsor NAVY/OFC OF NAVAL RESEARCH

ontract/Grant No. N00014-86-K-0626 Contract Entity GTRC

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itle RESEARCH ON OPTICAL COMPUTING ALGORITHMS & ARCHITECTURE

ffective Completion Date 910930 (Performance) 911130 (Reports)

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loseout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	Y	930607
Classified Material Certificate	N	
Release and Assignment	Y	
Other	N	

CommentsEFFECTIVE DATE 7-1-86. CONTRACT VALUE $460,800.

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ubproject Under Main Project No.

ontinues Project No.

istribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other CARL BAXTER-FMD	Y
FRED CAIN-OOD	Y

NOTE: Final Patent Questionnaire sent to PDPI.

E-21-706

Publications/Presentations Report on Contract No. N00014-86-K-0626

Research on Optical Computing Algorithms and Architectures

Thomas K. Gaylord and William T. Rhodes
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

Covering Period 1 July 1986 through 30 June 1987

A. Papers Submitted for Publication in Refereed Journals:

Gaylord, Thomas K., and Erik I. Verriest, "Matrix Triangularization Using Arrays of Integrated Givens Rotation Devices," invited and accepted for publication in *Computer* (to appear December 1987).

Mait, Joseph N., and William T. Rhodes, "A Pupil Function Design Algorithm for Bipolar Incoherent Spatial Filtering," accepted for publication in *Applied Optics*.

Goodman, Stephen D., and William T. Rhodes, "Symbolic Substitution: Applications to Image Processing," accepted for publication in *Applied Optics*.

Xu, Jack P., and William T. Rhodes, "A Convenient Formula for Calculating the Effective Acousto-Optic Coefficient," submitted to *Applied Optics*.

Hereford, James M., and William T. Rhodes, "Nonlinear Optical Image Processing by Time-Sequential Threshold Decomposition," submitted to *Optical Engineering*. (Paper invited by feature editor for special issue.)

Xu, Jack P., Eddie H. Young, and William T. Rhodes, "General Theory for Calculation and Design of TeO_2-Type Acousto-Optic Bragg Cells and its Applications," submitted to *Applied Optics*.

B. Papers Published in Refereed Journals:

Mirsalehi, Mir M., and Thomas K. Gaylord, "Logical Minimization of Multilevel Coded Functions," *Applied Optics*, vol. 25, pp. 3078-3088, September 15, 1986. (Paper solicited by Associate Editor.)

Mait, Joseph N., William T. Rhodes, "Two-pupil Synthesis of Optical Transfer Functions - 2: Pupil Function Relationships," *Applied Optics*, vol. 25, pp. 2003-2007 (June 1986).

C. Books Prepared for Publication:

Attachment #3

D. Books Published:

E. Patents Filed:

Thomas Gaylord, Erik I. Verriest, and Mir M. Mirsalehi, "Integrated Optical Givens Rotation Device," Georgia Tech Research Corporation record of invention No. 899, May 1987.

F. Patents Granted:

G. Invited Presentations:

Rhodes, William T. and Kirt S. O'Neill, "Morphological Transformations by Hybrid Optical-Electronic Methods," presented at SPIE 1986 conference on Hybrid Image Processing; paper published in *Hybrid Image Processing*, D. Pape, ed. (Proceeding of SPIE, Vol. 638, 1986), pp. 41-44.

William T. Rhodes, "Optical information processing research at Georgia Tech," Physikalisches Institute der Universitaet Erlangen-Nuernberg, West Germany, July 1986.

William T. Rhodes, "Optical information processing research at Georgia Tech," Optical Computing '86 Conference, Novosibirsk (USSR), July 1986.

H. Contributed Presentations:

Mirsalehi, Mir M., and Thomas K. Gaylord, "Residue Number System in Content-Addressable Memory Processors," presented at SPIE 1987 conference on Digital Optical Computing; paper published in *Digital Optical Computing*, R. Arrathoon, ed. (Proceedings of SPIE, vol. 752, 1987), pp. 175-178.

I. Honors:

William T. Rhodes was made editor of *Applied Optics* (published by the Optical Society of America) in June 1987. *Applied Optics* is the world's largest scientific/technical journal in the optics area.

J. Technical Reports Published:

K. Graduate and Postdoctoral Students:

Michael T. Eisman
James M. Hereford
Joseph VanderGracht
Robert W. Stroud

E-21-F06

CONSOLIDATED TWO-YEAR REPORT

Office of Naval Research

Contract No. N00014-86-K-0626

1 July 1986 - 30 June 1988

Research on Optical Computing Algorithms and Architectures

1 July 1988

Georgia Institute of Technology

School of Electrical Engineering

Atlanta, Georgia 30332

CONTENTS

SUMMARY REPORT

Research was conducted in a variety of areas, with a total of 16 publications (published, accepted, submitted, or nearly ready to submit) resulting. The following paragraphs summarize our efforts in these different areas and make reference to the appropriate publications.

- *Symbolic Substitution and its Relation to Image Processing*

  Although a number of researchers have since reported an interest in the subject, we were first to study seriously the relationships between symbolic substitution, mathematical morphology, and image processing. Reference [7], published in the 1 May 1988 feature issue of Applied Optics on optical computing, lays out the key issues and establishes the principal connections between these forms of 2-D signal processing and computing. We were motivated by the observation that symbolic substitution is a particularly viable candidate for implementation in a commercial optical computing system. If we presume that high-speed symbolic substitution hardware will become available, then it is appropriate to consider its application to such image processing applications as 2-D convolution, correlation, median filtering, and shape transformations. The results of an engineering study of system complexity for linear filtering is presented, and a novel application to nonlinear noise-removal is described.

