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13. ABSTRACT *(Maximum 200 words)*

POC investigated the feasibility of developing a holographic waveguide array rollable display based on holographic optics and a multilayer polymer waveguide substrate. The Phase I investigation included a preliminary study of the multiplanar waveguide by computer modeling; an investigation of possible display system architectures, characterization and evaluation of several types of photopolymers for holographic and multiplanar waveguide fabrication, and a proof of principle laboratory demonstration of multiplanar waveguide fabrication and a planar display. The results show that (1) 1 to 2 μm polymer waveguide layers allow efficient, low loss propagation of three primary colors (RGB) of laser light simultaneously, with sufficient tolerance in the coupling angles; (2) dichromated gelatin and DuPont photopolymers showed maximum index modulation of 0.02 to 0.06 achievable for holographic waveguide recording, and for high efficiency input/output coupling hologram fabrication; (3) the most practical image forming approach for image input into the multiplanar polymer wavguide substrate appears to be 1-D line image scanning, which can give >2560 horizontal resolution with an available low speed 1-D scanner; (4) for image output, a surface relief holographic grating multiplexed with a directional diffuser produces a wide horizontal field-of-view and high contrast images.

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PROJECT SUMMARY

POC investigated the feasibility of developing a holographic waveguide array rollable display based on holographic optics and a multilayer polymer waveguide substrate. The Phase I investigation began with a preliminary study, modeling the multiplanar waveguide and analyzing its light propagation characteristics. Based on the waveguide requirements, possible display system architectures were investigated. In parallel, several types of photopolymers were characterized to evaluate their suitability for holographic and multiplanar waveguide fabrication. Finally, a proof of principle of a multiplanar waveguide fabrication and planar display was demonstrated in the laboratory. The main conclusions to be drawn from this investigation are: (1) Computer modeling, analytical calculation and experimental analyses have shown that it is possible to use very thin (1 to 2 μm) polymer waveguide layers with realistic refractive indexes corresponding to commercially available polymer films to allow efficient, low loss propagation of three primary colors (RGB) of laser light simultaneously with sufficient tolerance in the coupling angles. Total thickness of the polymer substrate can be 2 to 4 mm for a vertical resolution of 1024; (2) Dichromated gelatin and DuPont photopolymers showed maximum index modulation of 0.02 to 0.06 achievable for holographic optics and waveguide recording. DCG shows higher diffraction efficiency (98%) and lower (<2%) loss than DuPont photopolymer, while in terms of processing and stability DuPont polymer is more suitable for input/output coupling hologram fabrication; (3) Three image forming approaches -- 2-D laser beam scanning; 1-D line image scanning; and 2-D direct image projection without scanning -- are suitable for image input into the multiplanar polymer waveguide substrate. The most practical approach appears to be 1-D line image scanning, which can give high (>2560) horizontal resolution with an available low speed 1-D scanner. For image output, a surface relief multiplexed holographic grating coupler with directional diffusion produces wide horizontal field-of-view and high contrast images; and (4) A practical rollable display is indeed feasible. Multiplanar polymer substrate fabrication, based either on POC's holographic technology or on existing multi-layer lamination techniques of coextrusion or polymer evaporative web coating, could be combined with POC's unique holographic coupler and diffuser technologies to bring this display concept to reality.

In order to fully develop this technology into a commercially viable product, POC plans to develop a fully functional HOWARD prototype system in Phase II. To accomplish this goal, the following further investigation should be pursued: (1) Optimization and refinement of the HOWARD architecture using a fully developed multiplanar polymer waveguide model as well as 3-D HOE coupler design and ray tracing software to simulate and analyze its performance; (2) Extension and optimization of the multiplanar polymer waveguide fabrication process using both holography and multilayer lamination techniques, including extrusion and evaporative coating; (3) Development and integration of critical components, and optimization of their fabrication; and (4) Production of a practical, high resolution, rollable or flexible flat panel polymer display prototype, and evaluation of its performance.

1.0 INTRODUCTION

1.1 Background

Direct view displays measuring more than three feet on the diagonal and also flat and light enough to hang on the wall have been in the works since the 1960s. Recent developments in several flat-panel-display (FPD) technologies may finally mean that cost-effective displays will soon be available. Advances in many areas have occurred simultaneously, mainly with liquid crystal displays (LCDs), but also with plasma displays, electro-luminescent displays, and flat cathode ray tubes (CRTs) for specific applications. However, these displays have limited view angle, brightness, resolution, and color purity. Nor are they rugged or compact enough to be easily portable, and they are costly, especially large area screens, because they require glass substrates, and large scale lithography for fabrication.

