Output Devices for Dynamic Electronic Holography

by

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Abstract

A survey of electrically addressable light modulation mechanisms and spatial
light modulation devices for the real time display of moving holographic
images is presented. Bandwidths of visual display holograms using reduced
information formats are near the limits of current electro-optic devices, and
high density structures required for an addressable diffraction element are
rapidly being developed by the semiconductor industry. Here the author
examines physical mechanisms and current technologies for spatial light
modulation which could be developed to meet the requirements of dynamic
holographic image generation. Output devices based on high resolution
linear array modulators and an emissive array of phase locked laser diodes
are suggested. Various high speed addressing schemes are investigated for
these arrays, including the use of scanned electron or photon beams in
conjunction with electro-optic and photorefractive materials. Novel wafer
scale integrated drivers or CCD addressed output devices utilizing VLSI
fabrication techniques are proposed, including the use of holographically
patterned substrates for high density modulator structures.

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Chapter 1

Introduction

Human beings depend on communication in increasingly significant ways, with ever increasing budgets of time, energy and material resources apportioned to communications systems and their usage. This advancement toward more communications has prompted the development of better communications, with frequent and significant increases in the number and types of media available, accompanied by the simultaneous development of communications channels with greater bandwidth. In addition to improving the quality of the human/human interface, technologies that extend man's senses, abilities and intellectual resources have greatly amplified the need for more advanced communication and information display devices. It is no longer enough to send and receive messages, maintain a dialog, or interface with an information system with only sound and pictures.

A system enabling the practical reconstruction of three-dimensional information, transmitted from remote scenes or instrumentation, synthesized mathematically or from stored data on various high capacity media, would lead to an increased awareness and heightened ability to deal with our environment, the requirements of our professions, and each other. The advent of powerful and sophisticated new technologies for the generation and control of light has put us in a time when the fulfillment of this dream is within our reach, inspiring a concerted effort toward this end. This thesis examines
some of these technologies in an effort to formulate practical methods for accomplishing dynamic electronic holography.

Since the advent of wavefront reconstruction photography (holography), researchers in the field have endeavored to describe and produce a means of transmitting holograms from one place to another, reconstructing a three-dimensional image quickly and efficiently, just as television systems now send and receive two-dimensional images. The application of such a system would bring about profound changes in both the way we communicate and what we communicate.

1.1 Overview of Thesis Goals

The goal of the research reported in this thesis has been a thorough analysis of devices, physical mechanisms, materials and technologies which might be used to accomplish a demonstration of dynamic electronic holography. The secondary goal of this work has been to evaluate the proposed development of a system for communications via electronic holography in the context of the evolution of a new media technology.

This study predicts the selection of an appropriate set of techniques for realizing dynamic electronic holography which could lead to the fabrication of operating output devices. No devices have been fabricated and no experiments have been performed during this research, however several are suggested. The information, analysis and ideas presented in this thesis should prove helpful in accomplishing that task.
1.2 Problems Facing Electronic Holography

A broad range of technical problems must be solved before the concept of electronic holography can become a reality. An electronic hologram is considered here to be an output device which functions in a manner similar to a film hologram but differs significantly in that it is an electrically addressed wavefront modulating device. Like its film counterpart, the electronic hologram is an output device only when illuminated (an emissive electronic hologram is discussed in section 4.4.4.2).

A definition of electrical addressing is left here purposely vague, framed around a requirement that the hologram driving signal is either electrical in nature or capable of being so. An electronic hologram must be capable of the accurate reconstruction of a spatially multiplexed signal when presented with a temporally multiplexed signal. This signal would be derived from either detected or synthesized information about the phase and/or intensity of a wavefront diffracted by some real or imaginary object.

Because of the nature of light diffraction at visible wavelengths, it is apparent from this description of the electronic hologram that it will require a very large number of modulating elements. For the device to be dynamic in its operation, i.e. present moving images, the modulating elements will have to be capable of high speed addressing. Addressing of the device in a serial manner will require that the device or its associated circuitry do the necessary conversion of the information contained in the serial signal into a parallel address form required for output (wavefront modulation). In succeeding chapters a detailed analysis of the output device resolution (maximum spatial frequency), speed (address and refresh rates) and serial to parallel conversion requirements will be presented.
Additional problems associated with dynamic electronic holography involve the lack of an imaging input device, the complexities of very high bandwidth signal processing, restrictions in the viewing angle resulting from limits in output device resolution, computational aspects of synthesizing an object representation, illumination systems, optics and associated hardware especially for large scale displays, and the requirements of white light illumination and color reproduction.

The only component of a dynamic electronic holography system which is not a major problem is the information channel as is discussed in Chapter 2. Each of the problem areas will require some solution before a useful dynamic electronic holography display system can be implemented for communications purposes. However, demonstration of the concept will quickly follow the development of an output device.

1.3 Potential Impact of Dynamic Electronic Holography

A motion displaying electronic hologram could help solve many problems in systems control and data display, and could contribute significantly to visual communications. The rate at which information can be accumulated, calculated or processed in most computer applications is far higher than the rate of its efficient display. This is true in medical imaging systems, in the control of complicated machinery like spacecraft or nuclear reactors, in the output of scientific instruments such as particle accelerators or seismographic stations, and in object design and engineering simulations. In these applications computed or accumulated data is converted into a (more easily) understandable form before display. Naturally, the more accurately this display is matched to the limits of the sensory system of the user, the more
efficient will be the transfer of information. Because the human visual system is designed for stereo viewing, presentation of information in three dimensions is an inherently more efficient system than presenting redundant information to both eyes.

The display of information for three-dimensional viewing is in numerous applications the naturally preferred method, and in some situations the only way to make extremely complex information available in a form useful to humans. A holographic system with an electrically addressed modulator could serve as an efficient real time output device for this purpose, especially for display applications which involve complex and changing information or the display of objects or representations moving about in three-space. A system for visual communications based on dynamic electronic holography would allow an increased information exchange for similar reasons. Further discussion of these topics is found in Chapter 2.

Other obvious areas of application for an electronically configurable hologram are as elements of optical processors and optical memories, in electronic computation as addressable optical interconnects for device, chip and board level signal directing, in VLSI device fabrication as exposure masks and mask projectors for submicron lithography, and in applications where reconfigurable optical elements or a high resolution spatial light modulator is required. Regardless of the predictions for a device's usefulness, unexpected applications will be discovered once it is a reality.

1.4 Resource Technologies and Information Sources

Development of an electronic hologram would contribute to endeavors in many diverse fields, similarly the background material for this research has
been gathered from numerous areas of research and technology development. Only a few attempts have been made by other researchers at addressing the specific problem of this investigation, however, there is a rich body of literature following investigations into the development of allied technologies. The significant body of work reporting research into high resolution light modulators for two-dimensional display applications has proven very helpful for this investigation, as has material from work towards spatial light modulators for image transformation and projection. The investigation of dynamic optical devices for optical processing has provided a wealth of data on materials, as has the research and development efforts into optical memory technology. VLSI development and fabrication techniques have given insights into the range and limitations of high density device structures. It is from these well researched areas that this investigation has collected data, background analysis, techniques, and concepts. It has been the task of this research effort to assemble from this very large body of work, in numerous diverse fields, a clear view of the possibilities for the emerging technology of dynamic electronic holography.

1.5 Research Philosophy

The philosophy of this research effort has been to try to avoid focusing solely on what have been shown to be technically feasible approaches to similar problems. Instead the approach to this investigation has required a technically unbiased look at the range of extremely high resolution display devices, keeping a clear focus on the goal of dynamic electronic holography. It is important to recognize the problem at hand as a significant departure from the needs for which the other technologies under examination were developed.
It is a natural tendency of researchers to adopt a favorite technology or preferred solution when addressing a problem. In pursuing this study, inspired with the belief that there can be development of original solutions to these new problems, it has been important to stay clear of the technical, economic and scheduling prejudices accompanying the often precarious path into new technology development.

1.6 Organization of the Thesis

The concept of electronic holography is shown in Chapter 2 to be one stage in the continuing evolution of communications technology. Examined are the forces shaping the evolution of three-dimensional displays, as are some of the non-holographic responses to these forces.

Chapter 3 is a concise overview of the problem at hand, using applications parameters as a framework for developing the specific requirements of a display device for dynamic holography. Computer and communications displays are used as models.

Chapter 4 is a compilation of a number of techniques and methods for accomplishing a DEH. The chapter is built around analyzing potential means of addressing the high resolution spatial light modulating devices involved. Designs and fabrication techniques for a range of devices are presented.

Chapter 5 investigates light modulation, pointing to several of the mechanisms and and materials that show significant promise in high speed and high density light modulators.

Conclusions and suggestions for the next steps of development are presented in Chapter 6.
This is the most complete text of the thesis available. The following page(s) were not correctly copied in the copy of the thesis deposited in the Institute Archives by the author:
These are days of miracle and wonder,
this is a long distance call ...
These are days of lasers in the jungle
don't cry baby, don't cry...

- from "Boy in the Bubble" by Paul Simon

Chapter 2
A New Media Technology
2.1 The Evolution of Electronic Holography

Evolution can be modeled as the interaction of the various forces found in an environment, pushing and pulling on the components of the environment, continuously producing change. When we take a snapshot of any scene we see one particular state of affairs, another picture later gives us a different organization of the same scene modified by the changes that have occurred in the interim. Heisenberg's Uncertainty Principle notwithstanding, a series of these time separated glimpses can help to assemble knowledge of where things were at an earlier time and possibly where things will be in the future. This notion has been applied here in an attempt to look at the "big picture" of electronic holography and its relationship to media technology development. The vision of the future of electronic holography is, to a large extent, defined by previous notions of electronic holography that have formed in the minds of display researchers and media technologists, as well as visual artists and authors of fiction and science fiction.
2.2 Media Technologies and the Artist

Important concerns in the development of media technology become apparent when following the evolution of a new media concept such as electronic holography. The impetus for the development of a new media technology often stems from the need for a particular mode of communication, with this need inspiring a quest for the means of expressing ideas that can not be expressed otherwise. Who then are the individuals or groups best suited for the development of new media technologies? Are the expression of new ideas the province of any particular profession or discipline, or is it found in equal proportions among all vocations and lifestyles?

The evolution of art forms into media technologies suggest that there may be a method of accelerating the rate at which media developments occur through the use of individuals that are trained to respond to the collective imaginations and expressive needs of the professions and of the masses. These individuals are frequently referred to as "artists." It is suggested here that the involvement of artists in the development of new medias be be pursued and cultivated as early in the development cycle as possible. The creative contributions of serious artists can have significant value both in defining possible applications of a new media and in challenging the goals of a media development program.

2.3 Premonitions of Dynamic Hologram Displays

Since the dawning of the technological age, the authors of fantasy and science fiction stories and novels have described systems of communicating
and displaying information that could (in their inner visions at least) present a	hree dimensional image to the viewer. These written descriptions of
imagined visual displays are a precedent, and to some extent a measure, of the
current task of three-dimensional imaging. Inspiration for these imagined
visualization devices probably came from familiarity with the use of early
photographic three-dimensional display techniques such as the Wheatstone
stereoscope (1830's), the Holmes-Bates viewer (1860's) and Ives parallax
photography and projection system (1930's), and most certainly preceded the
description and first demonstrations of holography in the late 1940's (non-
laser) and early 1960's (laser).

Prior to the machine age, image production involved hand manipulated
materials and tools. Visual displays were limited to the forms of the
traditional arts and crafts. Story tellers of those times would have had a hard
time describing an image projecting apparatus, resorting instead to the spirits
or magical devices for the creation of visuals, moving and intangible. This did
not stop early writers from conceiving and describing all manner of ghosts,
apparitions, phantasms, mirages, spectres, airy images and the like. These
usually took form out of light or vapors, and sometimes would exist as
shadows. It would have been interesting to see the methods used in earlier
times for the stage portrayal of apparitions such as the ghost of Hamlet's
father or Ariel in "The Tempest".

Today's special effects wizards are constantly "conjuring up" credible
visions (at least on movie and television screens) from dynamic three-
dimensional displays. Audiences have been treated to various special effects
fantasies of what these displays look like in use, how they could be used for
communications and the kinds of information they could display. It might be
argued that the concept of electronic holography is an invention of Hollywood.
The 3-D images range in size, are usually projected, and are often viewable in well lit rooms, with high resolution, color and motion. The apparatus which produces the image is not often visible in the scene, usually the seemingly self luminous image floats in space. In another common presentation format, the subject of the display has the ability to interact with its environment visually, with the display acting as an input-output communication device.

2.3.1 The Princess Leia Effect

The "Holy Grail" of holography, a dynamic light construction viewable from all directions and capable of being stored and replayed at will, has come to be known as the "Princess Leia Effect" after the use of a projected(?) 3-D image of the heroine in George Lucas's film Star Wars, the Adventures of Luke Skywalker.

The "Princess Leia" effect for cinematographic use was created through a several step process. First, the Princess Leia character (actress Carrie Fisher), was recorded on videotape using a camera turned on its side, the image was then displayed on a video screen also rotated 90 degrees, this was filmed and the resulting footage was superimposed onto the footage of a real scene with photographic techniques.

Several techniques were used to make this display seem convincing. The exaggerated vertical scan lines make the display image look like something other than television (probably an attempt to acquire the look of a multiplex hologram), the background could be seen through the seemingly transparent display, and the actors and (we) the audience were all 'viewing' the display from different widely spaced angles. Additionally, as with the optical image placement technique currently the vogue in Japanese "3-D" displays, the very
colorful character is seen in a mostly colorless surround, heightening the
dimensionality of the character in relationship to the background.

Lucas had made an earlier attempt at portraying dynamic multi-
dimensional displays in his movie **THX1138**. In this film a holographic dancer
(Yophat Kotto) is shown as an entertainment projection, transmitted by some
undisclosed means into the living room of the main character of the film
(Robert Duvall). In this not too distant view of the future the living room
becomes a darkened space where luminous dancers, newscaster, and sumo
wrestlers are invited in at the push of a remote control button.

These and myriads more portrayals of moving, seemingly holographic,
multi-dimensional visual displays have generated a broad public acceptance
and familiarity with a medium and a technology that as yet do not exist. The
impact of this on the development and integration of a real system, especially
one in its infancy, is an interesting backdrop to its development.

2.3.2 A Communications Fantasy?

In a television advertisement shown in the New England area recently, the
NYNEX Corporation presented an interesting view of the future. A business
discussion between three individuals takes place in what seems to be a very
sophisticated, yet unpretentious office. The camera is looking onto the action
from inside the room, as if the viewer where the fourth participant in a
simulated two-on-two business interaction. At one point in the meeting an
electronic display is called upon, and preceded by some sparkling visual static
in "mid air", the three-dimensional image of a high-rise building in miniature
appears to float above the center of the table. The building, in full color, seems
to be slightly transparent as it moves in slow rotation while the parties on
opposite sides of the small conference table/desk carry on a succinct business conversation, referring frequently to its image floating between them.

One participant's suggestion is followed by an instruction to the desk computer, and the miniature building which originally had two towers, quickly shows three. The only part of the actual display hardware that is seen is what appears to be a thin flat rectangular frame which the image bisects. This mechanism, almost invisible itself, extends vertically about half a meter above the surface of the table when the device is first initialized.

Another instruction is sent to the display, and the building is replaced by a three dimensional graph, again discussion is accompanied by pointing at the information as it is exchanged for new representations several times. At the close of the meeting, instead of normal handshake goodbyes as the participants on the furthest side of the table get up, in what appears to be a signal of departure, there is a wave from across the table and with another instruction to the desk computer it becomes apparent (as a wall appears where they stood moments before) that they too had been present only in a reconstructed form.