- *Nonlinear Optical Image Processing*

  Encouraged by conclusions reached in our symbolic substitution research, we began serious investigation of nonlinear optical image processing methods based on optical mathematical morphology. The key idea investigated is a decomposition of a gray-scale image into a finite number of binary "slices," each slice being obtained by thresholding the input image at a different intensity level. These slices are then processed using optically-implemented nonlinear shape-changing operations (e.g., erosion, dilation, ranked-order filtering, etc.), and the results summed to yield a processed gray-scale image. Initial results of this research are to be found in published references [6] and [9] and in reference [16], which is currently in preparation. One significant result was the successful median filtering of an image corrupted by "salt-and-pepper" noise. With suitably-developed thresholding/hard-limiting spatial light modulators such operations can be performed in parallel at high frame rates.

- *Crossed Bragg Cell Acousto-Optic Processors*

Certain of our long-term research objectives involve the use of a crossed Bragg cell processor that can be used for outer product computations, triple-product computations, and other related two-dimensional and quasi- two-dimensional signal processing operations. In the design and construction of this processor we have advanced significantly the state of the art of TeO2-type Bragg cell analysis and design. Reference [13], now in final draft form, reports on a compact crossed Bragg cell triple-product processor that does not require the use of anamorphic optics and exhibits a space-bandwidth product in each direction of 470. The absence of anamorphic optics (made possible by use of TeO2 Bragg cells operating in the slow shear wave mode) simplifies construction considerably. The high space-bandwidth- product achieved exceeds that of any reported triple-product processor we are aware of. Reference [14], also in the final draft stage, advances significantly the understanding of TeO2-type acousto-optic materials, including the mercurous halides being considered for radar signal processing applications. A rigorous general method for calculation and design is presented and simplifying approximations investigated. The design theory is then applied to a new class of TeO2-type Bragg cells: deviated off-axis devices. Case studies indicate a significant improvement in TeO2 Bragg cell performance is achievable.

- *1-D to 2-D Mappings in Optical Signal Processing*

  In a brief investigation, reported in Reference [10], we have studied a generalization of the important falling raster-folded spectrum relationship first introduced by C. E. Thomas (and subsequently applied to the spectral analysis of large time-bandwidth-product signals). Of particular interest in connection with numerical optical computing, we show that the generalized family of raster mappings together with their 2-D Fourier transforms form a continuous analog of the I. J. Good fast Fourier transform algorithm.

- *Incoherent Spatial Filtering System Constraints*

  Incoherent optical convolvers and correlators can perform important tasks in computing systems that are based on optical interconnections and optically-implemented symbolic substitution. In Reference [11] we analyze the case where the illumination sources are spatially discrete and periodic and determine what conditions must be met if linear-in-intensity processing is to be maintained. This case is of considerable practical interest, since sources like LED arrays and CRT rasters exhibit just such discrete and periodic characteristics.

- *Optical Truth-Table Look-Up Processing*

  In Reference [1], the extension of truth-table look-up processing beyond primitive operations (such as addition) to higher-level operations (such as discrete matched filtering) is presented. Use of the residue system and logical minimization techniques to reduce the required number of reference patterns stored in a content-addressable memory is illustrated for 16-bit full-precision addition, and multilevel coding of the numbers is introduced as a method to achieve further truth-table reduction. In addition, an optical implementation for processing multilevel-coded numbers is presented. We have also undertaken an exhaustive study of truth-table look-up methods as applied to the important case of 8-bit addition. The results are reported in Reference [12]. Three number representations are treated: binary, residue, and modified signed-digit. We reach the important conclusion that, even when all overhead computational activities are considered, the residue number system requires the least amount of storage.

- *Number Representations*

A major aspect of the research program has been the detailed analysis of number representations as they relate to optical processing, particularly content-addressable-memory and associative-memory methods. In Reference [3] we present a simple new method for reducing multi-valued functions for use in minimum-storage optical truth-table lookup processors. The method is applied to truth tables representing (1) modified signed-digit addition, (2) residue addition, and (3) residue multiplication. Also presented in that paper is a programmable logic array gate configuration for the modified signed-digit adder. Understanding that we obtained in this research was applied to clarification of the issue of the direct implementation of discrete and residue-based functions via optimal encoding, as presented in Reference [2]. The advantages of using the residue number system in content-addressable-memories has been studied and discussed in Reference [8].

- *Electro-Optical Implementation of Givens Rotations*

One particularly exciting part of this research program has been the investigation of the use of integrated optical devices for implementing Givens rotations for algebraic computations. The key to electro-optic implementation lies in the basic physics of thick-grating (Bragg regime) diffraction that can be performed by integrated optic devices. We have reported on this work in an invited paper published in Computer magazine (Reference [4]) and are preparing a paper providing more detailed analysis for submission to Applied Optics (Reference [15]). Key ideas are also recorded in a patent application, Reference [17].

