

AFOSTR 970691

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE	3. REPORT TYPE AND DATES COVERED	
			Final 15 JUL 92 to 14 SEP 97	
4. TITLE AND SUBTITLE			5. FUNDING NUMBERS	
HOLOGRAPHIC INTERCONNECTS FOR OPTICAL NEURAL NETWORKS				
6. AUTHOR(S)			61102F 2305/DS	
PROFESSOR GMTRO				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)			8. PERFORMING ORGANIZATION REPORT NUMBER	
University of Arizona Office of Research & Contract Analysis, Rm 412 888 N Euclid PO Box 210158				
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
AFOSR/NE 110 Duncan Ave RmB115 Bolling AFB DC 20332-8050			F49620-92-J-0407	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT			12b. DISTRIBUTION CODE	
APPROVAL FOR PUBLIC REL. EASED; DISTRIBUTION UNLIMITED				
13. ABSTRACT (Maximum 200 words)				
<p>this research work focussed on the development of diffractive optic interconnect elements (DOIEs), which are computer-designed, e-beam fabricated holograms used for implementing free-space optical interconnects. Accomplishments of the work included development of an improved hybrid design strategy for the design of phase-only holograms, development of a versatile software package for hologram design and analysis, continued development and characterization of the e-beam fabrication technology, careful measurement of the performance achieved by fabricated holograms, and investigation of applications that utilize the technology. The applications included optical neural networks, which require analog-weighted interconnects, and digital optical computers utilizing binary-weighted interconnects. The software package for interconnect design, evaluation, and reconstruction (SPIDER) was written to run on Unix-based computer platforms and is freely available over the Internet.</p>				
14. SUBJECT TERMS			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT	
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	

19971217 010

Final Report

Holographic Interconnects for Optical Neural Networks

Grant # F49620-92-J-0407

Submitted to the Air Force Office of Scientific Research
9/14/97

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Abstract

This research work focussed on the development of diffractive optic interconnect elements (DOIEs), which are computer-designed, e-beam fabricated holograms used for implementing free-space optical interconnects. Accomplishments of the work included development of an improved hybrid design strategy for the design of phase-only holograms, development of a versatile software package for hologram design and analysis, continued development and characterization of the e-beam fabrication technology, careful measurement of the performance achieved by fabricated holograms, and investigation of applications that utilize this technology. The applications included optical neural networks, which require analog-weighted interconnects, and digital optical computers utilizing binary-weighted interconnects. The software package for interconnect design, evaluation, and reconstruction (SPIDER) was written to run on Unix-based computer platforms and is freely available over the Internet.

Objectives

The primary objectives of this research were to develop improved methods for the design, analysis, fabrication, and testing of computer generated holograms for use as free-space optical interconnects, and to develop applications, such as optical neural networks and digital optical computers, that can advantageously utilize free-space optical interconnects.

Summary of Research Effort and Major Accomplishments

The major focus of this research work was in the area of free-space optical interconnects implemented by computer-generated holograms. These are referred to as diffractive optical interconnect elements (DOIEs). Important issues in the design, fabrication, and utilization of DOIEs were addressed as part of the research effort. Methods for designing and fabricating both binary-amplitude and phase-only holograms were investigated; however, over the period of the research program, the emphasis shifted almost entirely to phase-only holograms because of their higher efficiency and their ability to realize interconnect patterns on-axis. Both issues are critical to the development of practical computational systems utilizing DOIEs as discussed in detail in a publication by Keller and Gmitro [1].

Design:

Nearly every technique available for the design of computer-generated holograms was investigated during the course of this research program. For phase-only holograms, there exists no direct inversion (design) technique that yields a solution for the hologram given the desired interconnect pattern. All phase-only design techniques are, therefore, iterative. One of the major accomplishments of this research program was the development of a new design strategy that combines two (or more) of the existing iterative methods into a hybrid approach that achieves better performance than any single method alone. The improved performance achievable via this approach was documented in a publication by Keller and Gmitro [2].