The entire scene took 30 seconds of air time. Many, if not most, television viewers that saw the ad probably missed the significance of the message. This was a communications company telling the public what it sees as part of the company mission, previewing for the consumer at home the services that are going to be made available through their efforts, and in the near future. On an almost subliminal level the communications possibilities looming large and expensively on the horizon were presented to the eventual users of the service. It is as if with the failure of the first round of video telephone services, the developments to come in this realm of "more than just telephones" must be pre-sold to the public. The selling job may be easy compared to making the services a reality.
2.4 The Potential of Expanded Bandwidth, Why HOLO-TV?

The NYNEX Co. example of an advanced communications techno-fantasy serves to illustrate two distinct areas of application predicted for the electronic hologram. The concept of "telepresence" or virtual human presence in a teleconferencing situation is a familiar theme which has yet to prove itself to be technically feasible [Negroponte 79, Perker 80].

As large bandwidth fiber optic services have become available, the first users to be able to afford their cost have also been those most needing their expanded information carrying capabilities. The proliferation of expanded bandwidth communication via fiber optic channels has been rapid and large scale, going from laboratory demonstrations to field installations in the period of a few years, with networks currently reaching from community to community and soon, home to home.

The question then remains as to why have the advances in display technologies which could be efficiently linked to high bandwidth channels not yet presented themselves? To a large extent this has been because the expansion in communications bandwidth has not been matched by a simultaneous increase in imaging systems capabilities, both input and output. Additionally, there is an ongoing debate as to the best use of the increases in communication systems capabilities, with allocation of the available bandwidth as the focus of the discussions. The ability to utilize high bandwidth services for the incorporation of computing into home entertainment and information channels has been offered as an additional dimension to the current media, an alternative to using the greater bandwidth available for simply increased resolution [Lippman 87]. The end result of
these discussions will likely be framed around factors of economy and growth, but in the interim the arena for applications of the bandwidth gain offered by current and next generation technologies is open to all comers, among them would be included electronic holography.

2.4.1 The Hi-Band Push for Added Dimensions

It is abundantly clear that the abilities of contemporary output devices will be outstripped by the advent of new high bandwidth channels for communication, especially when considering that future systems will be measured in gigabit per second rates. This is orders of magnitude above currently utilized rates. The resulting rate overflow will most likely be utilized, but how to best use it is the question being considered by the individuals and groups most concerned with the technology or those responsible for its regulation. There are two ways to channel the overflow, one is to use it to carry higher resolution information, the second is to increase the dimensionality of the information being transmitted. A system which offers more kinds of information is offering more dimensions of information. In this definition, the dimension of computing access could be compared in its bandwidth requirements and information content to the dimension of visual depth (traditionally known as the third dimension). The problem becomes one of addressing the needs and preferences of the user while utilizing the available bandwidth efficiently.

2.4.2 The Third Dimension

While a significant increase in two-dimensional image quality is undoubtedly a valuable use of the increase in available communications bandwidth, it may also be argued that since the human visual system is
designed for stereo viewing, it is probably a better use of an increased information rate to address it to the display of information three-dimensionally, i.e. to present each eye with a different view. A psychophysical analysis designed for comparing a display with increased two-dimensional resolution to the addition of depth information will show that for some tasks more 2-D is better than any 3-D, conversely some tasks can not be accomplished without depth information. The realm of this research is the area where a display with no increased resolution, but with depth information, has bandwidth allocation advantages over one with no depth information and an increased resolution.

The sampling and display of visual scene elements can, with various available technologies, be organized to extend into depth as well as height and width. The basic three-dimensional display concept is based on an ability to use data transmitted, recorded or synthesized about a scene organized into three spatial dimensions. The addition of a temporal dimension to either a two- or three-dimensional display will make the display dynamic.

### 2.5 Dynamic Three-Dimensional Displays

Some dynamic formats currently exist for the presentation of three dimensional data, and many more have been proposed for a variety of purposes. A review of non-holographic three-dimensional display devices has been given by Hesselink [85]. In this overview of the (then) available display devices and the technologies which could find application in the production of three dimensional displays, holography was intentionally not considered. The evaluation did include other three-dimensional display techniques such as
video and non-video stereoscopic imaging, integral photography, varifocal mirrors, computer graphics, revolving LED arrays and the beam addressed fluorescent cube. Each of these techniques has the capacity to be used as a dynamic output device in electronic communications or information display. All of the techniques presented have limits in their ability to display information in high resolution in one or more of their dimensions. In the systems reviewed a significant limitation is also found in the need to see the actual display hardware, or some part of it, in order to view the displayed image.

2.5.1 The Ideal System - A Projected Space Filling Display

An ideal three-dimensional display would have the ability to project an image some distance away from the display hardware, and in this way make the image viewpoint dependant or "space filling," while being hardware location independent (the mechanism "stands-aside"). Although most fantasies of dynamic three-dimensional displays have this property, none of the current technologies are capable of operating in that manner. Technology has been proposed for a stand-aside space filling three-dimensional display created by the interaction of multiple energetic beams with fluorescent materials. While holography does not fit this description of the ideal 3-D display, it comes very close.

2.5.2 Something Entirely Different

A wholly different approach to 3-D is the viewer position sensing, helmet mounted system for stereoscopic display of virtual environments which, while not being space filling, has the capacity to be viewpoint dependant [Fisher 86]. In this system the viewer wears the display as a helmet visor or pair of
glasses. A system of position sensors relates the viewer's location and viewpoint in three space to a control system which updates the visual display correspondingly, directly addressing the viewer's visual system with remotely sensed or computer synthesized views. Both the movements of the viewer and the movement of the displayed image are coupled. In effect there is no longer a display, only a virtual visual environment with virtual objects in it.

The development of a computer driven position sensing stereo display is an important step toward "display" techniques that would involve direct interconnection with the brain/vision system. The concept of a virtual visual environment is perhaps the ultimate three dimensional display.

2.6 Proposals for Real Time Holography

Researchers in a broad range of fields are preparing for the day when real-time holography is a reality. The research efforts in computer generated holography are rapidly expanding. These efforts currently rely on much less than real-time translation of computations into wavefront modulating interference patterns, using various output methods. Computers are the only current source of the high bandwidth signals required to drive a real-time hologram, signals that eventually may come from phase sensitive light detector arrays. Work has been done on analyzing potential systems for holographic output devices which could be computer driven, and laboratory experiments have been done in the field. Presented in this section are some of the published accounts of this work.
2.6.1 Goetz, Mueller, and Shupe - 1973

The authors proposed a 3-D display system which would be useful as an information display for everything from aircraft cockpits to interactive terminals. The envisioned system consists of scanned laser beams to generate holograms of points in space using a thermoplastic recording material. The resolution is expected to be similar to that of television and refresh at a rate of between 0.1 and 1.0 frames per second. Problems with the system include the frequency shifts which are reported to result from the use of acousto-optic scanners in the system. These shifts prevent the formation of stationary fringes during the exposure times being used. The authors expected to solve the problem with the use of short laser pulses generated by cavity dumping their argon laser. The recording material had also presented some problems because of its high output noise and limited frequency response, both problems were expected to be solved through the use of a thinner and cleaner thermoplastic layer. The research was reported as progressing to the breadboard stage, but no subsequent reports followed the 1973 publications. This work was done at the Bendix Research Laboratories.

2.6.2 Mok, Diep, Liu and Psaltis 1986

This publication was one of the first reported uses of a liquid crystal television (LCTV) receiver for making real-time holograms. A computer derived binary phase hologram of a circle was produced with a IBM PC computer, the output was displayed on the LCTV while illuminated with coherent light. The resulting phase modulation by the liquid crystal display resulted in the reconstruction of the circle. It is noted here that the irregularities in the LCTV display are capable of causing severe phase-
distortions. The work reported here was done at the Caltech Jet Propulsion Laboratory.

2.6.3 Schulze, 1987

This is a proposal for a real-time holographic imaging system using multiplexing techniques to record and synthesize holograms using a combination of photographic and optoelectronic techniques. The reconstruction would involve the use of a liquid crystal light valve or a very high resolution spatial light modulator using a thin deformable liquid layer that is light addressed by a multitude of two-dimensional projections. This element is referred to in his paper as the optoelectronic hologram. The author is at the Heinrich-Hertz-Institut in Berlin, where a research program towards real time holography and holographic television has been ongoing since 1983.

2.6.4 Boudreaux and Lettieri, 1987

The authors report on the generation, display, and animation of three-dimensional holographic images. They predict a system for computer display of moving images using the optical computer to accomplish many of the necessary computational functions. The output device they predict would use light valve technology with a resolution of about 2000 element per mm² to reconstruct holographic stereograms. They propose that the display device present a large number of different horizontal views, sequentially and rapidly enough so that there is the appearance of a three-dimensional image. The authors are at the NBS Center for Manufacturing Engineering.

2.6.5 Benton, 1987

The goal of this research program is to demonstrate a real-time hologram which is capable of displaying a three dimensional image, with each view
having 100 lines of resolution in both horizontal and vertical directions. The size specified for the test display is 50mm by 50mm. It is proposed to use a single horizontal line output device with spatial frequency high enough for 12° of view, the line is to be scanned vertically in order to present 100 lines per frame, one frame every 1/10 of a second. Being a horizontal parallax only display, the bandwidth will be reduced to as low a value as possible, while still generating a recognizable image. The bandwidth of the display is to match that of current fiber optic technology. It is suggested that the signal to drive the display be derived from a massively parallel computer, specifically a Connection Machine. Various techniques are to be explored for the output device, focussing on use of wide aperture acousto-optic modulators with large time-bandwidth products. This work is ongoing at the MIT Media Laboratory.
Chapter 3

Modulator Device Requirements

The previous chapter has considered the electronic transmission of holograms, and the bandwidth reduction requirements for a holography based visual communications system. This chapter will examine the applications requirements for holographic display devices. The product of this investigation will be a set of specifications that will be used in the analysis of potential display device technologies in chapter 4. These specifications will reflect the various methods of high efficiency bandwidth reduction previously discussed.

The two display applications areas to be considered here are 1.) animated computer generated holograms and 2.) face-to-face telephonic communications. Other important applications for dynamic electronic holograms and holography (DEH) exist, largely as extensions from these two application areas.

3.1 Interfacing with Computer Generated Signals

Computers are used extensively as tools to make holograms. Two types of holograms are referred to as computer generated, both are computed 3-D representations of imaginary or synthetic objects. In one common usage, the technique of computer generated holography (CGH) refers to holographically
generating a stereogram from synthetic objects and scenes that have been computed and recorded as a number of angularly separated views.

The usage of the term "computer generated hologram" in this text, however, pertains specifically to the production of computed diffraction patterns. These patterns would produce a desired spatial wavefront modulation when properly recorded and illuminated, thus it would be possible to make the first type of CGH (holographic stereogram) using the techniques of the second (computed diffraction).

Computer generated holography (CGH) is a rapidly expanding field which utilizes computationally constructed holograms for a variety of purposes. Various mathematical approaches have been used to compute CGH's, using a range of processing algorithm based programs operating primarily on linear processors, generally involving time consuming calculations [Caulfield 85, Tricoles 87].

Methods used to output CGH's are additionally time consuming. Techniques have involved the use of an X-Y recorder, mechanical plotter, drum scanner, or facsimile machine to print the hologram pattern in an enlarged scale. Photographic reduction techniques have been used to transfer the hologram pattern onto the wavefront modulating medium, usually photographic film [Bryngdahl 75,84, Yaroslavskii, Just 85]. The process is slow, taking as much as a day or more to produce the hologram. Laser scanners have decreased the time required for the printing and reduced the photoreduction requirements by using a 4μm spot diameter on a 10μm raster for writing the pattern [Frere 86].

Electron beam exposure techniques, using integrated circuit mask making equipment, allow rapid output of the computed diffraction patterns, as well as submicron structures. Vector scanning [Athale 83, Farhoosh 87, Leung 80] or
raster scanning [Freyer 83] of an electron beam is used to write the diffraction pattern onto a multitude of small contiguous sectors on a mechanically translated substrate, exposing a few mm$^2$ at a time. Although this technique is capable of directly writing a diffracting structure with high spatial frequencies over as large an area as 12cm by 12cm, it too is a very time intensive process.

The electron beam CGH recording involves the hologram calculation, preparation of a resist coated (chromium on glass) substrate, a careful step-and-repeat exposure followed by development, baking, etching, washing and drying to make the final hologram. The operation requires several hours to make a hologram. This technique has been used extensively in preparing holographic optical elements.

Special resists such as Novolak (Olin Hunt Products) are required for electron beam exposure. The use of silver halide emulsions is limited by charge spreading to multi-micron resolutions [Thompson 73, Heidereich 73].

The advantages presented by a dynamic electronic hologram display over even the best of these CGH hardcopy techniques are that, although computation time is still required, a DEH would allow the "real-time" viewing of computer generated holograms.

### 3.1.1 Computer Driven Displays

Although it is conceivable that computers will someday be designed specifically for generating holograms, especially once an appropriate display technology is perfected, current development of DEH devices is dependant on computers designed for output onto 2-D visual information displays.

Data and information that computers now generate is converted into spatially modulated light signals (images) using various picture mapping
techniques with non-coherent self-luminous displays (cathode ray tube- CRT, plasma display panel- PDP, light emitting diode- LED, electroluminescent- EL, etc.) or non-coherently illuminated displays (liquid crystal displays- LCD, electrophoretic displays- EPD, etc.).

Each light generating or modulating element of the display has a mapped memory address that holds the current brightness value for that picture element (pixel). The values in each of the map locations are read in sequence and transferred to the display device via a video signal. Depending on the resolution of the display, this information can form images with as many as 8,000 lines of resolution.

For a high resolution (2,000 line) RGB color CRT, addressing involves as many as 12 million sequentially addressed pixels from as many memory map locations. The standard NTSC video line rate of 15,750 Hz utilizes bandwidths of 32 MHz per color channel for such a high resolution display, giving address times of $3 \times 10^{-8}$ seconds per pixel, or $6.3 \times 10^{-5}$ seconds per line. The DEH display device, when computer driven, would need to interface with the output of these display drivers or a suitable buffer.

3.1.2 Connection Machine Hologram Computation

The current program of research in electronic holography at the MIT Media Laboratory calls for the computer generation of the information content of a synthetic hologram, which would then be displayed using a DEH device. To implement the computational end of this, massively parallel computation is used, involving a Thinking Machines Corporation "Connection Machine" (CM). This "supercomputer", with 16,384 processors operating simultaneously, is capable of computing the wavefront distribution for an
object composed of 16,384 self luminous points more rapidly than serial computers currently available.

Experiments in wavefront computation using the CM and a suggested object geometry of approximately 100 by 100 elements explored several approaches to the processing algorithm [Underkoffler 88]. The first procedure tested, the Chunky-style algorithm, involved the simultaneous production of wavefronts from a data base derived object that were organized into a 128 by 128 cell array. It was found that this method was not as efficient as generating a one-dimensional array with the same total number of elements (Spaghetti-style algorithm).

The current program produces a one-dimensional "hologram" strip composed of 16,384 samples. This number is based on the maximum parallel variable (pvar) distribution length inherent to the architecture of the processor. Additional sample lengths can be calculated, but at a cost of greatly increased computation time. The linear output array as computed, is filtered to remove unusable spatial frequencies with additional computational passes. This linear array technique follows the proposal by Benton [87] that the DEH device could be a single linear diffracting structure that is vertically scanned to compose a 2-D frame.