- *Magneto-Optic Spatial Light Modulator (MOSLM) Studies*

  MOSLM's are growing in their importance to optical processing and computing. Potential problems associated with the use of MOSLM's include the lack of a design for a general minicomputer interface, lack of interactive data-page file generation software, lack of the ability to switch single pixels in some cases, lack of remote-from-computer operation capability, spurious pixel switching, and catastrophic failure due to thermal effects. We designed hardware and software components of a versatile minicomputer interface that has been successful in overcoming all of these problems. The basic system is reported in Reference [5]. The system will be used in further investigations of MOSLM characteristics in optical computing.

PUBLICATIONS AND PATENTS

July 1986 through June 1988

Optical Computing Architectures and Algorithms Research Program

Georgia Institute of Technology

T. K. Gaylord and W. T. Rhodes, Principal Investigators

SDI/ONR (ONR Contract No. N00014-86-K-0626)

Published in Refereed Journals

1. M. M. Mirsalehi and T. K. Gaylord, "Truth-Table Look-up Parallel Data Processing Using an Optical Content-Addressable Memory," *Applied Optics*, Vol. 25, pp. 2277-2283 (15 July 1986).

2. M. M. Mirsalehi and T. K. Gaylord, "Comments on Direct Implementation of Discrete and Residue-Based Functions via Optimal Encoding: A Programmable Array Logic Approach," *IEEE Transactions on Computers*, Vol. C-35, pp. 829-830 (September 1986).

3. M. M. Mirsalehi and T. K. Gaylord, "Logical Minimization of Multilevel Coded Functions," *Applied Optics*, Vol. 25, pp. 3078-3088 (15 September 1986).

4. T. K. Gaylord and E. I. Verriest, "Matrix Triangularization Using Arrays of Integrated Givens Rotation Devices," *Computer*, Vol. 20, pp. 59-66 (December 1987).

5. A. Knoesen, N. F. Hartman, T. K. Gaylord, and C. C. Guest, "Minicomputer Interface for Magneto-Optic Spatial Light Modulator," *Review of Scientific Instruments*, Vol. 58, pp. 1843-1851 (October 1987).

6. James M. Hereford and William T. Rhodes, "Nonlinear Optical Image Processing by Time-Sequential Threshold Decomposition," *Optical Engineering*, Vol. 27, pp. 274-279 (April 1988).

7. Stephen D. Goodman and William T. Rhodes, "Symbolic Substitution Applications to Image Processing," *Applied Optics*, Vol. 27, pp. 1708-1714 (1 May 1988).

Published in Conference Proceedings

8. M. M. Mirsalehi and T. K. Gaylord, "Residue Number Systems in Content-Addressable Memory Processing," in *Digital Optical Computing*, R. Arrathoon, ed. (Proc. SPIE, Vol. 752, 1987), pp. 175-178.

9. James M. Hereford and William T. Rhodes, "Nonlinear Optical Median Filtering by Time-Sequential Threshold Decomposition," in *Hybrid Image and Signal Processing*, D. P. Casasent and A. G. Tescher, eds. (Proc. SPIE, Vol. 939, 1988), pp. 40-45.

Submitted for Publication

10. David N. Sitter and William T. Rhodes, "Generalization of the Falling Raster-Folded Spectrum Relationship" submitted to *Applied Optics.*

11. Joseph van der Gracht and William T. Rhodes, "Source Sampling for Incoherent Imaging and Spatial Filtering" submitted to *Journal of the Optical Society of America A.*

12. M. M. Mirsalehi, T. K. Gaylord, D. C. Fielder, and C. C. Guest, "Eight-Bit Addition Using Truth-Table Look-up Processing" *Applied Optics.*

In Preparation

13. Jieping Xu, Eddie H. Young, David N. Sitter, and William T. Rhodes, "New Designs and Measurements of TeO2 Bragg Cells Used in Compact Triple-Product Processor Systems" to be submitted to *Optical Engineering* (summary attached).

14. Jieping Xu, Eddie H. Young, and William T. Rhodes, "General Theory for Calculation and Design of TeO2-Type Acousto-Optic Bragg Cells and Its Applications," to be submitted to *Applied Optics* (summary attached).

15. E. I. Verriest, E. N. Glytsis, and T. K. Gaylord, "Performance Analysis of Givens Rotation Integrated Optical Interdigitated-Electrode Cross Channel Bragg Diffraction Devices," to be submitted to *Applied Optics.*

16. William T. Rhodes and James M. Hereford, "Optical Nonlinear Image Processing," to be published in *Real-Time Signal Processing for Industrial Applications*, B. Javidi, ed. (Proc. SPIE, Vol. 960, 1988).

Patent Application

17. T. K. Gaylord, E. I. Verriest, and M. M. Mirsalehi, "Integrated Optical Givens Rotation Device," Patent Application No. 049,722, Georgia Tech Research Corporation, Filed 12 May 1987.

E-21-F06

Progress Report
Research on Optical Comptuing Algorithms and Architectures

William T. Rhodes
Georgia Institute of Technology
3 April 1990

: area of acousto-optic interconnections for optical computing, we ıade an extremely significant theoretical advancement. The theory of :ooptic (AO) interaction can be established from a wave (diffraction) oint or a particle (photon-photon scattering) viewpoint. Recently the ' of Feynman diagrams was used with some success to further develop a :romg-based theory of acousto-optic interactions. During the past ve have augmented that approach with a state-space representation of ›ssible scattering interactions. This state-space representation :y simplifies the combinatoric problems that must be solved to ıine scattering amplitudes (diffraction efficiencies) in different :o-optic diffraction regimes. We have used it to extend the Feynman ım theory of AO interactions to include the case where an arbitrary : of acoustic frequencies are present in the AO device. No other l, wave- or particle-based, has been successful in this regard. The approach has been worked out and results obtained for multiple- ency diffraction in four different regimes: Raman-Nath, isotropic or jenerate birefringent Bragg, axial birefringent Bragg, and ractable birefringent Bragg [1].