The process of designing DOIEs for a specific application involves many tradeoffs and degrees of freedom that the designer must address in order to achieve an acceptable solution. These include the pixel size in the hologram, the number of hologram pixels used, the number of replications of the fundamental hologram, the wavelength of light used for illuminating the hologram, and the specification of the output plane constraints and degrees of freedom. The output plane constraints are the integrated irradiance values (interconnect strengths) for a given size, spacing, and position of detectors in the output plane. Degrees of freedom are locations in the output plane where one does not care about the irradiance. A specific application will typically have a set of performance specifications, such as the accuracy of the interconnect strengths, the diffraction efficiency, and/or a maximum deviation from a set of interconnect strengths. A detailed description of the design procedure for DOIEs will not be given here, but can be found in a publication by Gmitro and Coleman [3]. This paper is included as appendix material with this report.

A major accomplishment of the research program was the development of a software package to provide a design environment with the necessary tools to solve general

DOIE design problems. The package includes tools for layout of the interconnect pattern, selection and input of the physical constraints in the problem, interactive implementation of the design procedure, evaluation of the predicted performance, and generation of the data files for DOIE fabrication. The software package is called SPIDER for (Software Package for Interconnect Design, Evaluation and Reconstruction). It is written in C and runs under UNIX on several hardware platforms including DEC, SUN, SGI, and HP computer systems. The software has a nice graphical interface that provides an interactive design environment for laying out patterns and evaluating the performance one can achieve. This feature is very useful in the initial phase of development, where the designer is varying parameters and exploring the range of tradeoffs available. A command line mode is also available, which is very useful for large problems that require many different DOIEs. The designer can write a script to solve the design problem and then let it run for whatever period of time is necessary (days or more may be required in some cases).

SPIDER is available free of charge over the Internet (<http://www.opt-sci.arizona.edu/medopt/opticalComputing.html>). A copy of the software manual for SPIDER is included in the appendix material of this report and describes the features of the software package and gives instructions on using it. This manual is available on-line for those users who download SPIDER to their computers.

Fabrication:

Design of DOIEs is only part of the story. The holograms must also be fabricated, and their actual performance must be adequate for the specific task for which they were intended. This part of the investigation was done in close collaboration with Paul Maker at the Jet Propulsion Laboratory (JPL). Paul Maker has developed a technology for the fabrication of multi-level phase-only transmission masks utilizing variable e-beam exposure of PMMA. The work focussed on determining the effects of fabrication errors on the performance of the DOIEs. Fabrication errors include random and systematic errors in the etch depths, side-wall etching effects, stitching errors associated with writing holograms larger than the fundamental scan area of the e-beam machine, and material refractive index variations. A significant amount of effort was directed at measuring the optical performance of fabricated holograms and at identifying the sources of fabrication error that account for degradation in the measured performance relative to the performance predicted by the design.

A highly accurate optical testbed was constructed to make detailed measurements of the performance of fabricated DOIEs. A detailed description of this system can be found in the "Diffractive Optic Measurement Report", which is included as appendix, and in Christopher Coleman's Ph.D. Dissertation (Optical Sciences Center, University of Arizona, 1998). The system was able to make accurate photometric measurements and to assess critical performance issues for the holograms, such as diffraction efficiency, interconnect accuracy, crosstalk, etc. These data were compared to predicted performance using models of the various fabrication errors to better understand the limits to performance in this interconnect technology.

The JPL fabrication technology was compared to the more conventional method of fabricating DOIEs using multiple e-beam masks, and multiple steps of photoresist exposure, development, and reactive ion etching into the substrate, which is a technology

that has been developed at several facilities. DOIIEs fabricated by Honeywell using this multi-mask technology were compared to DOIIEs fabricated at JPL. The general finding was that the Honeywell holograms suffered from mask alignment errors, but had smoother surfaces compared to the JPL holograms. Overall performance of the JPL holograms was slightly superior to the Honeywell holograms at the same number of phase levels. However, with the JPL technology, holograms could be fabricated with essentially continuous phase (up to 64 effective phase levels), and the performance of these holograms was substantially superior to the 8-level phase holograms produced at Honeywell for the same interconnect task. Given the problems with mask alignment, it does not appear to be reasonable to consider making multi-mask holograms with greater than 8 levels, and therefore, the JPL technology does appear to offer a significant advantage for hologram fabrication.