The time required for the hologram generating calculations using the current hardware configuration precludes real-time animation of a synthetic object's holographic reconstruction. Using the most efficient and longest sample length of 16,384 elements reduces the calculation time of the computer while maximizing the time-bandwidth of the proposed output device. Initially, the three-dimensional dynamic display device will have to be driven by a server with data accumulating capabilities. More advanced machines, such as the CM2 or another array processor, will allow a more direct link between the
computer and the display in the near future as well as faster updates of the image.

3.1.3 Computer Display Requirements

Projecting from the constraints applied by the computer hardware and software, and using the reduced bandwidth reconstruction format, the requirements for a computer driven device can be partially specified.

The DEH device under development would be called upon to display as many as 16k elements (as determined by the current maximum number of computed samples in a single horizontal line, and more as the processing hardware is upgraded). The displayed image would consist of approximately 128 lines per frame, with a frame rate to be determined by hardware and software capabilities.

This is far from a complete set of display specifications, giving primarily an indication of the diffraction structures that could be computed with available hardware. In the following section more requirements are to be developed leading to a full description of the DEH device from its applications.

3.2 Interfacing with Communications Channels

An application of dynamic electronic hologram displays in the areas of broadcast and networked communications would have a significant impact. Responding to the challenges of advanced communications needs, and to the possibilities presented by advanced communications systems, is looked upon as a major activity of the DEH device development program by the MIT Media Laboratory's Spatial Imaging Group.
Although the development of the display device is dependent currently upon computer generated hologram signals, in the future, image sensing techniques may be developed which will allow the driving signal to be derived from real objects and scenes. This is an acceptable development scenario because, except for the signal source and subject matter, communications systems applications of a DEH would be very similar to those of computer information display and object simulation.

A high bandwidth fiber optic communications transceiver and cable made available from the USWest Corporation has made testing an experimental output device at bandwidths up to 500 Mb/sec possible. The lack of a comparably large bandwidth "hologram" signal, computer generated or otherwise, currently limits the application of the transceiver capacity. It would, however, be reasonable to direct the DEH device development towards this target bandwidth as it is near the lower bandwidth limit for "normal" or non-reduced bandwidth holographic imaging.

3.2.1 Telephony Requirements

Telephonic applications suggest that the display be capable of being viewed primarily by an individual and only occasionally by a group, thus the viewing zone can be quite small and still prove useful for experimental and demonstration purposes. The viewing zone might be the size of a small pocket television screen, 50mm by 50mm, and use lenses to magnify the image if required. The use of small (or inexpensive) lenses will, however, impose an aperture restriction on the viewing zone as well as introduce to the image astigmatism and other aberrations.

At close viewing distances (approximately one foot), the small display would have a limited but acceptable viewing zone. A 12° viewing angle has
been proposed for the horizontal view zone with a 4° viewing angle vertically. An image plane hologram with a spatial frequency of 325 cy/mm would give the 50mm wide hologram 16,250 cycles. This would require 32,500 elements, assuming two elements per cycle. In this application, as in the CGH reconstruction mentioned in the previous section, the vertical dimension would contain only image information and would be scanned not diffracted, using diffraction to generate horizontal parallax only.

Telephony applications give an insight into the refresh rate requirements of the demonstration device as well. Experiments with videophones have shown that the rate of motion of the subject in most conversational modes allows a lower frame rate than that required by broadcast television with its complex scenes and rapid translational movements [Pratt 79, Schreiber 85]. For the experimental demonstration DEH system it seems likely that an acceptable frame rate will fall between 10 frames per second (one third normal video rate) and 20 frames per second (videophone rate).

3.3 Device Design Overview

With a generally fixed input and reconstruction bandwidth, a dynamic electronic hologram would show only two degrees of freedom in an operational constraint analysis. The exchange of temporal and spatial resolution is the only option available for the DEH, a problem shared by spatial light modulators, being generally fixed or limited bandwidth devices themselves. Light modulating systems and materials show a decrease or limit in the number of spatially resolvable points with higher addressing rates, and a similar limit or decrease in addressing rate when called upon to resolve more points.
In considering possible methods and geometries for physically arraying the modulating elements that make up the DEH device, two factors should be taken into account, the method used to apply the drive signal to elements (addressing) and the element density. These two factors are corollaries to the resolution/time relationship mentioned above, and because of this, impose limitations on each other in most geometries. When considered together, however, they can help determine the most efficient geometry of a potential DEH device.

The individual elements of any DEH device will have to be operated in a parallel manner in order to generate diffraction in the illuminating wavefront. This requires, whatever method of addressing is used, that all of the device elements be in the proper modulating state at the time of interaction with the wavefront. Any element not in the proper state will contribute to phase and amplitude errors in the reconstructed wavefront. In order to accomplish the desired synchronization, the device will have to incorporate a memory cycle or be driven by a serial-to-parallel converter. The addressing issue will be considered in greater depth in the following chapter, its relationship to device structure and geometry is considered here.

3.3.1 Density Considerations

It is important to remember that it is the total number of elements in the hologram that determine the visual resolution of the hologram, and not necessarily the density of the elements [Cathey 74]. Physical and to some extent economical constraints dictate the lower and upper limits to the modulating element spacing, and thus the total device size.

A decreased density of modulating elements could be accomplished with an optical system that increases the apparent spatial frequency of the
modulating elements by a demagnification of the modulating array to a smaller region with resulting increased diffraction angles. Proper reconstruction is dependant on the exact preservation of the phase relationship between elements of the wavefront as they pass through the demagnifying optical system. This puts demands on the size and required quality of the optics and the overall design of the system. Depending on the size of the modulating array, large lenses with very little wavefront distortion could be required, adding significantly to the cost of the display. It is conceivable that a holographic optical system could be designed and implemented to take the "glass" out of the system while achieving the required wavefront phase maintenance.

A device with a low density of elements may involve more simplified fabrication, however, because of its size it may have more difficulty in the addressing of large numbers of elements quickly or accurately than would a more compact device. The addressing problems would be due to increased address (access) time and accumulated addressing errors. This is particularly true for beam addressed systems. In line addressed systems, additional problems arise from interline crosstalk and signal delay times involved with large devices, especially at high speeds.

3.3.2 2-D Array Geometries

In considering the required time-bandwidth product for the DEH device, it is important to note that 2-D devices currently exist with the required number of display elements for the minimal model of 16K line elements refreshed 1000 times a second. For example, a HDTV CRT has 27 million addresses per second, almost twice as many as in the proof of principle line-scan hologram.
Some raster scanned light valves are capable of being coherently illuminated and have bandwidths approaching 100MHz [Noble 79].

Several researchers in the field of electronic holography have suggested that it may be possible to utilize sub-hologram sampling methods to make a wider viewing zone image from a series of small two-dimensional holograms that are scanned horizontally [Boudreaux 87, Parker 87, Schulze 87, Kollin 88]. 2-D sub-hologram elements with a modulating structure density similar to that of a HPO stereogram could be spatial-temporal multiplexed to present a 3-D image using integral holography techniques.

Boudreaux suggests that sub-holograms could be generated with conventional display devices, such as light valves, some of which are capable of 50 lines per mm resolution or 2.5 \times 10^3 elements per mm^2 density. Three-dimensionality would be the result of a horizontal scan across the viewing zone of a single sub-hologram element as it is rapidly rewritten for each new spatial location.

The required speed of the device to make a holographic stereogram with 50 perspective views would be 150 views per second, this would allow 6.7 \times 10^{-4} seconds to generate each sub-hologram. Assuming each sub-hologram was the size of a pupil, or 3mm diameter, then each view would be composed of 1.4 \times 10^4 elements, and the stereogram when refreshed at 30Hz would have a bandwidth of 21MHz.

This result, when compared to the line at a time technique, seems to offer some distinct advantages. For example the time to address each modulating element of each sub-hologram is 4.7 \times 10^{-8} seconds, giving 50% more time per element than for a vertically scanned single line hologram, and the required bandwidth at an equivalent frame rate would be 80% less.
There are a few problems with this concept that should be mentioned. Most significantly is that the sub-hologram spatial frequency of 25 cy/mm would diffract 633nm light less than half a degree, giving a very small viewing angle for each element. Raising the spatial frequency to 350 cy/mm would increase the bandwidth by a factor of fifty, to 1 GHz. Additionally, viewing would require a lens to project the peep-hole image to the viewer's eyes.

The acousto-optic (a-o) modulation technique currently being refined at the MIT Media Laboratory utilizes a modification of this concept to horizontally scan a vertically swept computer generated single line (1-D) diffraction pattern. The viewer's visual system is called upon to assemble the sequentially presented sub-holograms into a three-dimensional view [Kollin 88]. Similar modulation schemes have been developed for wideband signal recording and holographic storage of electric signals [Arm 69, Blosser 83, Coppock 83].

A non-horizontally scanned a-o hologram using the same modulating technique, generating only vertically swept lines, would have required an a-o modulator with a far greater one-dimensional time-bandwidth product than is currently available to achieve the design goals. With the 2-D scanning technique bandwidth burden is spread over the two operations of scanning and sweeping, making the modulator requirements less severe. Image stability will be affected by wobble in two dimensions requiring an additional electro-optic feedback system and electronics to error correct and synchronize the multiple activities involved.

The method of composing the DEH by 2-D scanning an area with an array that is itself scanned suggests that there should be a nomenclature distinction between the two addressing processes involved. We will refer to the two scans as the "composite" addressing and the "local" addressing respectively. This
distinction will be considered again when we examine addressing techniques in chapter 5.

3.4 Summary of Device Requirements

The real-time production of a hologram will require a wavefront modulator with a large number of elements that are rapidly addressed. Many geometrical arrangements are possible for these elements in a DEH device. Three variations on this theme have become apparent, ranked in the order of complexity, highest to lowest they are 1.) a device with a spatially scanned electronically generated hologram sub-element, using either a 2-D or 1-D array of modulating elements, 2.) a device with either a 1-D or 2-D array of modulating elements with a low spatial frequency which uses an optical system to reduce the element spacing to the desired distance and 3.) a device that uses either a 2-D or 1-D array of elements at the required spatial frequency.

For the simplest arrangement, a one-dimensional array device as contemplated by the applications requirements, each element pair in the device would be used to assemble spatial frequencies of 325 cycles/mm, yielding 12° of viewing angle when the illumination is with plane wave laser light at a wavelength of 633 nanometers.

The time-bandwidth (and space-spatial frequency bandwidth product) for a one-line-at-a-time device would be limited by the present computer hardware at MIT to approximately 16,000 elements per line. This would allow 8,000 cycles of diffraction at 320 cycles/mm in a 25mm wide array. Each element in
the array would be 1.5 microns wide. This device would suffice for the earliest
testing, however the goals of the research program call for a device with 50,000
elements in a 50mm diffracting array, having element widths of 1 micron or
less. This smaller element should be considered as a long range goal of the
DEH device development.

A computer hardware upgrade as planned will at least double the
addressable element count in the near future. Designing the line array in
consideration of this upgrade gives a factor of two increase in the width of the
320 cy/mm array to 50mm, without changing the density requirements of the
device. When scanned vertically this would yield a frame size 50mm by 50mm.
Since the object resolution as computed will be approximately 100 lines
vertically, 100 scan lines will be sufficient.

In order to give an appearance of "continuous" motion, the device will be
refreshed at a rate of at least 10 frames per second, although higher speeds are
suggested by the applications considered. This frame rate and element count,
together with a vertical resolution of 100 non-diffracted lines, will yield a low
spatial and temporal resolution horizontal parallax only (HPO) hologram.
Image fidelity motion rendition would not be very accurate in this early
demonstration system. Accomplishing this "one-liner" will require
identifying technologies that can address each line of 16,250 elements in 10^{-3}
seconds, thus, if addressed in a serial fashion, giving 6 \times 10^{-8} seconds of
address time per element. Both the device and the information channel
supplying it will need a bandwidth of 16 MHz, or four times normal video
rates. The output channel rates of high resolution frame buffers as are used
in graphics computers are in this bandwidth region. Computed holograms
should be available for experimental devices to display, generated by the
Connection Machine, and planned initially to be objects composed of 16,384 elements.

Modulation depth for the device has not been considered in the previous discussions primarily because, at this point in the research, the contrast range is of less concern than the time-bandwidth and speed-density products of a potential modulating technology or device. Contrast in the range of holographic film, approximately 100:1, would be adequate for experimental devices although 8 bit devices with a contrast of 256:1 should be planned for lower noise.

The following chapters will examine mechanisms for addressing high density structures of light modulating materials with the required speed to satisfy the requirements developed here.
Chapter 4

Light Modulators for DEH Part 1:

Modulator Addressing

In its simplest description, dynamic electronic hologram reconstruction involves spatially modulating lightwaves with the information contained in an electrical signal. A "black box" of some sort will be necessary to accomplish this, that is, a device that takes a (high bandwidth) signal and a source of light, and creates with them the moving three-dimensional image of some object. Such a device can be considered as a type of spatial light modulator (SLM).

The goal of this chapter is to specify the modulating mechanisms and devices with which this might be made to happen, i.e. a range of possible contents of the "black box." Although a great deal of development towards faster and higher resolution SLM devices has occurred in the last two decades, none of these are presently usable "off the shelf" to meet the dynamic electronic holography requirements developed at the end of the previous chapter.

The methodology used in the research presented in this chapter has been to approach the development of a DEH device by capitalizing on existing SLM devices and techniques, specifically analyzing the speed, resolution, time-bandwidth product and speed-density product of each. Technical and commercial endeavors in many fields outside of holography such as high
speed electronic printing, video projection, integrated optics, optical computing and optical data storage have prompted the development of devices similar in many ways to those sought in this research. Because the technology necessary to accomplish the task at hand has not yet been demonstrated, this perusal of the "SLM smorgasbord" will serve to assist in picking out those spatial light modulating devices/mechanisms deserving further development and suggest new alternative solutions. Transmissive and reflective devices are considered.

Addressing schemes for DEH devices are the primary focus for this chapter. A systematic classification of existing light modulating devices (4.1) is followed by a discussion of possible DEH devices using the two currently available addressing schemes, line addressing (4.2) and beam addressing (4.3). Chapter 5 is concerned with some light modulating materials and effects that could be used in these devices, and examines their limitations.