'his work was presented at the 1989 Annual Meeting of the Optical ociety of America in Orlando, 16 October 1989. A major manuscript, 'State-Space Representation for Multifrequency Acousto-Optic :nteractions" is nearly completed.

ıas also progressed in the area of digital optical computing. Truth- look-up techniques are now being applied directly to arithmetic :ions such as addition, subtraction, multiplication and division [2] .1 as to control logic microcode for general-purpose optical computers ıding that being developed by Peter Guilfoyle). It has been shown :he practicality of truth-table look-up techniques depends critically : logical reduction of the truth tables. The sizes of the truth : may be reduced by one or a combination of the following techniques: :ing the residue number system, (2) using the modified signed-digit ' system, (3) applying multi-level coding (ternary, etc.), and (4) .ng Boolean logical minimization techniques. Furthermore, it has been that analytic methods exist for predicting the reduced sizes of these : [3] thus alleviating the necessity of computationally intensive :tive reduction techniques.

:. M. Mirsalehi, T. K. Gaylord, D. C. Fielder, and C. C. Guest, Number representation effects in truty-table look-up processing: ight-bit addition example," Applied Optics, vol. 28, pp. 1931-1939, 5 May 1989.

:. M. Mirsalehi and T. K. Gaylord, "Analytic expressions for the sizes f logically minimized truth tables for binary addition and ubtraction," Applied Optics, vol. 29, 1990 (submitted).

E-21-F06

FINAL TECHNICAL REPORT

Office of Naval Research

Contract No. N00014-86-K-0626

1 July 1986 - 30 September 1989

Research on Optical Computing Algorithms and Architectures

Georgia Institute of Technology

School of Electrical Engineering

Atlanta, Georgia 30332

CONTENTS

1. Summary Report

Research was conducted in a number of areas relating to optical computing algorithms and architectures. The following paragraphs summarize our efforts in these different areas and reference resulting publications.

1.1. Table Look-Up Optical Computing

This research has centered on extending earlier Georgia Tech results on optical holographic content-addressable memories to the direct implementation of truth tables to perform fast, parallel data processing. The use of optics in computing systems provides important advantages of parallelism and interconnectivity that may be directly applied to massively parallel processing applications such as automatic target recognition and tracking.

At Georgia Tech, advances in number representation, multi-level coding, and large-scale truth-table reduction techniques, together with the growing need for faster parallel computation, have stimulated strong interest in table look-up implementations. Truth-table look-up techniques are being applied directly to arithmetic operations such as addition, subtraction, multiplication, and division as well to control logic microcode for general purpose optical computers including the system designed by Peter S. Guilfoyle. It has been shown that in order to determine the practicality of truth-table look-up techniques for a particular operation, the sizes of the logically reduced tables must be determined. In turn, the sizes of the truth tables may be reduced by one or a combination of the following techniques: 1) using the residue number system, 2) using the modified signed-digit number system, 3) applying multi- level coding (ternary, etc.), and 4) applying logical minimization techniques. Furthermore, it has been shown that depending on the operation being implemented, each of these can produce very significant reductions.

In an article published in *Applied Optics*, we presented the first complete comparison of number systems for a specific operation (8-bit addition) when all the steps of encoding, processing, and decoding are included [1]. The input was two 8-bit binary numbers together with an input carry. The output is a full precision 9-bit binary sum. Three number representations were treated: binary, residue, and modified signed-digit. The numbers in all three representations were in binary-coded form throughout the processing. The critically important steps of encoding the numbers into the residue and modified signed-digit systems and then decoding the results back into direct binary were also treated using truth-table look-up methods. For the direct binary representation, a total of 2545 gates (2519 AND gates or holograms in holographic content-addressable memory implementation) are required. For the residue representation, a total of 1764 gates (1686 holograms) are required. For the modified signed-digit representation, a total of 4142 gates (4052 holograms) are required. Thus for 8-bit addition, using the residue number system allows this operation to be done with the least amount of hardware. Furthermore, it has been shown that analytic methods exist for predicting the reduced sizes of these tables [2] thus alleviating the necessity of computationally intensive exhaustive reduction techniques.

It is now important to expand the above found advantages to other operations such as 16-bit addition, 16-bit multiplication, and the reduced instruction set microcode (RISC) used in other optical parallel computers.

[1] M. M. Mirsalehi, T. K. Gaylord, D. C. Fielder, and C. C. Guest, "Number representation effects in truth-table look-up processing: Eight-bit addition example," *Applied Optics*, vol. 28, pp. 1931-1939, May 15, 1989.

[2] M. M. Mirsalehi and T. K. Gaylord, "Analytic expressions for the sizes of logically minimized truth tables for binary addition and subtraction," *Applied Optics*, vol. 29, pp. 3339-3344, Aug. 10, 1990.