A final issue regarding fabrication is replication of the holograms. E-beam fabrication is far too expensive to use in every DOIIE. Investigation of replication of the DOIIEs using injection molding technology was initiated as a collaboration with Donnelly Corporation in Tucson, AZ. Initial attempt at making a nickel-plated master from a JPL hologram were unsuccessful, but work is continuing in this area and it is anticipated that replication will be feasible with inexpensive injection molding.

Applications:

Three application areas for DOIIEs were investigated during the course of this research program. The application areas were optical neural networks, implementation of a high-speed optical A/D converter, and digital-optical computing.

The initial interest in DOIIEs was for optical neural networks. It is clear that DOIIEs can be used for implementing large-scale neural networks. However, a major drawback for the DOIIEs considered here is that they produce only fixed interconnects. Thus training (i.e. specifying the interconnect strengths) must be done off-line and then transferred to the optical hardware. This is a major disadvantage because the system is inflexible and does not adapt to errors in the hardware implementation itself. The other issue with neural networks, in general, is that the training of large networks has proven to be a formidable problem. Research in the use of neural networks for large-scale pattern recognition problems has stagnated in recent years, and the potential impact of optical implementation is unclear at this point.

An architecture for a high-speed optical A/D converter utilizing DOIIEs was developed during the course of this research program. One of the tasks of the DOIIEs in this system was to produce an accurate set of optical intensities for a bank of SEED-based optical comparitors. The conclusion on this work is that the performance of the DOIIEs is not sufficient for this purpose. Furthermore, the performance of the opto-electronic components (SEED comparitors) is not sufficient that this optical approach will be competitive with the increasing speed/performance of electronic A/D converters that are now at 8 bit, 1G sample/s.

The final application area is digital-optical computing. In this area, a collaboration with Peter Guilfoyle at OptiComp Corporation and Paul Maker at JPL was established. OptiComp provided several design problems with performance specifications related to their work on building digital-optical computers. SPIDER was used, tested, and improved

to meet the challenge of the specific design problems. Holograms were fabricated at JPL, and then a detailed evaluation was performed on the optical testbed at the University of Arizona. For the most part, the fabricated DOIEs were able to meet specifications.

Measurement Report:

A copy of a report on the hologram evaluation work is included as appendix material for this AFOSR final report. Highlights of this report include: 1) a description of the optical testbed system, 2) data on the reliability/repeatability of the system measurements, 3) data comparing the JPL holograms to the Honeywell multi-mask holograms, 4) data on the analog-weight holograms, which were considered for the optical neural network and optical A/D applications, 5-8) data on the specific OptiComp holograms, 9) results from a lenslet array, and 10) results from an array of holograms that incorporated a Fourier transform lens into the hologram phase function. These last data are interesting because they demonstrate the concept of a free-space optical interconnect system with a source array, a hologram array, and a detector array without any additional optical elements. This represents the type of system that can exploit power of optics in the high-performance computational systems of the future.

Personnel Supported

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3. Christopher L. Coleman, Graduate Research Associate, Optical Sciences Center, University of Arizona.
4. Andrew Rouse, Graduate Research Assistant, Optical Sciences Center, University of Arizona.

Publications

1. P.E. Keller and A.F. Gmitro, "Design and Analysis of Fixed Planar Holographic Interconnects for Optical Neural Networks", *Appl. Opt.* **31**, 5517-5526 (1992).
2. P.E. Keller and A.F. Gmitro, "Computer-Generated Holograms for Optical Neural Networks: On-Axis versus Off-Axis Geometry", *Appl. Opt.* **32** 1304-1310 (1993).
3. A.F. Gmitro and C.L. Coleman, "Multilevel Phase Holograms for Free-Space Optical Interconnects: Design and Analysis", *Optoelectronic Interconnects and Packaging*, R.T. Chen and P.S. Guilfoyle, eds., SPIE Vol. **CR62**, 88-105 (1996).

Appendices

1. Ref. 3: "Multilevel Phase Holograms for Free-Space Optical Interconnects: Design and Analysis".
2. SPIDER 3.0 Reference Manual.
3. Diffractive Optic Measurement Report.