4.1 Taxonomy of Spatial Light Modulation Devices

In the 1960's, two SLM methods were noted as possible candidates for electrically reproducing the high spatial frequency diffracting structures required for holography. These were: the generation of surface thickness variations in a fluid layer via a scanned electron beam (an Eidophor light valve); and the generation of absorption variations in a photochromic material using a scanned laser beam (an erasable optical memory) [Leith 65, Enloe 68]. These two methods demonstrate the combination of a (high resolution) modulating mechanism with a (high speed) addressing scheme that are necessary for a DEH device. Table 4.1 indicates some of the SLM devices that have been developed exhibiting a range of addressable phase modulation techniques.
<table>
<thead>
<tr>
<th>Name</th>
<th>Modulating Material</th>
<th>Light Sensor</th>
<th>Resolution (lp/mm)</th>
<th>Sensitivity (uJ/cm²)</th>
<th>Phase Dynamic Range (Radians)</th>
<th>Operating Voltage (Volts)</th>
<th>Time Write (msec)</th>
<th>Time Erase (msec)</th>
<th>Time Store (sec)</th>
<th>Developed At</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photo-titus</td>
<td>KD*P</td>
<td>amorphous Se</td>
<td>6</td>
<td>10</td>
<td>0.5a</td>
<td>250⁸ (-51°C)</td>
<td>0.01</td>
<td>0.03</td>
<td>-1 hr (-51°C)</td>
<td>France</td>
</tr>
<tr>
<td>LCLV</td>
<td>Twisted nematic</td>
<td>CdS</td>
<td>33⁵</td>
<td>5</td>
<td>1.7a</td>
<td>5 - 15 (ac)</td>
<td>10</td>
<td>15</td>
<td>15mssec</td>
<td>Hughes⁹</td>
</tr>
<tr>
<td>(FERICON)</td>
<td>Liquid crystal</td>
<td>PLT</td>
<td>33⁴</td>
<td>5</td>
<td>1.7a</td>
<td>5 - 15 (ac)</td>
<td>10</td>
<td>15</td>
<td>15mssec</td>
<td>Hughes⁹</td>
</tr>
<tr>
<td>Ruticon</td>
<td>Strain-biased</td>
<td>ZnCdS</td>
<td>20⁴</td>
<td>5</td>
<td>3a</td>
<td>525² (1mm thick)</td>
<td>-1</td>
<td>10</td>
<td>hrs</td>
<td>Bell Scandia</td>
</tr>
<tr>
<td>Promo</td>
<td>Deformable</td>
<td>amorphous Se</td>
<td>10-45⁴</td>
<td>5</td>
<td>0.2a</td>
<td>300 (for 0.1⁵)</td>
<td>10</td>
<td>1000</td>
<td>15min</td>
<td>Xerox</td>
</tr>
<tr>
<td>EDM</td>
<td>Deformable membrane</td>
<td>Si</td>
<td>3⁵</td>
<td>2</td>
<td>3a</td>
<td>3900²</td>
<td>5</td>
<td>1</td>
<td>&lt;2hrs</td>
<td>Itex⁹</td>
</tr>
<tr>
<td>Thermo-</td>
<td>Thermo plastic</td>
<td>PVK:INF</td>
<td>20-120⁴</td>
<td>5</td>
<td>&lt;a</td>
<td>700-900</td>
<td>10</td>
<td>250</td>
<td></td>
<td>Perkin-Elmer</td>
</tr>
<tr>
<td>Plastic</td>
<td>Oil-film</td>
<td>Polysiloxan</td>
<td>5¹ b</td>
<td>10⁴</td>
<td>14a</td>
<td>0 (passive)</td>
<td>100</td>
<td>&lt;100</td>
<td>&lt;0.2 sec</td>
<td>Switzerland</td>
</tr>
<tr>
<td>PELM</td>
<td>Deformable membrane</td>
<td>Photocathode</td>
<td>5</td>
<td>0.001</td>
<td>0.5a</td>
<td>&lt;0.1</td>
<td>100</td>
<td>sec</td>
<td></td>
<td>England</td>
</tr>
<tr>
<td>MSLM</td>
<td>Electroptic crystal</td>
<td>Photocathode</td>
<td>20³ c</td>
<td>0.002² e</td>
<td>&gt;5³ a</td>
<td>250-800²</td>
<td>&lt;1²</td>
<td>&lt;1²</td>
<td>weeks</td>
<td>MIT</td>
</tr>
</tbody>
</table>
A broad range of materials exhibit light modulating mechanisms and effects, many of which could be applied to high speed, high resolution spatial light modulation. There are, however, fewer methods of electrically addressing these materials, with only two schemes available currently: 1.) the use of a conductive pathway to reach the elements of the array (line addressing) and 2.) scanning the array with focused electrically modulated energy (beam addressing).

The two classes of addressing methods suggested, used in conjunction with a broad range of light modulating mechanisms and materials, have spawned an expansive field of SLM's. The various classes of modulation mechanisms may be further divided into sub-classes yielding many distinctly separate techniques of light modulation. Several hundred material types are organized into these sub-classes as the agents for the modulation, each material having a measurable set of qualities and limitations dependant on their means of addressing.

A major problem in the study of spatial light modulators, and a substantial headache in the organization of this thesis, has been in structuring a clear relationship between modulator materials and addressing techniques. The relationships between the physical effect of modulation, the material in which the effect is produced and the means by which the effect is controlled are evidenced in the actual SLM device. Because none of the existing SLM's are capable of the tasks required of a DEH, assembling a proper attack on the problem has required dividing the known devices into their operative parts and attempting a reassembly.

Table 4.2 demonstrates an organization among the line and beam addressing schemes in relation to modulating mechanisms and the devices which use them. Parentheses are in place where devices are not yet reported.
<table>
<thead>
<tr>
<th>Line Addressed</th>
<th>Modulating Mechanism</th>
<th>Beam Addressed</th>
<th>Electron</th>
<th>Photon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>photographic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>electro-optic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-liquid crystals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mos-LCLV, VGM CCDLV</td>
<td>electrochromic</td>
<td></td>
<td></td>
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4.2 Line Addressing

The DEH device as we have specified it in previous chapters will consist of a physically very compact modulator array with a very large number of elements. Each of these elements will have a light modulating state that can be varied in response to a time varying electrical signal. The number of states or dynamic range of modulation varies greatly from mechanism to mechanism and material to material, e.g. the various phase modulating systems show a dynamic range varying from a fraction of π to several π. The elements will be read simultaneously requiring that individual elements are either parallel addressed or serially addressed and have memory.

An approach to the addressing problem using a linear array of electrodes to line address an electro-optic (e-o) material is shown in figure 4.1. Several types of devices have been constructed using similar designs incorporating multiple electrodes to address a single crystal of e-o material [Johnson 83, Henderson 79, Meyer 72, Land 77, Esener 87]. These devices as discussed in the references indicated are used in optical signal processing, tunable optical filters, beam steering, page composing and optical computation, respectively.

![Diagram of Electrode array addressed e-o modulator](image)

Figure 4.1: Electrode array addressed e-o modulator (after Johnson)
The maximum spatial frequencies and time bandwidth (T-B) products for multi-electrode line addressing are limited by the available fabrication techniques and the choice of modulator material. Additional considerations which affect line addressing are the device power dissipation (to avoid thermal distortion of the modulator) and inter-electrode capacitance (in order to achieve maximum speed and minimum crosstalk). Similar problems have been the concern of the designers of integrated optical circuits and guided wave optical devices, where the modulating material is configured with address lines and light carrying channels of light wave scale dimensions on the same substrate [Holman 85].

Experimental integrated optical devices demonstrate that high density and large time-bandwidth discretely addressed devices are feasible using electrodes that are either deposited on the modulating material or placed in close contact with it [Turner 82]. A 5000 element, one dimensional array, total internal reflection (TIR) spatial light modulator has been considered for applications such as page composition applications [Johnson 83]. Although referred to, this device has not been reported as operational. If it were available it would compete favorably with the highest time-bandwidth acousto-optic (a-o) modulator crystals currently available. It is possible that it has been fabricated but that its use is limited to security related projects, thereby clamping any reports of its existence or properties.

Devices which utilize the e-o modulating material in a transverse manner require a lower applied voltage than that needed by a co-axial modulator to produce the same optical phase shift. In these devices the fringe field between electrodes is utilized for modulation so that unless carefully configured, the device resolution is limited by fringe field spillover, instead of being fabrication limited.
4.2.1 A Buried Waveguide Integrated E-O Array

An array of electro-optically active light "pipes", or optical waveguides, with integrated driving electrodes is a possible configuration for a line addressed device. Figures 4.2a, 4.2b and 4.2c show a device built on an optical substrate having subsurface optical waveguides parallel to individual address lines located beneath. Techniques such as ion implantation [Moutonnet 74] or thermal diffusion would be used to selectively dope the substrate to alter the refractive and electro-optic properties of the waveguide regions. A common electrode coating is evaporated onto the cover surface after the waveguides are implanted.

The device would use a set of input and output coupling prisms to get the light into and out of the modulator array. Another construction method would involve the use of holographic fabrication techniques and ion milling to prepare an array of individually addressed waveguide channels which would be filled with an electro-optic material, such as liquid crystals, and covered with an electrode array which had been similarly holographically generated. These techniques are detailed in section 4.3.5.
4.2.2 The Interconnection Problem

Applying the drive signal to the modulating elements individually, as with one address wire per element, is made cumbersome due to the fact that the device has a large number of closely spaced elements. Parallel operation requires that each element have an interconnect line, however short, to couple it to a driver circuit or to a memory array. To get a picture of the interconnect problem, consider a model device with 16,000 interconnect lines running between the modulating elements and their memory/driver cells. Three models, with decreasing size, will be considered in order to get a "feel" for the problem.

First, for perspective, consider the model at a "human size" scale. If we imagine the modulating device so that each element of the linear array was the size of a sidewalk block, ~3' wide, then a continuous sidewalk with 16,000 such elements would be nine miles long. This would be comparable to a single
sidewalk the length of Manhattan Island. Running a wire to each of these blocks would be fairly easy, especially since the wire could be very much smaller than the block. For example, using 1/16" diameter wires to connect with each "element" would result in a (flat) wire braid 1000" wide, (83 feet).

Reducing the scale by ignoring the device size and specifying that it be placed on a circuit board made with the finest pitch lines used for standard printed circuit fabrication, currently 10 mil (250μm) [Bregman 88], the wiring braid would now be 160" wide (13' 4").

There is only a factor of six difference in the connecting wiring width between these two very different situations. Distributing the 10 mil width interconnects around the perimeter of the printed circuit package would result in a square package over 3 feet on a side. Pushing the technology and shrinking the lines to the limit of current screening techniques, or 3 mil pitch, would result in a one foot square package.

Fabricating the modulating device in the center of a large silicon wafer or other suitable integrated circuit substrate is the third model. Its individual address lines would be spread out to connection pads on the circumference of the wafer for interconnection to the drive circuits on a carrier or surface mounting package substrate. In order to equally space 16,000 connection pads or pins around an 8" wafer, each could be no more than 40 microns wide, which is 10 microns less than the smallest pitch currently available using anisotropic tape bonding methods (soft connections).

Mounting and lead attachment could be done using the 22 micron pitch technique developed by Mosaic Corporation to wire bond chips to carriers. Utilization of pin grid array I/O techniques with solder bump chip attachment, as used by IBM on alumina substrates (25 μm pitch) and AT&T on silicon
substrates (50 μm pitch), gives high conductor densities with minimum capacitance and resistance in the signal lines.

High density array processor chips utilize 200 to 400 I/O pins to give addressability to approximately 1 million gates, versus the 16 to 50 thousand parallel connections that would be involved in a line addressed DEH device. Mounting the DEH device onto a driver board with this large a number of hard edge connections would probably result in mechanical bonding and thermal expansion/contraction problems regardless of the technique used (tape, solder bump or wire).

From these three models it is apparent that in order to minimize the substrate size for a device that has board level interconnection to its drivers, the lines connecting the elements to their drivers, or to memory cells, should be smaller than the elements themselves. With micron size elements this will require submicron line widths, especially difficult to generate unbroken or unbridged over lengths of 1cm or more. Clearly then, the modulating device and its driving circuits are going to have to be on the same substrate to avoid major interconnect problems.

4.3 Single Substrate DEH Device Fabrication

Current VLSI mask and wafer fabrication techniques are applicable to making a DEH device on a single substrate. Holographic (interferometry) fabrication techniques may offer the non-VLSI equipped laboratory an alternative fabrication technique. These two means of fabrication are discussed here, without special regard for the modulating material to be used. It is hoped that from the range of materials available, one with the required characteristics will be found.
4.3.1 Integrated Circuits and VLSI Fabrication for DEH Devices

The continuing development of electronic devices has inevitably lead to a "solid state" configuration for any device, or its replacement by a like performing solid state device. In solid state devices electrons move very short distances, obviously advantageous for small and fast circuits. Lower production cost and higher reliability usually result when a complex device can be fabricated essentially "all at the same time" and with no separable parts, i.e. an integrated circuit (IC).

IC fabrication techniques, expensive as they may be, led to "many identical devices, all at the same time," making even extremely complicated devices, involving a large number of processing steps, commercially viable. The operating parameters and scale of the DEH device is in the right range for solid state fabrication techniques, although it may require techniques and materials for its fabrication that are as yet not developed or perfected. Additionally, the "push" ($) for the use of large scale and very large scale integration (VLSI) and extremely large scale integration (ELSI or wafer scale) techniques in DEH fabrication will be missing at this stage of its development because there is currently a limited commercial interest for this particular device. Programs of device development that justify the effort and expense of these technologies should be expected in the immediate future because in part to the wide reaching applications of spatial light modulating devices.

Over the last twenty years, while holography was coming of age, significant advances were made in the development of very small, very high density and very fast electronic circuits. Dynamic random access memory chips less than a few cm\(^2\) area are routinely fabricated with 4 million memory cells, having access times well under 100 ns. In devices of this type each
memory cell consists of a single transistor and a capacitor (1-T cell). Using .8 μm technology, a 1-T memory cell can be made 2μm by 4μm. More reduced scale design rules and advanced side wall fabrication techniques could yield even smaller devices. Depending on the availability of a modulating material, an IC spatial light modulator with the desired density and speed specifications for the DEH device seems very feasible.

4.3.2 A "Quickie" Addressable Diffraction Element

An IC based DEH-type device could be demonstrated quite quickly (in four to six weeks) by using a readily available high density memory chip as the addressing system that is overcoated with a thin layer of liquid crystals to act as the light modulating material.

The liquid crystal "Quickie" addressable diffraction element (ADE) is a precursor to the DEH that relies on a technique developed initially to locate hot spots in operating integrated circuits. It was found that the electric fields on the surface of a functioning IC chip could be visually inspected through the local electro-optic rotation of nematic liquid crystal (LC) molecules [Channin 74].

This technique could be applied to a nude memory chip in operation, taking advantage of the memory array organization and address structures which result in an addressed array of electric fields that have a component perpendicular to the chip surface. Thus, a high spatial frequency light modulating device might be made without the time and effort needed to specially fabricate the required electrode structures and drivers.

In utilizing this technique for a demonstration ADE, a suitably organized memory chip (256k to 4M DRAM), either on a wafer or surface mounted to a lead-out package without a cover, would be used in conjunction with a memory
driver acting as buffer and server. A mounted chip would first be spin coated with a material that produces molecular alignment of the liquid crystal layer parallel to the surface, such as a surfactant solution, i.e. lecithin in trichloroethylene. Alternately, various normal alignment techniques such as surface rubbing might be used with appropriate caution. A similarly treated cover slip would be placed over the chip with a small amount of LC material placed between, forming a layer a few microns thick (2π phase shift).

N-(p-methoxybenzylidene)-p-butylaniline (MBBA) has been used for this purpose because of its high negative dielectric anisotropy, which results in the molecules rotating perpendicular to the electric field. Liquid crystals with positive anisotropy could also be used, possibly with better results.

Areas of the chip with exposed electric field components above the LC’s critical voltage, and perpendicular to the surface of the chip, would demonstrate an induced optical rotation. LC’s in the hybrid field effect mode, starting with a 45° twist, would rotate linearly polarized illumination in proportion to the charge in each cell of the memory. The reflected output light would be converted to an intensity modulated pattern with the use of another 90° polarizer as analyzer. Diffraction would be the result of the pattern of charge states in the memory array. The micron scale cells would give the modulator array thus produced space-bandwidth products of 4,000 and better.

High frequency charging/discharging of the storage capacitor in each memory cell would result in a continuous local optical rotation by the LC in the active field areas. As long as the rate of memory strobing is above the LC response time, the optical rotation will be a non-zero average. Areas with continuous DC fields would have no visible effect because of a dielectric passivating layer (BPSG or polyimide) normally placed over the surface of these devices. This layer may itself demonstrate some significant electro-optic
properties or might be suitably modified to demonstrate some sort of electrically induced light modulation.

Using a fast access memory chip the modulator refresh rate would be limited to approximately 300 nsec per memory cell access time, and by the LC response time. The resulting two dimensional modulating array would have a large time-bandwidth product, and a very high density. Although such a device might not satisfy the requirements for a 16,000 element 1-D array, the appropriate choice of the device architecture could result in an array with a favorable 2-D array aspect ratio (as discussed in the previous chapter).