1.2. Integrated Optical Givens Rotation Device

The Givens rotation operation plays a central role in linear algebraic signal processing. An integrated optical coherent implementation of an elementary rotation matrix deviceto perform this operation was designed [3]. The device uses a thick diffraction grating. It has been shown that existing electro-optic phase shifting and grating diffraction devices can be combined to produce a very fast Givens rotation device. Operations that could be performed with this device include matrix-vector multiplication, matrix-matrix multiplication, matrix inversion, solution of linear equations, solution of least square problems, singular value decomposition, the discrete Fourier transform, and calculation of eigenvalues and eigenvectors.

[3] M. M. Mirsalehi, T. K. Gaylord, and E. I. Verriest, "Integrated optical Givens rotation device," *Applied Optics*, vol. 25, pp. 1608-1614, May 15, 1986.

1.3. Computer Interface For Spatial Light Modulators

Digital optical data storage and processing are rapidly increasing in technological importance. The magneto-optic spatial light modulator (MOSLM) is a relatively low-cost, small-pixel optical parallel input device that is capable of binary amplitude or binary phase modulation of each pixel. Thus it is well matched to digital optical coherent storage and processing technology. However, there are potential problems associated with its use, including lack of a design for a general minicomputer interface, lack of interactive data-page file generation software, lack of ability to switch single pixels in some cases, lack of remote-from-computer operation capability, spurious pixel switching, and catastrophic failure due to thermal effects. The hardware and software components of a versatile minicomputer interface that has been successful in overcoming all of these problems was designed [4]. This interface allows easy data entry of entire data pages or single pixels and minimizes crosstalk and noise developed over long cable lengths. In tests, the designed interface has produced highly stable operating characteristics.

[4] A. Knoesen, N. F. Hartman, T. K. Gaylord, and C. C. Guest, "Minicomputer interface for magneto-optic spatial light modulator," *Review of Scientific Instruments*, vol. 58, pp. 1843-1851, October 1987.

1.4. Magneto-Optic Spatial Light Modulators

A precision optical system, developed for characterizing the amplitude and phase properties of spatial light modulators, was used to characterize a 48 × 48 pixel magneto-optic spatial light modulator (MOSLM). Considerable variations in the amplitude (~25%) and phase transmittance (~50%) over the area of a given pixel were observed with coherent light illumination [5]. The pixel-to-pixel variations in the average amplitude (~5%) and average phase (~6%) were considerably less. The contrast ratio and the polarization rotation for full frame monochromatic illumination were about 10:1 and 11.25° respectively. For illumination within a single pixel, the contrast ratio and polarization rotation were about 100:1 and 14.0° respectively. A theoretical model is presented showing that the reduced values for full frame illumination may be described by the coherent addition of light of unrotated polarization (transmitted between pixels and around the edges) with the polarization rotated light. The amplitude and phase characteristics of the MOSLM were found to be a very stable with repeated switching of the pixel and with switching of neighboring pixels. This stability is a central requirement in coherent optical information processing applications.

[5] N. F. Hartman and T. K. Gaylord, "Coherent optical characterization of magneto-optic spatial light modulators," *Applied Optics*, vol. 29, pp. 4372-4383, Oct. 10, 1990.

1.5. Ferroelectric Liquid Crystal Spatial Light Modulators

Surface-stabilized ferroelectric liquid crystals (FLCs) are promising materials for semiconductor integrated-circuit-based spatial light modulators. For coherent optical processing applications, phase stability upon repeated switching is critically important. The phase characteristics of an FLC device were measured at switching rates up to 1kHz and found to be very stable [6,7]. The change in the total optical path length through the cell was found to be less than 0.0025λ at a wavelength of 632.8nm. The static optical characteristics were measured for a range of temperatures at and above room temperature in order to be able to identify any temperature-induced phase changes upon switching. The temperature of the FLC cell was externally varied, and changes in the birefringent optical path difference, the optical path length, and the optic axis tilt angle were measured. However, due to the observed phase stability of the FLC, the change of temperature due to switching was determined to be less than 0.046° C. It is clearly shown that FLCs can exhibit the stability needed for critical coherent and incoherent optical data processing applications.

[6] N. F. Hartman, T. K. Gaylord, T. J. Drabik, and M. A. Handschy, "Phase stability measurements of ferroelectric liquid crystal switches" (Abstract), *Optical Society of America Annual Meeting Technical Digest Series*, vol. 17, pg. 215, November 1991.

[7] N. F. Hartman, T. K. Gaylord, T. J. Drabik, and M. A. Handschy, "Phase stability of ferroelectric liquid crystals upon repeated switching and static temperature characteristics," *Applied Optics*, vol. 32, pp. 3720-3725, 1993.

1.6. Optoelectronic Parallel Processing Arrays

It is now generally acknowledged that incorporating the advantages of optics into digital multiprocessor systems can benefit performance. Considerable interest exists in the implementation of massively parallel systems, tailored to problems having high inherent parallelism, that use optics to implement some or all of the tasks of interconnection, logic, and clocking. We explored the design of digital systems based on two-dimensional arrays of electronic processing elements (PEs) produced at or near the wafer-scale level of integration, that are optically interconnected and synchronized by means of light modulators and detectors incorporated within the PEs and an external optical routing network [8,9]. Provided a fast, reliable light modulator technology is developed that is compatible with silicon or GaAs VLSI circuit technology and signal levels, such systems will compete with all-electronic and all-optical computing systems in the regime of highly parallel and structured computation.