Projection systems offer large images, in the range of 40 - 60 inches diagonal, and both front-view and rear-view projection systems are now available. Recently, laser beam scanning projection displays [1] have been demonstrated with inherent high brightness, full color and high resolution not possible with conventional projection systems. However, these systems are still very large and bulky, and safety remains a major issue for laser based systems, especially in a home environment.

In an effort to produce laser scanning that is compact and safe, a form of flat panel display using planar optic waveguiding has been proposed and demonstrated at Brookhaven National Laboratory. Their planar optics display (POD) uses stacks of thin glass plates, with a modulated laser beam for scanning [2]. Unfortunately, this device uses rigid glass waveguides and a bulky scanning system, and its resolution is intrinsically limited by inefficient coupling of light in and out of the waveguides.

In spite of its deficiencies, this POD approach clearly suggests that using flexible polymer material instead of glass would make possible a unique, compact, lightweight rollable large area display. This display paradigm is neither front nor rear projection system. It is a guided wave internal projection system with the color richness and brightness of rear laser projection, and is more compact and portable than current FPDs. However, to realize this potential would require that a practical, commercially viable means be found to fabricate hundreds or thousands of polymer layers into an assembly still thin enough to be rollable, as well as an efficient way of coupling light in and out of these waveguides to display the image.

A unique set of technologies are in place at Physical Optics Corporation (POC) that directly support rollable polymer display development. These technologies include polymer waveguide arrays for high density optical interconnects [3], multilayer holographic polymer mirror design and fabrication [4], planar holographic input, output, and beam routing techniques [5], and the polymer embossing technology for holographic light shaping diffusers and LCD backlighting panels (these are already POC commercial product lines).
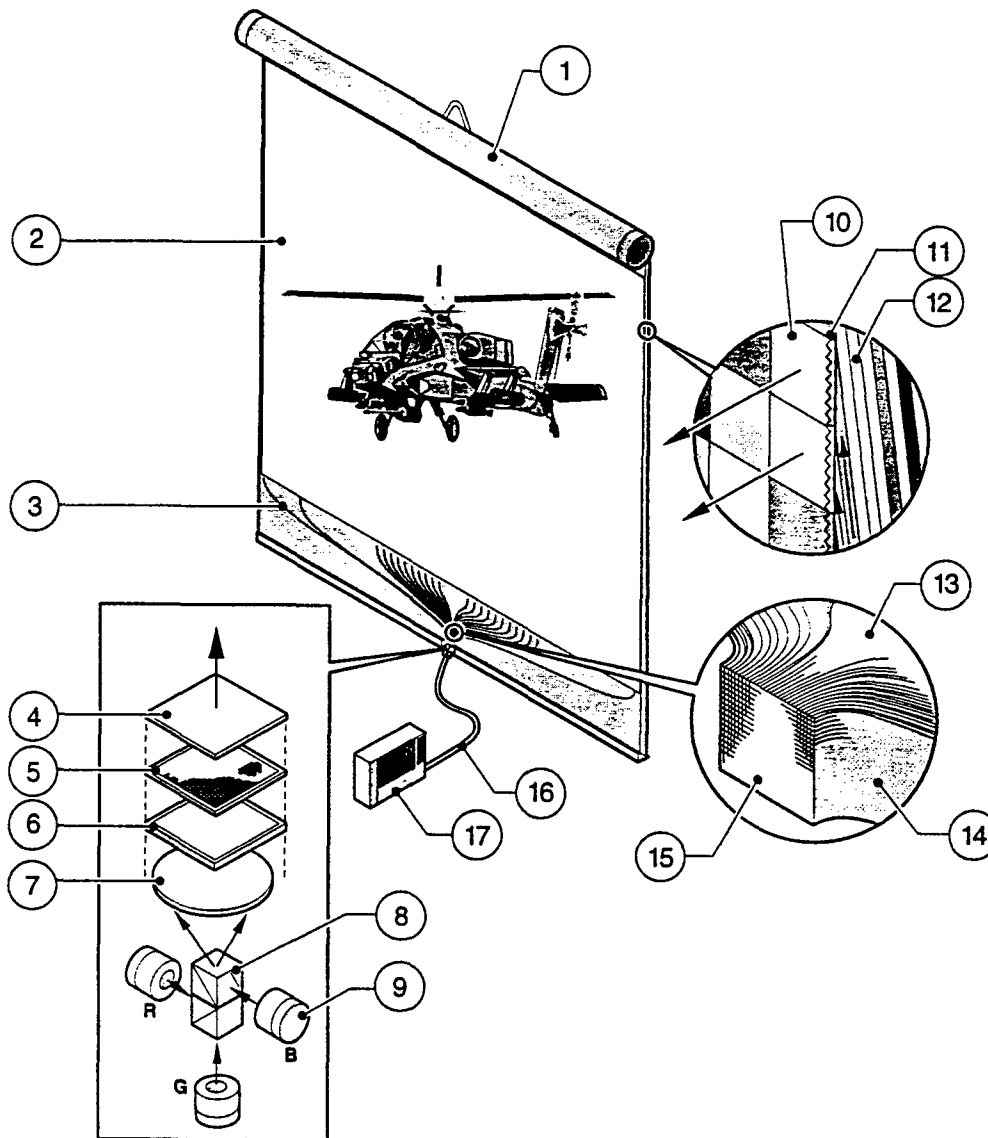
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1.2   POC's Proposed Approach