A standard 512K memory device, organized 128 word lines by 4,000 bit lines, would diffract 1/4 of the full frame of the desired hologram. Four such chips, or one 2 meg chip, could potentially make a full 12 degree by 128 line composite hologram, using optical methods to combine the images. A search of manufacturer's specifications may turn up a chip structured and organized so as to produce the full 16k by 128 element full frame, i.e a 2 megabit chip organized 4k by 128 elements in four blocks of 512k.

The advantages to this technique, other than being an impressive demo, is that it would allow some very quick tests of various modulating materials in a high density and high spatial frequency array. These electro-optic materials would include liquid crystals, the normally present IC passivating glasses (BPSG) and polymers (doped polyimide), chemical vapor deposited electro-optic organic materials (i.e. polydiacetylene) and sputter or vapor grown accentric crystalline materials.

This experimental investigation would demonstrate the SLM potential for solid state structures fabricated with VLSI techniques, and give some experience in the problems associated with VLSI scale devices. One of these problems is unwanted field fringing, or *inter-element modulation bleed* (IMB),
which limits resolution in high density electro-optic modulators. The study of such an experimental device, considering its layout and operation, could help in the development of techniques to minimize this effect in future devices.

A good choice for an experimental driver chip with minimum IMB would be a circuit using memory cells with trench isolated sidewall or buried capacitors, so that only the bit lines and cell plates are "exposed" to the electro-optic modulator. With this construction the modulating material would interfere the least with the cell operation. Figure 4.3 shows the cross section of a cell with such a construction, this particular device uses technology developed by Mitsubishi called a FASIC cell, for "folded-bit-line adaptive sidewall-isolated capacitor" [Mahiko et al, 87].

![Figure 4.3: FASIC Memory Cell, bit lines are 2µ pitch](image)

The disadvantage of the technique is the speed with which the memory can be refreshed limits the dynamic aspect of the device. Techniques used in video
memory such as pre-addressing a memory array would be applicable to achieving video rates with the "Quickie".

4.3.3 VLSI Device Fabricated on a Transparent Substrate

If a line addressed device were to be designed "from the ground (substrate) up", with VLSI techniques, it could be made as a high density one-dimensional modulating array with its integrated drive circuitry all on the same transparent substrate (fused silica, quartz, glass, sapphire, diamond etc.).

Since the drive signal will be serial in nature, or as would be possible with several parallel signal lines, a combination of serial and parallel formats, the array might be placed in close conjunction to a set of serial-to-parallel converter/drivers as is shown in figure 4.4. Placing the drivers on the same substrate as the modulating elements reduces the address line (wiring) problems but creates significant additional problems involving device fabrication techniques and materials compatibility. Many of these problems are being addressed by the manufacturers of LCTV displays using matrix addressed thin film transistors on transparent substrates (Mimura 88, Bigelow 85, Howard 86).

Wafer scale integration techniques would maintain the size of the device, with integrated drivers, to a practical set of dimensions, ideally no larger than the largest substrate that can be processed with modern VLSI fabrication masks and tools, 200mm (8"). A device using optimized line widths would have short run-length lines between the modulating elements and on-board drivers, using lines no larger than the elements.

As the device will be used in transmission mode, with a large coherent illuminating wavefront, it will be important to use optical quality substrates of
at least 1/10 flatness. These are available commercially in glass, quartz and sapphire from a mask fabrication supplier, i.e HOYA Electronics.

Figure 5.4: VLSI DEH Device with Distributed Drivers

Fabrication of high density 2-D display devices using silicon on insulator (SOI) techniques using thin film silicon transistors for the active matrix switches has shown that fabrication with either amorphous or recrystallized silicon is possible on a glass or quartz substrate. These devices have been made with 25 micron wide cells in arrays of up to 600 by 600 elements [Howard
86]. Figure 4.5 shows some typical thin film transistor (TFT) structures as are used on transparent substrates for miniature LC displays. Figure 4.6 shows the layout of a generic LC/TFT cell. The line in the drawing cutting across the transparent electrode region indicates the reduction of the cell that would allow higher density fabrication of 1-D arrays.

![Diagram of TFT structures](image1)

Figure 4.5: Typical Structures for SOI Liquid Crystal TFT Devices

![Diagram of TFT layout](image2)

Figure 4.6: SOI TFT Modulating Element Layout
4.3.4 CCD Driver Based Device

Use of a charge coupled device (CCD) array to address the individual elements would accomplish the required serial to parallel conversion on-chip with high density and high efficiency. This would be very advantageous in reducing the complexity of the device by removing the cascading serial to parallel converters shown in figure 4.4. A similar technique is used by Hughes Co. in their CCD liquid crystal light valve (CCD LCLV) [Efron 83, 85]. This concept uses a single long shift register which is fed serially by the input signal. When the register is fully loaded, the entire line of information (charge) is shifted, transferring data in parallel to the modulating array.

Even the best CCD's loose charge, however, about \(10^{-5}\) per transfer in a buried channel device [Young 83]. This places a statistical limit to the number of addressable elements per linear segment of CCD array at approximately 4,000. Longer arrays would require either a sequence of phased inputs along the length of the array or charge amplifiers spaced at appropriate intervals to replace the lost charge. CCD's are not the fastest devices that could be used for the element memory/driver purposes, with normal charge transfers clocked at 10 MHz rates [Howes 79], although some devices have operated in excess of 100MHz [Gandolfo 76]. Their most important quality is a significant simplicity of design.

4.3.5 Holographic Substrate Fabrication

The production of an address line pattern in preparation for the placement of a modulating material can be done with integrated circuit mask techniques, using a mask generating program to produce a pattern that is transferred to a substrate using deposition or lift-off techniques. An alternative would be to use a holographic (interferometric) technique to expose a simple pattern of lines
directly onto a photoresist coated substrate. This pattern would have address lines that diverge rapidly from an area of modulating element placement to an area for driver interconnect, divergence ratios of 100:1 should be possible on 4"×5" plates.

This technique was designed to allow the fabrication of test substrates with address lines as fine as 1μm in a non-cleanroom facility, using a procedure referred to here as a "local cleanroom".

Using the "local cleanroom" an optical quality ultraclean glass block is index matched to the photoresist coated plate in a continuously purged glovebox. The index matching fluid will need to be filtered to remove all particulate materials .2 μm or larger. The glass substrate would have a conductive indium/tin oxide (ITO) coating with a thin photoresist overcoating (Shipley 1470 series).

Once the sandwich has been made the rest of the procedure can be carried out in a "dirty" environment without concern for the introduction of particulates in the exposure area. "Black" (light absorbing) glass on both sides of the sandwich prevents the internal reflections from air interfaces from producing undesired exposure patterns that would break the continuity of the lines.

The photoresist exposure is done on an optical table with the deep blue line of an Ar+ laser using the output split into two opposing equal intensity beams. Maximum irradiance hyperbolic surfaces would be generated by the interference of the two spherical wavefronts, in this case produced by two small ball bearings [Chander 87], and cut by the plane of the plate, make a pattern of curved expanding lines with closest separation of approximately one wavelength.
Following exposure the resist is developed and baked, then placed in an RF dry etch chamber using argon ions to remove the ITO in the exposed areas. It may be advantageous to use a mixed gas dry etch to control the etch rate and profile. A similar technique has been used to transfer holograms into glass or other surfaces [Hanak 71, Darbyshire 86]. The resulting conducting lines will be extremely fine and closely spaced along the axis between the sources, and expand to a width large enough to make connections at the edge of the plate using anisotropic elastomeric conductive strip contacts.

A full element count device will not be possible using this technique for reasons discussed earlier, however it will be a quick and convenient test bed for high density modulation materials.

4.4 Beam Addressing Schemes

An alternative to line addressing the modulating device is to beam address the modulating material with charge carrying or energetic particles, i.e. electrons or photons. The modulator could be a continuous material or a series of discrete elements. Addressing it with a small spot diameter time varying beam would result in the high spatial frequency modulation of an illumination wavefront. Spatial frequency would be limited by the spot size of the beam and the characteristics of the modulating material. The address rate is determined by the speed of the beam deflection, which in turn is limited only by the inertia of the particles and the deflecting system.

4.4.1 General Considerations Concerning Beam Addressing

Because an illuminating wavefront interacts simultaneously with the entire DEH modulating array, the modulating elements are "read" in parallel.
Being "written" in serial with a scanned beam will require that the elements have memory. Most modulating materials have at least a short term memory (persistence), and high bandwidth beam scanning systems are commercially available, so that the beam addressing technique may be an attractive method for producing the DEH device with off-the-shelf-hardware. The memory might exhibit a natural time decay to the "zero" or unmodulated state, or involve a state change that requires additional input (erasure) before returning to the zero state.

Both flying-spot electron beams and scanned photon beams (serial input), as well as projected 1-D and 2-D images (parallel input), can deposit charge or energy in the modulating array at high spatial frequencies. Light addressed arrays use photon energy to generate electron transitions which in turn produce changes in the optical constants (absorption coefficient or refractive index) of the modulating material. Electron beams use the charge deposited by the beam to create mechanical deformation or electro-optic effects. A variety of thermal effects and (photo)conductivity variations in the modulating material are produced by beam addressing as well.

Electron beam and photon beam scanning are capable of very high writing speeds, several million mm per second. In a 50mm wide modulating device the scan speed would need to be only 50 meters per second for a 100 line 10 frame per second display. This is far slower than the normal scan rate limits for both optical and electron beam systems.

The resolution limits of a scanning system are the result of the difficulties in maintaining a precise beam focus and accurate aim over the entire scanned area. A small diameter or well focused beam is required for a large number of resolvable spots. The longer the scan (more spots), the more difficult it is to keep the entire length of the scan in perfect focus and all of the spots co-linear
(un-bowed). Additionally, the distance between spots changes from the center to the ends of the scan by the tangent of the scan angle (pincushion effect). Optical and electron optical systems are available to correct the focus, bow and pincushion distortion.

4.4.2 A Different Approach to Scanning

Overcoming the time-bandwidth limitations of a single beam scanning system might be accomplished by using techniques which will be referred to here as segmented scanning and distributed deflection. These concepts are similar to the use of distributed drivers in the line addressed schemes.

Proposed is the use of an addressing beam array composed of a number of individually modulated beams. These "gang scanned" beams would be used to address the a large array more accurately and rapidly than a single beam could. The total bandwidth of the display would be a multiple of the bandwidth for a single beam addressed display of similar dimensions. Each of several beams would scan over a small enough section of the array so that it focuses well within its uncorrected limits.

Referring to the discussion in Chapter 3 section 3.2, this concept is similar to what was referred to as "local" addressing. Local addressing will result in increased efficiency due to the beams' shorter scan distances and tighter focus control.

The design trade-off considered here is between a more complicated single beam system with the required focus and bow correction, and a larger number of (gang deflected) sources each with its own modulation input. When a number of sources are used, each beam is given a share of the total time-bandwidth. This is accomplished by using a number of parallel driven sources
which serially address local regions of the array. The distributed deflection technique would result in a beam addressed DEH device with far higher bandwidth and time-bandwidth than a single beam system could provide.

As was suggested in sections discussing line addressed device designs, many configurations are possible for beam addressed devices. We will present here a few of the possible techniques divided into the categories of electron beam and photon beam systems.

4.4.3 Electron Beam Addressing

Because of television, scanned electron beams (cathode rays) are the most commonly used method of dynamic visual display addressing. Over the forty years of continued development of television displays, significant advances in image quality produced by CRT's have been forthcoming on a regular basis. Most recently the line resolution of television systems has been the focus of concerted efforts. These efforts toward higher resolution and higher bandwidth CRT based spatial light modulators for television projection, high definition television displays and certain optical processing devices, will serve as launching points for several technologies useful for DEH devices. The reader is referred to P. Seats' "Fundamentals of Cathode-Ray Tubes" for additional background on the design of scanning electron beam systems.

Electrons, being charged particles with extremely small mass and very short wavelength, are ideal for focussing to small spot sizes and rapid scanning by means of electrostatic and/or magnetic fields. Very low current, and energy filtered electron beams, such as are used in electron microscopy, can be focused to attain a resolution of less than a nanometer. Higher current beams like those used in electron beam lithography are focused to spot sizes of 0.1μm, while in CRT applications the cathode size and beam current
requirements limit focus to 10-20μm spot sizes. Higher current beams have larger spot sizes due to the larger cathodes used to produce them and spot spreading at the target from local charging [Heidereich 73].

The relationship between spot size and scan length for electron beam systems gives one-dimensional space-bandwidth products from 3,200 for a very high resolution CRT (Watkins-Johnson 25V90) to 32,000 for an electron beam lithography pattern generator (Cambridge Instruments Model EBMF-6). It is reasonable to expect that between these two ends of the scan width spectrum, 625mm and 3.2mm respectively, there is the potential to design an electron beam based system with the spot size (1μm) and scan length (50mm) required by the prototype DEH device. To extend the electron beam addressed system to 50,000 or more elements will require advances in beam control, possibly available with the distributed deflection systems suggested here.

Electron optical systems are generally more complicated than equivalent light optic systems making focusing systems which can form small spot sizes, very large. For example the focusing and deflecting stack for the EBMF-6 mentioned above is over a meter long and weighs several hundred pounds. Limiting resolution for CRT's, in number of pixels per screen width (N), can be derived from the ratio of screen width to tube length (depth). This ratio is approximately by N/900 [Lehrer 80]. Using standard single gun designs this would result in an envelope approximately 2 meters long for a CRT with a 50mm one-dimensional scan of 32k pixels. If the DEH design is to be of a more reasonable length, a segmented scanning system (as discussed previously) should be considered in its design. Figure 4.8 shows a simple electrostatic gang-deflected magnetically focused electron gun layout for a 50mm target width and a 110mm envelope length.
Figure 4.8: Distributed Deflection CRT (DDCRT)

The distributed deflection CRT (DDCRT) design of figure 4.8 uses 8 separate cathodes to produce 8 parallel beams which are individually modulated at 2MHz. A similar concept was developed by IBM for a high
bandwidth multiple beam cathode ray tube (MBCRT), elements of which might be incorporated into the design of the DDCRT, especially the integrated electron sources [Piggin 85,86] and the bi-potential dynamic focus lens [Beck 85,86].

In devices that use electron beams for addressing, spot sizes normally vary from approximately 10 microns up to 25 microns. These spot diameter are determined by the cathode size. It is likely that the application of distributed deflection to these devices would reduce spot sizes dramatically for a given total cathode current yield, producing far higher resolution than is currently allowed in electron beam addressed devices.

If this design is feasible, the choice of modulator is left open to those mechanisms and materials with the required speed and resolution capabilities. In the following sections potential DEH devices are described that would utilize an electron addressed system based on a segmented scan or distributed deflection high resolution system.

4.4.4 E-beam Addressed SLM's

Several types of spatial light modulators, or light valves, are addressed by electron beams. These include refracting/diffracting systems such as the fluid film light valve and reflecting systems such as the the deformable mirror device, both of which produce phase modulation, the electron beam TITUS and MLSM electro-optic devices, electron beam addressed liquid crystal displays and cathodochromatic displays.

4.4.4.1 Electron Beam Addressed Fluid Films

Although it may yet be possible, the suggestions by Leith and Enloe, and recently by Schulze, that an electrostatically deformed fluid film could be used
to generate a hologram electronically have not been realized. These researchers have proposed the use of an Eidophor-type light valve as a means of spatially modulating light in response to an electrical signal generated by a hologram scanning system. Light valves are attractive because of their commercial availability and transmissive phase modulating operation.