We developed a system methodology that implements logic and local intra-PE interconnections in electronic circuitry and global timing and inter-PE interconnections optically, thus making optimal use of electronic and optical elements. This approach was contrasted with all-optical methodologies in terms of logic design, optical interconnect complexity, and physical limitations on size, density, and speed. Finally, a prototype shift-connected single-instruction, multiple-data (SIMD) array under construction at Georgia Tech was developed, and the performance of fabricated light modulator arrays, silicon photodetectors, and silicon logic building blocks determined.

[8] T. J. Drabik and T. K. Gaylord, "Silicon VLSI-compatible ferroelectric liquid crystal light modulator process," (Abstract) Optical Society of America Annual Meeting Technical Digest Series, vol. 11, pg. TuAA4, October 1988.

[9] T. J. Drabik and T. K. Gaylord, "Optoelectronic parallel processing arrays: System architecture and progress toward a prototype," *Optical Computing Technical Digest*, pp. TuH41-TuH44, Salt Lake City, Utah, March 1989.

1.7. Symbolic Substitution and its Relation to Image Processing

Although a number of researchers subsequently reported an interest in the subject, we were the first to study seriously the relationship between symbolic substitution, mathematical morphology, and image processing. Reference [10], published in a feature issue of *Applied Optics* on optical computing, lays out the key issues and establishes the principlal connections between these forms of 2-D signal processing and computing. We were motivated by the observation that symbolic substitution is a particularly viable candidate for implementation in a commercial optical computing system. If we presume that high-speed symbolic substitution hardware will become available, then it is appropriate to consider its application to such image processing applications as 2-D convolution, correlation, median filtering, and shape transformations. The results of an engineering study of system complexity for linear filtering is presented, and a novel application to nonlinear noise removal is described in this paper.

[10] S. D. Goodman and W. T. Rhodes, "Symbolic Substitution Applications to Image Processing," *Applied Optics*, vol. 27, pp. 1708-1714 (1 May 1988).

1.8. Nonlinear Optical Image Processing

Encouraged by conclusions reached in the symbolic substitution research, we began serious investigation of nonlinear optical imge processing methods based on optical mathematical morphology. The key idea investigated was a decomposition of a gray-scale image into a finite number of binary "slices," each slice being obtained by thresholding the input image at a different intensity level. These slices are processed using optically-implemented nonlinear shape-changing operations (e.g., erosion, dilation, ranked-order filtering, etc.), and the results summed to yield a processed gray-scale image. Initial results of this research are to be found in published references [11]-[14]. One significant result was the successful median filtering of an image corrupted by "salt-and-pepper" noise. With suitably-developed thresholding/hard-limiting spatial light modulators, such operations can be performed in parallel at high frame rates. Of special importance to practical implementation, threshold decomposition image processing using ranked-order filtering exhibits significant noise immunity, as noted in [15].

[11] J. M. Hereford and W. T. Rhodes, "Nonlinear Optical Image Processing by Time-Sequential Threshold Decomposition," *Optical Engineering*, vol. 27, pp. 274-279 (April 1988).

[12] J. M. Hereford and W. T. Rhodes, "Nonlinear Optical Median Filtering by Time-Sequential Threshold Decomposition," in *Hybrid Image and Signal Processing*, D. Casasent and A. Tescher, eds. (Proc. SPIE, vol. 939, 1988), pp. 40-45.

[13] W. T. Rhodes and J. M. Hereford, "Optical Nonlinear Image Processing," in *Real-Time Signal Processing for Industrial Applications*, B. Javidi, ed. (Proc. SPIE, vol. 960, 1989), pp.

[14] J. M. Hereford and W. T. Rhodes, "Optical asymmetrical median filtering using gray-scale convolution kernels," *Optics Letters*, vol. 15, No. 12 (15 June 1990), pp. 697-699.

[15] J. L. Tasto and W. T. Rhodes, "Noise immunity of optoelectronic order-statistic filtering using threshold decomposition," *Optics Letters* , vol.18, no. 16 (15 August 1993), pp.

1.9. Crossed Bragg Cell Acousto-Optic Processors

We devoted major effort to the investigation of crossed Bragg cell processors that can be used for outer product computations, triple-product computations, and other related two-dimensional and quasi- two-dimensional signal processing operations. In the design and constrcution of a prototype processor we advanced significantly the state of the art of TeO_2-type Bragg cell analysis and design. Reference [16] reports on a compact crossed Bragg cell triple-product processor that does not require the use of anamorphic opticsl and exhibits a space-bandwidth product in each direction of 470. The absence of anamorphic optics (made possible by use of TeO_2 Bragg cells operating in the slow shear wave mode) simplifies construction considerably. The high space-bandwidth product achieved exceeds that of any reported triple-produce processor we are aware of. References [17] and [18] advanced significantly the understanding of TeO_2-type acousto-optic materials, including the mercurous halides being considered for radar signal processing applications. A rigorous general method for calculation and design is presented and simplifying approximations investigated. The design theory is then applied to a new class of TeO_2-type Bragg cells: deviated off-axis devices. Case studies indicate a significant improvement in TeO_2 Bragg cell performance is achievable. References [19] and [20] report on applications of the system.