Physical Optics Corporation (POC) proposed to develop in this SBIR Phase I project a **rollable polymer waveguide display** technology based on POC's polymer waveguide and holographic techniques. Two key issues were addressed. The first is generating a **multiplanar array of waveguides** with very small cross sections (~1 μm × 100 μm) by holographic micropattern (i.e., fringe) generation. The second issue is using **waveguide hologram** recording techniques to generate input and output coupling hologram arrays. Both of these approaches are based on POC's previously developed polymer waveguide technology [3] and planar holographic technologies [4,5].

Figure 1-1 illustrates POC's approach to the design of the Holographic Optic Waveguide Array Rollable Display (HOWARD). In this passive multilayer polymer waveguide array, the number of layers equals the **vertical resolution of the display (~1024)** and the number of arrays equals the **horizontal resolution (~1280)**. A coupling waveguide hologram is fabricated at each position of the display sheet to couple each pixel of input image to the corresponding pixel of the output display. The output holographic coupler is integrated with POC's elliptical light shaping diffuser, which can produce large scale horizontal diffusion while keeping the vertical diffusion within a desired range.

The image can be displayed either by **serially scanning with a modulated three-color (RGB) laser beam, or by injecting the 2-D pattern in parallel by means of an LC spatial light modulator or LCD.** Either requires 2-D arrays of input couplers into the waveguides. Alternatively, **a one-dimensional array of laser diodes (LDs) can be used with only one-directional scanning.**

This final report describes POC's progress in the Phase I feasibility study based on holographic optics and multilayer polymer waveguide substrate. In Phase I, **POC conducted a preliminary study, modeling the multiplanar waveguide and analyzing its light propagation characteristics.** Based on the waveguide requirements, possible display system architectures were investigated. In parallel, several types of photopolymers were characterized to evaluate their suitability for holographic and multiplanar waveguide fabrication. Based on these results, a proof of principle of a multiplanar waveguide fabrication and planar display was demonstrated in the laboratory.

1. Roller case
2. HOWARD Screen
3. Polymer channel waveguides
4. HOE coupler
5. Microlens array
6. Liquid crystal display (LCD) panel
7. Collimating lens
8. Micro-optics beam combiner

9. Laser diodes (RGB)
10. Display pixel
11. POC light shaping diffuser
12. Polymer planar waveguides
13. Horizontal graded index waveguide array
14. Vertical graded index planar waveguide array
15. Waveguide channel input array
16. Electrical cable
17. Image source

Figure 1-1
Holographic Optic Waveguide Array Rollable Display (HOWARD) concept based on POC
holographic and planar waveguide technologies.

2.0   PHASE I OBJECTIVES AND TECHNICAL APPROACH

2.1   Technical Objectives

The overall goal of Phase I was to demonstrate the feasibility of holographically producing a multiplanar array of graded index waveguide structures in a single flexible polymer substrate, and to weigh its potential as a key component of a commercially viable rollable display device. The Phase I technical objectives were:

Objective 1.   Model and analyze characteristics of holographic multilayer planar waveguide structure, and determine a promising display system architecture.

Objective 2.   Experimentally characterize available volume holographic polymer materials, and investigate processing techniques for the implementation of the proposed fabrication concept.

Objective 3.   Fabricate a small area multiplanar waveguide structure and demonstrate the feasibility of the proposed rollable display concept.