The electron beam addressed fluid film two-dimensional light valve was originated by Dr. F. Fischer in 1939, and reduced to practice at the Swiss Federal Institute of Technology in 1944. A black-and-white commercial version of the device, designed specifically for large screen television projection, was completed in 1948 and named the "Eidophor" after the Greek term for "image bearer". Since that time there has been additional development of the device by Gretener A.G., of Zurich, and significant extensions of the concept, including the commercial production of color TV projectors and a compact coherent light valve optical processor, by the General Electric Corporation of Schenectady, New York [Good 75, Noble 79].

These systems use a finely focused video modulated electron beam to deform the surface of a raster scanned fluid layer (referred to as the control layer) into a spatially modulated phase grating. Schlieren optics are used to convert the phase grating representation of the video information into an amplitude modulated image for projection television.

The resolution of the deformable surface spatial light modulator is determined by the the size of the electron beam and the properties of the surface material. The writing speed is determined by the surface material's properties and the electron beam current, which also affects the spot size.

An analysis of fluid light valve control layers for high-definition TV projection by R. Tepe resulted in an understanding of the quantitative relationship between control layer time constants and resolution limits and the
viscosity, conductivity, capillarity, dielectric constant, and thickness of the fluid film and the charge deposition rate of the beam. The result of this 2 year theoretical and experimental analysis by a team of physicists and mathematicians at the Heinrich Hertz Institute is that the lower limit to size for deformable fluid film grating structures is 20\(\mu\)m for stable and continuous operation (Tepe 83, 85).

This result does not strongly support the contention that the fluid film light valve type device would be applicable to the task of electronic holography. However, by decreasing the spot size and increasing the scan rate through the use of a distributed deflection system it may be possible to achieve higher resolution in this type of modulator. Significant modifications in the deformable fluid properties and scanning conditions would also be required, as suggested by the results of Tepe, if a fluid film light valve were to used as a DEH device.

Shulze (87) also of the Heinrich Hertz Institute has continued this work, including the description of a real time holographic system using a fluid film light valve to generate hologram sub-elements. Since the device would have a space-bandwidth product of 1200 to 1800, depending on the scan width, it could in principle be used with a lens system to make a rudimentary small diffraction angle DEH output device.

4.4.4.2 Electron Beam Addressed Laser Diode Array

A dense array of electron beam addressed coherently emissive elements would be possible, and would solve several of the DEH hardware problems at one time [Bhargara 85].
Semiconductor diode lasers emitting at visible wavelengths could be fabricated into an array of mode-locked emitters that would be beam addressed. This device would couple the illuminating system with the diffraction structure.

Mode locked injection laser arrays are used as a means of generating beam powers greater than those that a single diode laser is capable [Herzog 70, Wittke 72, Ackley 83]. This involves arranging the lasers side by side on a single rigid substrate or fabricating them as a series of stripes in the same substrate. These techniques have been used primarily with GaAlAs and GaAs laser diodes, however, it is reasonable to apply this concept to visible wavelength diode lasers. Fabrication and mode locking an array that is 16 to 50 thousand elements long would be substantial technical feat, but seemingly possible in the near future.

Phasing and mode locking occurs because of the optical side-to-side coupling of the diodes, and produces individual beams that are either all in the same phase or that alternate from stripe-to-stripe by 180°. Various techniques have been developed to deal with periodic phase variations that occur in some modes of operation including internal phase shifters and selective facet coatings [Ackely 83, Botez 83].

Other means of mode locking solid state or diode lasers are available, including the use of a periodic pulse train from a fast laser to injection lock the laser diodes of an array [Tang 88]. Injection locking opens the possibility of direct modulation of the array by frequency modulating the injection locking laser and dispersing, via a grating or other frequency selective device, the spectral information into the (then) spatially modulated injection source for the array.
Electron beam addressing of an array would require a charge storage mechanism for true parallel operation. High modulation frequencies would be possible using a low current beam to control the output DC biased diodes. A feedback circuit with a (very) fast slew rate would be required to adjust the cathode current and thus the output level of the diodes in the array to compensate for drift. Distributed deflection or segmented scanning would allow the focus and scanning speed necessary, as well as provide the shortest path for a closed loop current foldback output feedback control.

Electron beam pumping of solid state lasers has been done with electron excitation both along the direction of light emission and perpendicular to it [Levy 83]. Direct excitation of an array of visible lasers has not yet been reported, but should be possible with reasonable efficiency. It has been proposed that even greater pumping efficiencies are possible by using the electron beam to excite a powder phosphor which then pumps the solid state laser [Shmulovich 86, Brown 81]. This indirect pumping technique could be applied to solid state lasers made from materials such as ruby for visible emission.

4.5 Light Addressed Systems

Light addressed spatial light modulators, light valves and image converters continue to undergo intense development. These devices accept non-coherent spatially organized optical information (images) and convert them into coherent optical information for purposes of image analysis, manipulation and processing.

Of interest to this research are those SLM designs that would allow scanned input and storage of information at high bandwidths (high spatial
frequency diffraction patterns) followed by a cycle of coherent illumination for reconstruction, erasure and repetition. The entire cycle would have to occur in a small fraction of a second. It is currently possible to focus and intensity modulate a laser beam with the speed, modulation depth and spot size necessary for this technique. Several materials and modulating mechanisms are available for this task and are discussed in Chapter 5. In question is the availability of scanner/deflectors with the required time-bandwidth product.

The number of resolvable spots produced by a deflector is determined by the Rayleigh criterion and is given by the equation:

$$N = \frac{f \cdot \frac{w}{\lambda}}{\tan \theta}$$

where $\theta$ is the half angle divergence of the beam deflected through an angle $f$. The half maximum beamwidth is given by $w$, $\lambda$ is the wavelength, and $\tan \theta = 1$ for a rectangular beam, 1.22 for a uniform circular beam, and 1.27 for a Gaussian beam [Fowler 66].

Flying spot laser scanners are capable of generating repetitive co-linear lines of elements (modulated spots) that are uniform in their size and spacing with few dropouts. The scanning is accomplished using either a galvanometer-mirror arrangement, a rotating polygonal mirror, a rotating holographic element, or an acousto-optic or electro-optic deflector.

Acousto-optic (a-o) and electro-optic (e-o) devices would be useful in the distributed deflection manner, as described in section 4.4.2, in order to increase time-bandwidth product. Such devices are not readily available and would rely on the parallel operation of numerous smaller T-B devices, with accompanying optical and electrical problems.
Current scanner addressability is limited to time-bandwidths of less than 3,000 for single crystal acousto-optic and electro-optic deflectors, and to around 10k resolution points for rotating mirrors or galvanometer scanners.

A recently development in scanning that utilizes a rotating or spinning holographic optical element is called by its developers the Hologon scanner. Hologon scanners are useful up to approximately 28,000 dots/scan, here the maximum scan-line bow and spot-size ellipticity become the limiting factors to resolution [Kramer 88]. For scan angles up to ±20° the Hologon technique with an appropriate scan lens should be able to produce 16k points on a 50mm target without excessive placement errors. The Hologon device is optically very similar to the high rotational speed holographic scanner described and patented by Beiser (73, 84), but has solved many of the mechanical problems of the earlier systems.

4.5.1 Beam Addressed Erasable Systems

A dynamic electronic hologram could be constructed using a beam addressable optical memory material using a write-read-erase cycle [Caimi 78, Parker 87]. Several classes of light modulating materials could be applied in this fashion. Photorefractive, photochromic, and photodichroic materials are most notable because of their extremely high resolution capabilities (atomic scale recording features). Thermoplastic recording materials would also be applicable, although within somewhat more limited spatial frequency bandwidths.

Refractive or absorptive structures in these materials are optically addressable allowing the rapid assembly of a complex grating structure with high spatial frequencies (up to 10,000 cycles/mm). Figure 4.10a and 4.10b show schematically a beam addressed one-line-at-a-time system which utilizes an
optical memory material and separate read, write and erase illumination sources.

Figure 4.9a: Beam Addressed Erasable Modulator System

Figure 4.9b: Beam Addressed and Erased Material
Figure 4.9b: Beam Addressed and Erased Material

The beam addressed erasable device uses a scanned intensity modulated laser beam which is scan expanded, focused and focus corrected with holographic optics. This yields a nearly diffraction limited spot size (.5 micron) which writes the grating structure in the erasable material. Separate sources at different wavelengths are used to do the writing, reading and erasing of the grating structure. For example a photochromic glass rod or tape could use green wavelengths for writing, red light for reading (reconstructing) the pattern (image), and then be erased with blue light. The various wavelengths involved with the separate parts of the use cycle could potentially come from one laser or from several separate sources. With some modulating materials, erasure could be accomplished with the read beam, further simplifying the hardware setup.

The modulating material need not be moved or replaced except at the end of its useful life, approximately $5 \times 10^2$ cycles (photochromic glasses) to $10^6$ cycles (magneto-optic thin films). Storing the material as a spooled thread or ribbon would facilitate replacement of fatigued sections. Materials with longer response times could be moved away from the writing area following exposure and reading, to allow sufficient time for refresh. This would involve a drum or disc type system as shown in figure 4.11. This type of system would be appropriate for thermoplastic recording materials.
Numerous optical memory systems with the required density and recording bandwidth exist, using a moving medium and fixed optics. A prototype DEH system using similar hardware and recording media would be possible, and could be accomplished in a fairly short time period. Using inertialess scanners (a-o or e-o) or a Hologon scanning system, the device would be driven from a source of high bandwidth serial data and act as an (optical) serial to parallel converter. As an alternative to developing an erasable system from scratch it may be possible to modify an existing optical memory device or work with one of the companies currently in this field.
Chapter 5

Light Modulators for DEH Part 2:
Mechanisms and Materials

Light may be modulated by producing changes in its phase, amplitude, or polarization. These changes are brought about through reflective, refractive, diffractive and absorptive effects. The physical effects that produce these changes in response to an applied modulating signal relate to the electro-optic, magneto-optic and acousto-optic properties of certain materials. Additionally, mechanical deformation can be used to alter the direction of propagation of a light wave through the previously mentioned effects. Thermally, mechanically, or electrically induced deformations and field redistributions can cause spatial variations in their structures which can be used to generate either temporary or permanent diffracting structures capable of being used for holography. For in-depth background on these effects the reader is referred to a number of excellent texts and surveys on the subject of optical modulation and modulating materials.

Physical effects that allow the production of high spatial frequency structures in storage or erasable materials are of interest here. Table 5.1 is a compilation of erasable and recyclable holographic recording materials.

It is apparent that the exposure energy requirements of most of the erasable materials listed in Table 5.1 are considerably greater than those of the standard silver-halide emulsions that are most commonly used in making
### Table 5.1: Erasable Holographic Recording Materials

<table>
<thead>
<tr>
<th>Storage Medium</th>
<th>Photo-Optic Materials</th>
<th>Electro-Optic Materials</th>
<th>Photoelectric</th>
<th>Piezoelectric Device</th>
<th>Thermal-Deformation Device</th>
<th>Liquid-Crystal Polymer Device</th>
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</thead>
<tbody>
<tr>
<td>Metallic</td>
<td>Molybdenum</td>
<td>LiNbO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Invar</td>
<td>PiT&lt;sub&gt;1&lt;/sub&gt;</td>
<td>PiT&lt;sub&gt;2&lt;/sub&gt;</td>
<td>N-Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Ceramic</td>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
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<td>Silicate</td>
<td>Silicate</td>
<td>Silicate</td>
</tr>
<tr>
<td>Plastic</td>
<td>Acrylate (see last)</td>
<td>Acrylate</td>
<td>Acrylate</td>
<td>Acrylate</td>
<td>Acrylate</td>
<td>Acrylate</td>
</tr>
<tr>
<td>Metal Films</td>
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<td>Bi</td>
<td>Bi</td>
<td>Bi</td>
<td>Bi</td>
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<td>20</td>
<td>20</td>
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<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
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<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
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<td>10</td>
<td>10</td>
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<tr>
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<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Li&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;</td>
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#### Recording and Erasure

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<thead>
<tr>
<th>Recording and Erasure</th>
<th>Write and Read Time</th>
<th>Record Process</th>
<th>Type of Erasure</th>
<th>Efficiency</th>
<th>Loss Time</th>
<th>Readout</th>
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<tr>
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<td>10 s to 100 s</td>
<td>1 to 20 s</td>
<td>10 s to 20 s</td>
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<td>10 s to 20 s</td>
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#### Cycle Life

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<th>Loss Time</th>
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#### Figure of Merit

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<th>Efficiency</th>
<th>Loss Time</th>
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<tr>
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<th>Type of Erasure</th>
<th>Efficiency</th>
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<td>1 to 20 s</td>
<td>10 s to 20 s</td>
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</tbody>
</table>
display holograms. Some electro-optic crystals (photorefractories) show promise in approaching a sensitivity to light similar to that of dichromated gelatin, and will be discussed further in this chapter. These materials could be used in light beam addressed devices because of their speed and high resolution capabilities, additionally, the photorefractive materials might be used with direct electrical addressing.

An important application of reversible optical effects capable of high speeds is in optical memory. Table 5.2 list effects which can be produced by light or heat that are proposed for use with the indicated materials in high density optical storage systems [Chen 84]. Similar tables could be structured for the other mechanisms and materials used in the various classes of optical and electro-optical modulators.

<table>
<thead>
<tr>
<th>Category</th>
<th>Physical Effects</th>
<th>Typical Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermally Induced</td>
<td>Curie-Point</td>
<td>Gd10Fe, GdFe, TbFe, MnBi</td>
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<td>Compensation Point</td>
<td>GdCo</td>
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<td></td>
<td>Coercivity Reduction by Heating</td>
<td>Co-P, Fe2O3</td>
</tr>
<tr>
<td></td>
<td>Thermoremanent</td>
<td>CrO2</td>
</tr>
<tr>
<td>Amorphous-Crystalline</td>
<td>Phase Transition</td>
<td>Te88Ge7As5, TeOx:Ge, TeOx:Sn</td>
</tr>
<tr>
<td>Semiconductor-Metal</td>
<td>Phase Transition</td>
<td>VO2</td>
</tr>
<tr>
<td>Photon induced</td>
<td>Photochromic</td>
<td></td>
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<tr>
<td></td>
<td>F-Center</td>
<td>KBr</td>
</tr>
<tr>
<td></td>
<td>Fg-Center</td>
<td>KCl with NaCl or LiCl Doping</td>
</tr>
<tr>
<td></td>
<td>M-Center</td>
<td>NaF</td>
</tr>
<tr>
<td></td>
<td>Photo Dimerization</td>
<td>Acridizinium, Toluene-Sulfonate</td>
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<td>YIG:Si</td>
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<td>Photon Activated</td>
<td>Thermo Plastic</td>
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<td>Composite</td>
<td>TFN-PVC</td>
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<td>Ruticon</td>
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<td>Single Layer</td>
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<td></td>
<td>Photoco nductive</td>
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<td>Two Layer</td>
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<td></td>
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<td>Photoco nductive</td>
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<tr>
<td></td>
<td>Composite</td>
<td>Gd2.5yBo.5Fe4.8Al0.2-Cds</td>
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</tbody>
</table>

Table 5.2: Erasable Materials for Optical Storage (after Chen 84)
As presented previously, the three types of light modulation can be brought about by a number of effects in a large variety of materials. This chapter will focus on materials in which electrically and photo-electrically induced changes in the refractive index may be used to modulate light at high speeds in high resolution structures.

The following three sections examine the resolution and speed of these effects in some crystalline materials, and ways to utilize the effects in a DEH device. Section 5.1 considers optically induced electro-optic (e-o) modulation (light addressed materials), in section 5.2 the use of bulk, or monolithic, e-o modulators will be investigated (electron beam or light addressed), and in section 5.3 the use of an array of discretely addressed multiple element modulators will be considered (line addressed).