[16] J. P. Xu, E. H. Young, W. T. Rhodes, and D. N. Sitter, "New designs and measurements of TeO2 Bragg cells used in compact triple-product-processor systems," in *Advances in Optical Information Processing III*, D. Pape, ed. (Proc. SPIE, vol. 936, 1988), pp.

[17] J. P. Xu and W. T. Rhodes, "General solution of multifrequency acousto-optic diffraction in Bragg cells," in *Advances in Optical Information Processing* III, D. Pape, ed. (Proc. SPIE, vol. 936, 1988), pp.

[18] J. P. Xu, N. Ma, D. N. Sitter, and W. T. Rhodes, "General solution of multifrequency acousto-optic diffraction in Bragg cells," in *Advances in Optical Information Processing III*, D. Pape, ed. (Proc. SPIE, vol. 936, 1988), pp.

[19] D. C. Hartup, W. T. Rhodes, H. F. Engler, and A. K. Garrison, "Channelized time- and space-integrating acousto-optic processor," in *Advances in Optical Information Processing IV*, D. Pape, ed. (Proc. SPIE, vol. 1296, 1990), pp.

[20] D. C. Hartup, W. T. Rhodes, H. F. Engler, and A. K. Garrison, "Channelized Time- and Space-Integrating Acousto-Optic Processor," *GTRI Technical Journal*, vol. 1, pp. 46-54 (1991).

1.10. One-Dimensional to Two-Dimensional Mappings in Optical Signal Processing

In a brief investigation reported in Ref. [21] we studied a generalization of the important falling raster/folded spectrum relationship first introduced by C. E. Thomas and subsequently applied to the spectral analysis of large time-bandwidth-product signals. Of particular interest in connection with numerical optical computing, we showed that the generalized family of raster mappings together with their 2-D Fourier transforms form a continuous analog of the I. J. Good fast Fourier transform algorithm.

[21] David N. Sitter and William T. Rhodes, "Generalization of the falling raster-folded spectrum relationship," *Applied Optics*, vol. 29, No. 17 (10 June 1990), pp. 2527-2531.

1.11. Incoherent Spatial Filtering System Constraints

Incoherent optical convolvers and correlators can perform important tasks in computing sytems that are based on optical interconnections and optically-implemented symboilic substitution. In Ref. [22] we analyze the case where the illumination sources are spatially discrete and periodic and determine what conditions must be met if linear-in-intensity processing is to be maintained. This case is of considerable practical interest, since sources like LED arrays and CRT rasters exhibit just such discrete and periodic characteristics.

[22] Joseph van der Gracht and William T. Rhodes, "Source sampling for incoherent imaging and spatial filtering," *Journal of the Optical Society of America A*, vol. 6 (1989), pp. 1165-1167.

2. Index of Technical Reports

Consolidated Two-Year Report, 1 July 1988

3. Index of Publications

3.1. Published in Refereed Journals

1. Mirsalehi, M. M., Gaylord, T. K., and Verriest, E. I., "Integrated optical Givens rotation device," *Applied Optics*, vol. 25, pp. 1608-1614, May 15, 1986.

2. Mirsalehi, M. M. and Gaylord, T. K., "Multi-level coded residue-based content-addressable-memory optical computing, " *Applied Optics*, vol. 25, pp. 2277-2283, July 15, 1986.

3. Mirsalehi, M. M. and Gaylord, T. K., "Comments on direct implementation of discrete and residue-based functions via optimal encoding: A programmable array logic approach," *IEEE Transactions on Computers*, vol. C-35, pp. 829-830, September 1986.

4. Mirsalehi, M. M., and Gaylord, T. K., "Logical minimization of multilevel coded functions, *Applied Optics*, vol. 25, pp. 3078-3088, September 15, 1986. (invited).

5. Knoesen, A., Hartman, N. F., Gaylord, T. K., and Guest, C. C., "Minicomputer interface for magneto-optic spatial light modulator," *Review of Scientific Instruments*, vol. 58, pp. 1843-1851, October 1987.

6. Gaylord, T. K. and Verriest, E. I., "Matrix triangularization using arrays of integrated Givens rotation devices," *Computer*, vol. 20, pp. 59-66, December 1987. (invited)

7. S. D. Goodman and W. T. Rhodes, "Symbolic Substitution Applications to Image Processing," *Applied Optics*, vol. 27, no. 13, pp. 1708-1714, 1 May 1988.

8. J. M. Hereford and W. T. Rhodes, "Nonlinear Optical Image Processing by Time-Sequential Threshold Decomposition," *Optical Engineering*, vol. 27, pp. 274-279, April 1988.

9. Mirsalehi, M. M., Gaylord, T. K., Fielder, D. C., and Guest, C. C., Number representation effects in truth-table look-up processing: 8-bit addition example," *Applied Optics*, vol. 28, no. 14, pp. 1931-1939, 15 May 1989

10. Joseph van der Gracht and William T. Rhodes, "Source sampling for incoherent imaging and spatial filtering," *Journal of the Optical Society of America A*, vol. 6, no. 5, pp. 1165-1167, May 1989.

11. J. M. Hereford and W. T. Rhodes, "Optical asymmetrical median filtering using gray-scale convolution kernels," *Optics Letters*, vol. 15, No. 12, pp. 697-699, 15 June 1990.