At the end of Phase I the project milestones were completely met, and the following questions had been answered:

1.   *What are the necessary parameter values of the holographic multiplanar waveguide structure to achieve acceptable light transmission characteristics?*
Computer modeling, analytical calculation and experimental analyses have shown that it is possible to use very thin (1 to 2 μm) polymer waveguide layers with realistic refractive indexes corresponding to commercially available polymer films to allow efficient, low loss propagation of three primary colors (RGB) of laser light simultaneously with sufficient tolerance in the coupling angles. Total thickness of the polymer substrate can be 2 to 4 mm for a vertical resolution of 1024

2.   *What is the best choice of holographic polymer material in terms of optical efficiency, waveguide loss, and multiplexability, as well as reprocessability?*
Dichromated gelatin and DuPont photopolymers showed maximum index modulation of 0.02 to 0.06 achievable for holographic optics and waveguide recording. DCG shows higher diffraction efficiency of (98%) and lower (<2%) loss than DuPont photopolymer, while in terms of processing and stability DuPont polymer is more suitable for input/output coupling hologram fabrication.

3.   *What are the most suitable image input and output architecture and image forming device?*
Three image forming approaches -- 2-D laser beam scanning; 1-D line image scanning; and 2-D direct image projection without scanning -- are suitable for image input into the multiplanar polymer waveguide substrate. The most practical approach appears to be 1-D line image scanning, which can give high (>2560) horizontal resolution with an available low speed 1-D scanner. For image output, a

surface relief multiplexed holographic grating coupler with directional diffusion produces wide horizontal field-of-view and high contrast images

2.2 Phase I Technical Approach

The key technology to be demonstrated in this Phase I effort was the fabrication of multiple layers of thin graded-index planar waveguide inside a single polymer substrate. This was accomplished by simply exposing a holographic polymer film (POC's dichromated gelatin or DuPont's photopolymer) to a collimated laser beam. The standing wave created between the incident beam and the beam reflected from the back of the polymer film produces a sinusoidal intensity pattern resulting in a modulation Δn across the depth of the film, forming a stack of planes parallel to the surface of the film. Properly adjusting the laser exposure and processing produces a non-sinusoidal, step-like Δn profile, resulting in a stack of a large number of slab planar waveguides with graded index interfaces. Since the period of Δn is on the order of the wavelength of the recording laser, the thickness of these waveguides can be ~0.5 μm to several microns. In this way, hundreds of waveguide planes can be produced simply and inexpensively in a polymer film. Several of these waveguide films can then be laminated to achieve a desired number of planes equal to the resolution of the display (i.e., ~512 for TV resolution, or 1024 for HDTV). The total thickness of the polymer substrate will still be only 1 to 2 mm.

To keep the laser beam from spreading in these planar waveguides, an array of channel waveguides can be created by a similar holographic recording technique and photolithographic recording using an array mask pattern. The advantage of using volume holographic polymer material is that a multiple exposure of the hologram can be made and then processed to develop a multiplexed hologram. This method is crucial for efficient coupling of light in and out of the multiplanar waveguide. An alternative approach to coupling light in and out of the waveguide is to cast the polymer film into a thin wedge and then fabricate the multilayer waveguides holographically. In this way successive layers of waveguide are exposed to the outside, and form a 2-D array of pixels. POC's polymer casting technique, developed for the fabrication of thick holographic mirrors, can be applied to this approach.

The Phase I technical approach that was pursued to accomplish the above objectives specifically involved the following tasks:

Task 1.	Computer Modeling and Simulation of Waveguide Structure and Analysis of their Performance
Task 2.	Investigation of Display System Architecture
Task 3.	Characterization and Selection of Polymer Materials
Task 4	Demonstration of Proposed Fabrication Method
Task 5.	Demonstration of HOWARD Concept
Task 6.	Exploration of Commercial Potential

2.3 Summary of Phase I Accomplishments

At the end of Phase I, POC had successfully accomplished all of its Phase I objectives. Specifically, the Phase I work carried out according to the above tasks significantly advanced the development of this unique rollable polymer waveguide display technology. These results indicated that a practical rollable display is indeed feasible. Multiplanar polymer substrate fabrication, based either on POC's holographic technology or on existing multi-layer lamination techniques of coextrusion or polymer evaporative web coating, could be combined with POC's unique holographic coupler and diffuser technologies to bring this display concept to reality. The following summarizes the Phase I accomplishments.

1. Developed a computer model for multiplanar polymer waveguide substrates
    *   Developed a general analytical model for multiplanar polymer substrate structure.
    *   Analyzed wave propagation characteristics.
    *   Demonstrated multi-color light propagation in very thin (2 μm) polymer waveguides.

2. Investigated display system architectures
    *   Analyzed two HOWARD architectures: (1) Holographically produced multi-planar and wedge coupling; (2) Multiplanar polymer lamination.
    *   Developed volume holographic and surface relief (prismatic) I/O coupling approaches.
    *   Analyzed three image forming approaches: (1) Single laser beam 2-D scanning; (2) 1-D line image 1-D scanning; (3) 2-D image projection.