It would be inappropriate in a work of this type to attempt to analyze and discuss all of the materials and modulation mechanisms that might be applicable to DEH devices, the ones presented here are considered to the most widely useful for the task at hand. At the end of this chapter several tables of properties for classes of electro-optic materials considered for spatial light modulators are given, without discussion, for reference purposes.

5.1 Photoinduced Electro-Optic Effects (Photorefractive)

The photorefractive effect is caused by the light-induced redistribution of charges in a single crystal material creating a space charge field which modulates the local refractive index of the material via the linear (first order) electro-optic effect. This allows for the creation of a volume phase hologram in the material from the application of a spatially varying optical input.
These effects are currently of importance in applications such as optical data processing [White/Yariv 80], phase conjugation [Feinberg/Hellwarth 80, Pepper 86], and laser beam steering [Pauliat et al 86, Wilde/Hesselink 87]. Materials which exhibit the effect are used increasingly for two and four wave mixing experiments by photoinducing a grating, an effect which may have important applications in dynamic holography [Kukhtarev 86, Feinberg 85, Huignard 80]. Wave mixing, or phase conjugate wavefront generation can be used for real-time holography as shown by figures 5.1 after Huignard, where the material being used is Bi$_{12}$SiO$_{20}$ (BSO), one of the materials to be investigated in this section.

Photoinduced gratings have applications in the sequential assembly of complicated or high frequency diffraction structures out of a series of smaller, simpler or lower frequency elements. For example, it would be possible to use a large enough photorefractive wafer to assemble a composite hologram from projected hologram sub-elements, producing an "instant H2".

![Diagram](image)

**Figure 5.1 Phase Conjugation Applied to Real-Time Holography, wave directions and wavefront amplitudes are as marked (Huignard)**
Because of the great interest in the photorefractive effects and their possible applications, materials developments are being reported continuously [Tanguay 84, Hesselink 87, Valley 85]. The photorefractive materials most commonly used are: lithium niobate (LiNbO₃), barium titanate (BaTiO₃), strontium barium niobate (SrₓBa₁₋ₓNb₂O₆ or SBN), potassium tantalate niobate (KTaO₃ and KNbO₃ or KTN), gallium arsenide (GaAs) based materials, bismuth silicone oxide (BSO) and bismuth germanium oxide (BGO). Each material has a magnitude of refractive index change \(Dn\) that is determined by the material's effective Pockels coefficient \(r_{eff}\) in the relationship:

\[
D_n = -\frac{1}{2}(n^3 r_{eff} E)
\]  

(5.1)

where \(E\) is the light induced electrostatic field. In this study photorefractive materials can be placed into use categories characterized by 1.) the strength of the Pockels effect they exhibit and 2.) their speed of charge redistribution. A comparison of the properties of the materials listed above is shown in Table 5.3.

<table>
<thead>
<tr>
<th>Material</th>
<th>Strength of Effect</th>
<th>(r_{eff}) (pm/V)</th>
<th>Speed</th>
<th>t(sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaTiO₃</td>
<td>strong</td>
<td>1640</td>
<td>slow</td>
<td>1.3</td>
</tr>
<tr>
<td>SBN</td>
<td>strong</td>
<td>1360</td>
<td>slow</td>
<td>2.5</td>
</tr>
<tr>
<td>LiNbO₃</td>
<td>weak</td>
<td>31</td>
<td>slow</td>
<td></td>
</tr>
<tr>
<td>BSO</td>
<td>weak</td>
<td>5</td>
<td>=fast</td>
<td>15 \times 10^{-3}</td>
</tr>
<tr>
<td>InP</td>
<td>weak</td>
<td>1.5</td>
<td>=fast</td>
<td></td>
</tr>
<tr>
<td>GaAs</td>
<td>weak</td>
<td>1.43</td>
<td>fast</td>
<td>8 \times 10^{-5}</td>
</tr>
<tr>
<td>KTN</td>
<td>strong</td>
<td>380</td>
<td>fast</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3: Comparison of Photorefractive Properties of Materials  
(\(r\) is after Holman 85 and \(t\) are measured values after Yeh 80)
The data in table 5.3 is from the reports of numerous different laboratories, the power of the illumination has been normalized to 1 W/cm², \( r_{eff} \) units are in 10⁻¹² meters per volt. The materials listed above will demonstrate response times \( t \), from minutes to nanoseconds, depending on the power in the illuminating field. It is apparent that except for KTN, which has proven very difficult to test because of difficulties in crystal preparation, there appears to be a significant tradeoff between shorter response times and increased strength of the effect.

The photorefractive effect requires a large photoinduced electric field component to generate a significant index change (equation 5.1), at visible wavelengths this can be brought about in most photorefractive materials by illumination in the range of watts per cm² over a period of a few seconds, corresponding to fields of \( 10^3 \) volts per centimeter (V/cm), or with pulsed laser sources, as high as \( 10^7 \) V/cm with corresponding response times as short as a few nanoseconds [Feinberg 82, Lam 81]. An externally applied electric field can increase the refractive index change by modifying the diffusion velocity of the photocarriers, but at the expense of a longer time constant. Conversely, an electrically induced decrease in time constant should be possible albeit with a resultant reduction in the index change, this would be of significant use for DEH but has not been reported in the field of study.

In four wave mixing situations the total power levels required are above those normally used in holography. However, because the effect is capable of exhibiting large gains, the modulating wave front may have extremely low amplitude (Pepper 86). This could be incorporated into DEH devices which would use low amplitude electronically modulated optical signals converted to higher power phase conjugate wavefronts using wave mixing techniques.
The photorefractive effect has the capability of producing very high resolution diffraction structures, and because of this fact, it has been examined extensively as a means of storing information holographically in optical memories devices [Amodei 72] for real-time optical information processing [Sternklar 87] and real-time holography [Burke 78, Feinberg 85].

The resolution is limited by the distance between traps, which for most crystals is approximately 100nm, and for heavily doped crystals is only 10nm [Staebler 77] this gives a lower limit for \( d \) of .1 micron, which is easily sufficient for holographic purposes at visible wavelengths.

Wavefront conjugation experiments with BSO have shown that the spatial frequency response of a photorefractive crystal is affected by the magnitude of an exterior applied electric field, demonstrating a very interesting inherent high and low pass spatial filtering capability. When the applied field is increased from 0 volts, the spatial frequency response goes from being high pass to flat over a range of a few thousand volts, and then becomes low pass with further increases in the voltage [Huignard 80]. Being able to remove selected frequency components with this technique would be very useful in controlling aliasing in a DEH display.

In considering the speed limitations of the photorefractive effect, currently its largest drawback for dynamic holography, it is important to examine the time related mechanisms which bring about the spatial modulation of the crystal's refractive index.

Photoconductivity is due to photon absorption phenomena, or the releasing of photocarriers (electrons and holes) from a donor or acceptor impurity. These carriers will transport and, when trapped, produce an internal electric field pattern as shown in Figure 5.2.
Figure 5.2: Redistribution of Charges in Electro-Optic medium with Exposure

The induced photoelectric field in turn produces a spatial modulation of the index of refraction. Thus, illumination by one wave can lead to the modulation of another wave passing through the same crystal by means of the formation of a phase hologram in the material. Each of these events has a characteristic time associated with it.

The hole-electron model of the photorefractive effect [Klein/Valley 80, Klein/Feinberg] suggests that the simultaneous occurrence of holes and electrons will result in the reduction in strength in the resulting space charge field. This is explained by the fact that photoconductivity, and gain, in a photorefractive material is found to be the result of an imbalance in the local hole-electron ratio. For example, if the majority charge carriers are electrons, then the largest field will result from the filling of the electron trap sites resulting in a larger concentration of electrons relative to holes. Because of this, increasing the relative concentration of donors has the effect of decreasing the response time of the refractive index change due to their greater mobility.
For the purposes of holographic information storage a decrease in response time through charge imbalance is not particularly advantageous, as trap recombination is a thermal diffusion rate limited effect, and would lead to rapid loss of data. For the purposes of adaptive optics or dynamic holography, however, a rapid response time with high gain is extremely important requirement. A dynamic hologram utilizing the photorefractive effects would have to exhibit refractive index responses to changes in the field concentrations (or locations) in the order of milliseconds for a line at a time parallel addressed device. Response times for CW sources at ten mW/cm² powers are in the tens of milliseconds with BSO [Huignard 80]. An example of the cycle time for a typical photorefractive material at power levels achievable by CW lasers is shown in figure 5.3.

Efforts to decrease response time have lead to a better characterization of the role of charge carriers in determining the time constants of the effect. Recent work towards the optimization of the photorefractive response time for BaTIO₃ [Klein 86] has met with good agreement between measured response times and theory.

![Figure 5.3: Typical Record and Erasure Cycle for BSO and Crystal Orientation (Huignard)](image-url)
Photorefractive response time theories relate the ratio of electron and hole donor ion concentrations with the resulting charge carrier photo-ionization cross sections and mobilities. The potential benefits of a photorefractive effect based DEH are to be realized only if a material with sufficient sensitivity and short enough response time is available.

In comparing gain with the dielectric relaxation time it is seen that the compensation point for electron and hole photoconductivity (peak response time) is far from the optimum gain point in "as-grown" samples. Most commercial samples of BaTiO$_3$ have a response time of 0.1 - 1.0 seconds at 1 W/cm$^2$. This contrasts sharply with the theoretical limit for the material, based on photo-ionization rates, of 1.5 milliseconds [Yeh 87]. The photoconductivity in these crystal is shown to be due to the presence of dopants, usually Fe$^{2+}$ and Fe$^{3+}$ ions in trace amounts, with the response time being determined by the ratio Fe$^{2+}$/Fe$^{3+}$, where Fe$^{2+}$ is the electron donor. Klein [87] has shown that a reduction in the response time by a factor of ten can be accomplished by baking a BaTiO$_3$ crystal in a reducing atmosphere to modify the Fe$^{2+}$/Fe$^{3+}$ ratio. This work demonstrates that the speed of the effect may be increased through the proper doping, however, the maximum attainable speed will still be limited by photo-ionization rates.

Clearly, the speed/power relationship for this material, even if it were optimized fully, would require a substantial amount of power for the writing rates discussed in chapter 4 of approximately 10$^{-8}$ seconds per element. This could be achieved with a focused laser beam rapidly scanning the material. A graph of the fundamental limit of the speed of the photorefractive effect in BaTiO$_3$ is shown in figure 5.4 (after Yeh).
Figure 5.4: Fundamental limit of the speed of the photorefractive effect for BaTiO$_3$.

As shown in the preceding discussion, decreases in response time should be feasible into the sub-millisecond region for sufficiently doped fast crystals, with a simultaneous increase in gain. Several practical materials problems need to be overcome, those of materials availability and the growth limits to crystal size. Currently high quality BaTiO$_3$ is limited to crystal dimensions on the order of .5cm$^3$, and SBN to dimensions of a few cubic centimeters. BGO crystals have been grown in centimeter scale diameters, and both BSO and LiNbO$_3$ have been available for some time in larger sizes, up to several inches in diameter. KTN crystals are very difficult to produce and have additional limitations due to the presence of fine birefringent lamellae which result in spatial variations in the Curie temperature [Fox]. These spatial variations in index might be subtracted out by an optical element carrying the conjugate of the disturbances. Such a technique could also be applied to negating some defects in a-o crystals.
The development of better techniques for the production of large optical quality crystals is being stressed for a number of commercial, research and military applications, and probably will lead to sufficiently large crystals for experimental DEH devices. The growth of crystals on orbiting platforms, which is being pursued by a number of U. S. companies and foreign countries, should also lead to larger and more optically uniform photorefractive modulator devices in the next few decades.

It is not clear that the photorefractive effect offers a simple means of dynamic electronic holography, but the possibilities of (perhaps) rapid high resolution wavefront modulation offered by the techniques may very possibly lead to a useful device in whole or in part. For example the combination of the electro-optic effect (section 6.3) with the photorefractive effect could lead to an electrically addressed crystal with internal amplification and adjustable spatial frequency filtering. It may also be feasible to utilize the holographic storage nature of the device to assemble a series of gratings of low spatial frequency into a single diffracting structure with the required dimensions and spatial modulation.

5.2 Monolithic Electro-Optic Modulators

Except for liquid crystals, which are a special class of electro-optic material, the direct influence of an electric field on a light wave can only be generated through materials demonstrating an electrically induced permittivity change. A large class of materials of a crystalline nature exhibit this potential, and unlike the photorefractive crystals (although many are used for both purposes) are not limited by a relatively long response time.
There are many eccentric crystals that may be used for electro-optic modulation such as KD*P with a low Curie temperature ($T_c=222^\circ$K), a few medium Curie temperature ferroelectrics such as barium titanate ($T_c=405^\circ$K) and SBN ($T_c=470^\circ$K), some high Curie temperature ferroelectrics such as lithium niobate ($T_c=89(t^\circ$K), members of the group III-V semiconductors based on GaAs at near-IR wavelengths, and nonlinear organics such as polydiacetylene.

These materials utilize either the linear electro-optic effect (Pockels effect) or the quadratic electro-optic effect (Kerr effect) for modulation. For a thorough review of the properties and applications of electro-optic materials including standing wave, Fabrey-Perot and phase reversal modulators, the reader is referred to Kaminow and Turner [66,71], and to Chen [70] for discussion of small aperture e-o modulators with lumped, zig-zag and traveling wave geometries. These effects and geometries are capable of very high speed modulation, and in some configurations, scanning and deflection of a light wave.

In the Pockels effect, the birefringence induced in a crystal is perpendicular to the applied electric field. Any transparent crystal lacking a center of symmetry will exhibit a first order electro-optic effect, and may be used as an electro-optic modulator. The magnitude of the effect is linear with voltage and is small, i.e. in the material KD*P a refractive index change of $10^{-5}$ is the result of an applied voltage of $4 \times 10^3$ volts/cm. This change is however sufficient to produce useful phase modulation, and through the addition of crossed polarizers, amplitude modulation. A common term used in describing the properties electro-optic materials and modulators is the half-wave voltage $V_{1/2}$, or the voltage applied to generate phase retardation.
equivalent to a half-wave plate. The $V_{1/2}$ and $T_c$ for some commonly used e-o materials is given in table 5.4.

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ ($^\circ$K)</th>
<th>$n_c$</th>
<th>$n_a$</th>
<th>$V_{1/2}$ (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KD*P (KD$_2$PO$_4$)</td>
<td>222</td>
<td>1.47</td>
<td>1.51</td>
<td>7.5</td>
</tr>
<tr>
<td>LiTaO$_3$</td>
<td>890</td>
<td>2.12</td>
<td>2.176</td>
<td>2.8</td>
</tr>
<tr>
<td>SBN</td>
<td>470</td>
<td>2.26</td>
<td>2.32</td>
<td>.48</td>
</tr>
<tr>
<td>BaTiO$_3$</td>
<td>405</td>
<td>2.36</td>
<td>2.42</td>
<td>.48</td>
</tr>
</tbody>
</table>

Table 6.4: Properties of some electro-optic materials, at 633 nm

The Pockels effect is utilized in two configurations, transverse and longitudinal, described by the orientation between the electric field and the light propagation in the material. For devices with co-axial orientation, the thickness of the crystal in the direction of light propagation will determine the field strength required for modulation. With a transverse field, the modulator aperture and effective length are determining factors for the field strength requirement.