12. Mirsalehi, M. M. and Gaylord, T. K. "Analytic expressions for the sizes of logically minimized truth tables for binary addition and subtraction," *Applied Optics*, vol. 29, no. 23, pp. 3339-3344, 10 September 1990.

13. Hartman, N. F. and Gaylord, T. K., "Coherent optical characterization of magneto-optic spatial light modulators," *Applied Optics*, vol. 29, no. 26, pp. 4372-4383, 10 October 1990.

14. Verriest, E. I., Glytsis, E. N., and Gaylord, T. K., "Performance analysis of Givens rotation integrated optical interdigitated-electrode cross-channel Bragg diffraction devices: Intrinsic accuracy," *Applied Optics*, vol. 29, pp. 2556-2563, June 10, 1990.

15. David N. Sitter and William T. Rhodes, "Generalization of the falling raster-folded spectrum relationship," *Applied Optics*, vol. 29, No. 17, pp. 2527-2531, 10 June 1990.

16. Verriest, E. I., Gaylord, T. K., and Glytsis, E. N., "Performance analysis of Givens rotation integrated optical interdigitated-electrode cross-channel Bragg diffraction devices: Extrinsic and inherent errors," *Applied Optics*, vol. 31, pp. 1754-1761, 10 April 1992.

17. J. L. Tasto and W. T. Rhodes, "Noise immunity of optoelectronic order-statistic filtering using threshold decomposition," *Optics Letters* , vol.18, no. 16 (15 August 1993), pp.

3.2. Published In Conference Proceedings

1. Mirsalehi, M. M. and Gaylord, T. K., "Content-addressable memory processing: Multilevel coding, logical minimization, and an optical implementation," *Proceedings of International Symposium on Multiple-Valued Logic*, pp. 174-178, Blacksburg, VA, May 1986.

2. Mirsalehi, M. M. and Gaylord, T. K., "Residue number systems in content-addressable memory processing," *Proc. SPIE*, vol. 752, pp. 175-178, 1987.

3. Drabik, T. J. and Gaylord, T. K., "Silicon VLSI-compatible ferroelectric liquid crystal light modulator process," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 11, pg. TuAA4, October 1988.

4. Drabik, T. J. and Gaylord, T. K., "Optoelectronic parallel processing arrays: System architecture and progress toward a prototype," *Optical Computing Technical Digest*, pp. TuH41-TuH44, Salt Lake City, Utah, March 1989.

5. Hartman, N. F. and Gaylord, T. K., "Magneto-optic spatial light modulator characterization," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 18, pg. THI2, October 1989.

6. Mirsalehi, M. M., Gaylord, T. K., Fielder, D. C., and Guest, C. C., "Comparison of number systems in truth-table look-up processing," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 18, pg. TuDD5, October 1989.

7. Drabik, T. J. and Gaylord, T. K., "CMOS-compatible detector building blocks for optically interconnected VLSI and WSI," *Optical Society of America Annual Meeting Technical Digest Series*, vol. 18, pg. TuQ3, October 1989.

8. Hartman, N. F., Drabik, T. J., Gaylord, T. K., and Handschy, M. A., "Optical characterization of ferroelectric liquid-crystal/silicon VLSI spatial light modulator," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 15, pg. 255, November 1990.

9. Hartman, N. F., Gaylord, T. K., Drabik, T. J., and Handschy, M. A., "Phase stability measurements of ferroelectric liquid crystal switches," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 17, pg. 215, November 1991.

10. J. M. Hereford and W. T. Rhodes, "Nonlinear Optical Median Filtering by Time-Sequential Threshold Decomposition," in *Hybrid Image and Signal Processing*, D. Casasent and A. Tescher, eds. (Proc. SPIE, vol. 939, 1988), pp. 40-45.

11. W. T. Rhodes and J. M. Hereford, "Optical Nonlinear Image Processing," in *Real-Time Signal Processing for Industrial Applications*, B. Javidi, ed. (Proc. SPIE, vol. 960, 1988), pp.

12. J. P. Xu, E. H. Young, W. T. Rhodes, and D. N. Sitter, "New designs and measurements of TeO2 Bragg cells used in compact triple-product-processor systems," in *Advances in Optical Information Processing III*, D. Pape, ed. (Proc. SPIE, vol. 936, 1988), pp.

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17. S. D. Goodman and W. T. Rhodes, "Symbolic substitution applied to image processing," 1987 Annual Meeting, (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, October 1987.

18. J. P. Xu and W. T. Rhodes, "State-space representation for multifrequency acousto-optic interactions," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 18 (Optical Society of America, Washington, DC, 1989), p. 36.

19. J. van der Gracht and W. T. Rhodes, "Computer simulation of partially coherent imaging by outer-product expansions," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 18 (Optical Society of America, Washington, DC, 1989), p. 165.

20. J. M. Hereford and W. T. Rhodes, "Optical morphological transformations using gray-scale convolution kernels," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 18 (Optical Society of America, Washington, DC, 1989), p. 177.

21. J. M. Hereford and W. T. Rhodes, "Non-ideal thresholding effects in the optical implementation of median filtering," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 15 (Optical Society of America, Washington, DC, 1990), p. 30.

3.3. Patent

1. Gaylord, T. K., Verriest, E. I., and Mirsalehi, M. M., "Integrated optical Givens rotation device," U. S. Patent No. 4,950,042 assigned to Georgia Tech Research Corporation, issued Aug. 21, 1990.