The optical Kerr effect is the creation of birefringence in a transparent isotropic substance through the application of an electric field. A Kerr effect affected material exhibits characteristics of a uniaxial crystal with its optic axis along the direction of the electric field. The magnitude of the effect is proportional to the square of the applied field, and like the Pockels effect, small. For a commonly used fast switching Kerr cell fluid like nitrobenzene, the $V_{1/2}$ is $3 \times 10^4$ volts. The $V_{1/2}$ for Kerr materials are generally a factor of 5 to 10 more than those for Pockels materials.
Both Pockels and Kerr electro-optical effects are capable of acting very rapidly, unlike the photoinduced version (section 5.1), giving intensity modulations up to the 10-100 GHz range. The problems to be encountered in applying the effect to dynamic electronic holography are in determining ways to address the modulator at the required speed, and in analyzing the resolution potential for the proposed electro-optic (e-o) materials and devices. The interest here is with the materials properties of potential e-o modulators and their limits to resolution (or T-B product).

Thin crystals (slices cut at the proper orientation from boules) of e-o material have been used in the longitudinal configuration to spatially modulate light with resolution elements smaller than the crystal thickness. The devices that have been produced are categorized as electro-optic spatial light modulators or ESLM's, and include the Pockels Readout Optical Modulator (PROM) [Horwitz 78], the Soviet version of the PROM the PRIZ [Petrov 81,Casasent 81], the TITUS [Marie 69], the PHOTO-TITUS [Donjon 73], the Microchannel Spatial Light Modulator (MSLM) [Warde 81] and the electron beam addressed MSLM. Additionally a second class of SLM's that operates with PLZLT ceramics has been developed which includes the FERPIC, FERICON and CERAMPIC devices [Land 78, Esener 87].

In all of these devices two-dimensional image information is deposited or recorded as charge distributions which induce electric fields in the electro-optic crystal. The induced fields result in spatial modulation of a polarized light wave through the electro-optic effects. These charge distributions can be the result of electron beam charge deposition, light charging of a photoconductive layer on the crystal, or in the case of the PROM, light charging of the material itself.
The resolution of these SLM devices depends directly on the relationship between local charging and the resultant spatial modulation of the voltage across, and the field within, the crystal. The image information results in a charge distribution that is confined in the transverse dimensions, but the electric field lines from it will spread throughout the device. The resultant field fringing will limit the device output resolution and simultaneously affect the sensitivity of the device.

Owechko and Tanguay [84a,84b] analyzed the limitations to the resolution of electro-optic devices, examining 1.) the relationships between the crystal orientation and field fringing, and 2.) the device structure (layer thicknesses) considering blocking layer resistivity and dielectric permittivity. This is in basic agreement with the work done by Roach [74] which indicates that for maximum resolution the crystal should be used in the longitudinal mode, and should be a material that has a reduced transverse dielectric constant to minimize field fringing.

Owenchko and Tanguay found additionally that the transverse components that lead to undesirable phase modulation may be minimized with some crystal orientations, and that for maximum resolution the blocking layers should have high resistivity and high dielectric permittivity. Experimentation earlier by Horwitz and Corbett [78] with very high quality PROM crystals confirmed the inverse relationship between dielectric coating thickness, resolution and diffraction efficiency that had been proposed by Roach. A table of comparison of actual and theoretical limitations for some ESLM's is in figure 5.12, compiled from numerous sources [Donjon 73, Roach 74, Horwitz 78, Salvo 71, Cumins 71, Oliver 70, Hou 71, Casasent 81, Sprague 78, Warde 80, 84].
Of these devices the closest to its theoretical resolution is the PROM, with the others more significantly removed from their upper limits. This may be partly due to the greater effort invested in developing the PROM, but is probably due to the structural simplicity of the device.

<table>
<thead>
<tr>
<th>Device</th>
<th>Material</th>
<th>Temp.</th>
<th>$f_{\text{max theor.}}$</th>
<th>$f_{\text{max meas.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROM</td>
<td>BSO</td>
<td>25°C</td>
<td>&gt;500</td>
<td>108</td>
</tr>
<tr>
<td>PROM</td>
<td>ZnS</td>
<td>25°C</td>
<td>&lt;750</td>
<td>85</td>
</tr>
<tr>
<td>PRIZ</td>
<td>BSO</td>
<td>25°C</td>
<td>&gt;1000</td>
<td>&gt;100</td>
</tr>
<tr>
<td>TITUS</td>
<td>KD*P</td>
<td>25°C</td>
<td>&gt;750</td>
<td>50</td>
</tr>
<tr>
<td>TITUS</td>
<td>KD*P</td>
<td>-60°C</td>
<td>&gt;1000</td>
<td>&gt;150</td>
</tr>
<tr>
<td>PHOTOTITUS</td>
<td>KD*P</td>
<td>-50°C</td>
<td>&gt;1000</td>
<td>75</td>
</tr>
<tr>
<td>MSLM</td>
<td>LiTaO₃</td>
<td>25°C</td>
<td>&lt;100</td>
<td>10</td>
</tr>
<tr>
<td>MSLM e-beam</td>
<td>LiNbO₃</td>
<td>25°C</td>
<td>&lt;83</td>
<td>8</td>
</tr>
<tr>
<td>CERAMIC</td>
<td>PLZT</td>
<td>25°C</td>
<td>&lt;200</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 5.5 Comparison of electro-optic SLMs

It should be mentioned that in the case of the TITUS and MSLM the resolution is limited by the physical characteristics (size) of addressing technique involved, electron beam diameter and microchannel plate pore spacing respectively. Also, the modulation depth and device sensitivity have been normalized (as best as possible) to the 10% level in constructing this table. The actual usable spatial frequency, even in a theoretically maximized device, will be less than the figures indicate.
5.3 Electro-optic effects - Integrated Modulators

An approach to the resolution problem is to use individual electrodes to address the e-o material as discussed in section 4.2. The most desirable material for high speed, low power -electro-optic devices is potassium niobate/potassium tantalate (KTN) because of its high electro-optic coefficient and low permittivity [Holman 85]. KTN offers bandwidths higher than most e-o materials at considerably lower drive requirements, i.e. 4 volts drive versus 14.5 volts for SBN or 15 volts for LiNbO3.

As discussed earlier in this chapter, KTN is difficult to obtain commercially as crystals of optical quality in large dimensions. It is not known whether it may be possible to produce the material using chemical vapor deposition (CVD) process in thin films as are needed for large area e-o devices. The next best monolithic crystalline material for this purpose is probably lithium niobate, primarily because of its availability.

A variety of non-single crystal electro-optic materials can be used with line addressed configurations. Electro-optic (e-o) materials such as liquid crystals or variable permittivity crystals and glasses, as well as electrophoretic, electrochromic and electrodichroic materials would be capable of generating a required modulation in response to an electric field or current. The nonlinear organics and polymers with high electro-optic strength and low dielectric constants (like MNA and polydiacetylene) offer a desirable alternative to the inorganic crystalline and non-crystalline materials for high performance devices of this kind. There may be wafer scale designs for the DEH that could be realized with these materials as well.
5.4 Other Addressable Materials

Spatial light modulator devices have been either fabricated or predicted using electro-optic materials and effects other than those discussed in this chapter. The tables of optical effects at the beginning of this chapter and the tables of spatial light modulators in chapter 4 refer to materials with a range of electrical and optical responses, speed, and density capabilities. These materials modulate primarily through the effects of absorption, polarization rotation and refraction. Numerous references contain surveys of these materials.
Chapter 6
Conclusions

This examination of present day systems for spatial light modulation has confirmed the earlier assertion that a device for dynamic electronic holography is not currently available. It is further noted that although a great amount of effort is being placed in the research and development of high speed high resolution electro-optic devices for a variety of holographic and non-holographic purposes, none of the these devices have been devised with technology appropriate to the task of dynamic electronic holography.

It is the contention of this analysis that an electronic hologram is, however, possible with today's technology. Recent advances in the production of devices with submicron scale structures together with a deeper understanding of electro-optic effects, including the photorefractive effect, have made the production of a DEH, using several distinctly different approaches, within our immediate grasp.

Simplified specifications for the DEH, based on bandwidth reduction concepts, call for a high density diffraction structure in the form of a linear array of reasonable dimensions. An electronically addressed device could be constructed using fabrication processes common to integrated circuit manufacture. Additionally, either an electron or laser beam could be used to
generate a diffraction structure in an electro-optic material. Both of these approaches have been described in some detail in chapter 4.

In all cases the DEH device is required to have the following parts:
1. a high speed addressing means, be it serial, parallel or a combination of both, 2. in the case of serially addressed devices an inherent memory, and 3. a light modulating structure with a high resolution using a material with high enough speed and sufficient efficiency to fill the applications requirements of the device. Both reflection and transmission holograms would be possible with the structures as have been examined in this study.

Application of integrated circuit techniques involving fine line lithography or interferometric exposure with transparent substrates would result in line addressed devices with structures of the scale necessary for directly viewed DEH devices without resorting to further optical wavefront manipulation. Both CCD and TFT technologies would be applicable in building the addressing structures for these devices, with only minor "massaging" of the current fabrication techniques.

By using distributed deflection techniques with electron beams or holographic polygon scanning of photon beams, devices using beam addressing are possible. Much of the hardware for these systems is currently available, although in the case of electron beam systems, the parts would have to be fabricated rather than purchased off the shelf, as they could be with high speed high resolution optical scanners.

Key to the fabrication of a DEH device, regardless of the addressing technique applied, will be the choice of a material with the required speed and efficiency. Most, if not all, device concepts and designs that have been presented in this text are materials limited. Significant steps in the
qualification of proposed materials will be made once a structure is available on which they may be tested and analyzed.

Several modulator materials test structures are suggested in this study. These include the holographically generated high resolution substrate and the "Quickie" memory IC substrate addressable diffraction element (ADE), which would be useful for testing electrically addressed materials. With the scanning capabilities of an acousto-optic modulator system such as the one currently being used to attempt launched wave holograms, tests of photorefractive materials would be possible including the compositing of subholograms.

6.1 Immediately Feasible Electronic Holograms

6.1.1 2-D Arrays/Dimensional Reorganization Schemes

Design tradeoffs involving both density and addressing speed parameters take many forms when applied toward the construction of an immediate DEH device. Small, high density linear arrays are the most attractive form for the final device, but also the least available geometry for current spatial light modulating devices.

Low density arrays, both 1-D and 2-D, are usable in specific formats for the DEH display. In the 2-D geometry certain devices including liquid crystal and oil film light valves are available with aggregate time bandwidths greater than those of the proposed DEH device. Low density devices are, however, constrained in use by the optical systems required to increase the spatial frequency in the diffraction region. Addressing speed of these devices is also
density correlated by virtue of time/distance relationships in all addressing schemes, with larger element spacing producing longer address times.

A reasonable amount of time and effort toward a DEH device in the near term might be saved by finding a method of optically channeling the output of a currently existing 2-D modulator into a 1-D diffraction array. Identification and application of the necessary techniques may have some advantages over the design and fabrication of a large time-bandwidth 1-D (line) array.

Reorganizing the output of a two-dimensional spatial light modulator into a one-dimensional array using optical methods should be technologically possible. The use of fiber optic bundles would enable the re-wiring of the individual pixels of a liquid crystal television into a linear modulator array. The phase modulating ability of the individual liquid crystal cells would allow substantial compensation for phase errors generated by the differing lengths of the optical fibers. A computerized feedback system for phasing and optimizing the array would be easily constructed and calibrated.

It may also be feasible with currently available technology to electronically compose a hologram from scanned sub-elements using existing high resolution 2-D spatial light modulators to form the moving sub-element. This composite hologram would require, however, a great deal from the viewer's perceptual system in assembling the 3-D image. It is not clear that techniques that are available to accomplish the required local and composite scanning and optical reduction will be either inexpensive or efficient. The advantage to the concept is that making a small (low bandwidth) dynamic electronic hologram, that could be used as the sub-element, should be simpler than constructing the full size version. The production of a DEH in any size would be a significant step.
6.1.2 Suggestions and Caveat Concerning a VLSI Device

The "Quickie" has been proposed as a means of rapidly assembling an addressable diffraction element (ADE). This would not be the dynamic electronic hologram as it has been conceived, but it would be a significant step toward one. The cost would be low, and chances for success high. The ADE, assuming that it works, could be used to make hologram subelements or a number of them could be assembled to produce a sufficiently large wavefront diffracting structure that a convincing display of electronic holography would be possible.

Concerning the long term development of a DEH using this technology a few words of warning are important. As much as solid state devices have advantages in their size and cost in quantity production, it is difficult to make monolithic and solid state versions of some electronic devices owing to their complexity of either materials coincidence and/or process flow requirements. Additionally, devices that are multiply manufactured, such as memory IC’s that are made several hundred at a time on one silicon or GaAs wafer, or that are singly manufactured but have extremely large numbers of interconnected circuit elements, such as wafer scale VLSI, are often constrained in production by the size, complexity and cost of the tools required to make them. Small parts do not mean small tools.

Making large scale solid state devices with integrated circuit technologies is still in its infancy, and as has been demonstrated even by some of the giants of the industry, can lead to very expensive failures. Both Mostek and IBM, two of the largest chip makers in the world, have had to shut down the production
of certain devices because of yield or reliability problems of unknown origin. Most circuit fabrication process flows involve hundreds of steps, each of which must be nearly perfectly performed. There is little margin for error or sloppy work. The problems that would be associated with making DEH devices with integrated circuit techniques are too numerous to elucidate here. They will surface full blown as soon as attempts are made to fabricate the first solid state DEH.

Although it will be a very durable and fault tolerant device, the wafer scale DEH device, as envisioned with on-wafer drivers, using micron size modulating elements and standard VLSI design rules would easily tax the most sophisticated fabrication facility. It is the suggestion of this author that a very carefully planned fabrication procedure be developed for a VLSI or ELSI DEH prototype, and that the work initially concentrate only on the placement and characterization of the modulating material.

The element density of an experimental wafer scale line addressed 16,000 element linear array could start out as coarse as 8μm pitch and still fit on a 150mm (6") wafer using LSI techniques. Improvements could shrink the element spacing as more is known about the characteristics of the modulator material. It would be advisable also to gain early experience and information about very fine pitch modulating elements by simultaneously fabricating a lower element count array with 1μ or smaller elements. This would result in a mask replicatable "generic" fine pitch set of conductive lines on a transparent substrate, allowing analytical testing with a variety of modulator materials using off-substrate drivers. By limiting the total number of elements, interconnect could be done with an anisotropic elastomeric connection strip material with 125μm pitch.
6.2 Future Directions

It is likely that a combination (hybrid) of several of the known modulating techniques, or possibly a technology that is a direct extension from one of them, will prove successful at accomplishing the task at hand, but that the complete development and description of any such technique will involve data and experience that can only be generated through laboratory experimentation.

The use of photorefractive materials with optical addressing, electro-optic materials with either line or electron beam addressing, or an array of laser diodes with either electron beam or laser addressing are the most likely candidates for commercially usable DEH devices.

Considerable work is still required in specifying the operational requirements of a dynamic hologram device, some of which will be determined only after an exhaustive analysis of the probable development of the devices which will drive it. This is true of any display device, and especially true of a display with such a remarkable future ahead of it.
Author's note:

In earlier drafts this thesis was an attempt at analyzing each of the known light modulating devices, each of the addressing configurations of those devices, all of the mechanisms or effects which these configurations might use, all of the known materials which exhibit the effects, new devices that could work on similar principles as well as describing techniques of bandwidth reduction that might utilize these techniques. The goal was to "build up" from the basics into a theory of DEH device operation, then present the ideal device geometry, as well as the mechanisms and materials to support its fabrication and extend this into a new general theory of reduced bandwidth holographic communications. This would have involved writing a textbook on spatial light modulation and electronic holography. The effort turned out to be far too extensive a project for a thesis of this nature.
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