3. Characterized and selected polymer materials
    *   Determined index modulation characteristics of commercial holographic polymers (i.e., dichromated gelatin, DCG), and DuPont photopolymer (DPP) materials.
    *   Investigated light propagation characteristics of thin polymer films; Demonstrated DuPont's Mylar film and epoxy films as waveguide and buffer layers.

4. Demonstrated fabrication of multiplanar waveguide structure
    *   Demonstrated fabrication of holographically formed multiplanar waveguide structure.
    *   Demonstrated fabrication of multilayer laminated waveguide structure.
    *   Demonstrated integration of holographic and prismatic I/O coupler with multiplanar waveguide substrate.

5. Demonstrated HOWARD concept
    *   Demonstrated laser light input, propagation along a multiplanar waveguide substrate and output to display separate pixels.
    *   Demonstrated simultaneous two-color laser (red and green) propagation in a single thin polymer waveguide.

3.0   PHASE I RESULTS

3.1   Waveguide Structure Modeling and Analysis (Task 1)

The preliminary study of holographically formed waveguide structures and their light propagation characteristics was carried out as planned under Task 1. This included analytical modeling and computer simulation of Lippmann holograms and multilayer structures, specifically extended for use in HOWARD design. A simple model of a multilayer waveguide structure was first analyzed in terms of the three key mechanisms:

- Coupling light into the waveguide layers
- Light propagation through the waveguides
- Coupling light out of the waveguide layers.

Initially, the multilayer waveguide is assumed to consist of an alternating low index (n_1) and high index (n_2), step-wise structure with period Λ, as shown in Figure 3-1. This type of modulated index structure has been analyzed in terms of light wave propagation in the reflective (backscatter) mode (a), the transmissive low angle scattering mode (b), and the more general transmissive mode (c) [6]. The studies have focused on the two cases in which either L or T is relatively small (i.e., in the Bragg regime and Raman-Nath regime). No study had yet examined the case in which both L and T are very large compared to the wavelength of light. This is the new regime that is applicable for our multilayer waveguide structure.

POC had already developed computer simulation models for a general hologram/multilayer hybrid structure for the Bragg and Raman-Nath cases [4]. POC had also developed a general 3-D computer model for designing a holographic waveguide coupler, and also a general radiometric ray tracing (R^2T) model to simulate propagation of light from a general light source with arbitrary coherence properties [7]. All of these computer models are directly applicable to designing HOWARD and analyzing its performance. For the Phase I effort, we demonstrated the design of a multilayer waveguide structure, including both hologram and dielectric multilayer structure in the more general case, in which both L and T are large.
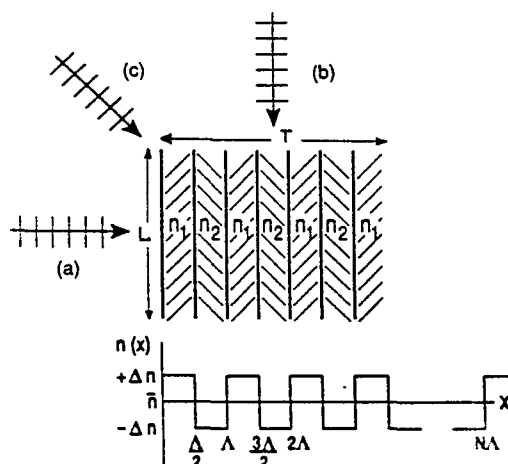

Figure 3-1
A simple step-index multilayer waveguide structure, used to model light propagation characteristics.

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3.1.1   Light Propagation Characteristics

Since the multilayer index structures are produced by Lippmann holographic recording, the period Λ is on the order of the wavelength of laser light used to record these holograph structures. The largest value of Λ is roughly several times the wavelength. The relation between the recording laser wavelength λ_0, the angle of incidence θ_0 inside the material with average refractive index n is $\Lambda = \lambda_0/2n \cos \theta_0$ (see Figure 3-9). For example, for $\lambda_0 = 514$ nm, the argon laser wavelength used with current volume hologram materials (e.g., DCG and DPP with $n \simeq 1.5$) the value of Λ can range from ~170 nm to 3 μm. For a given Δn, Λ must be large enough so that diffractive coupling between waveguide channels is negligible. For example, for $\Delta n = 0.03$, Λ must be ≥ 2.5 μm, and for large Δn which can be as large as 0.08, Λ can be smaller.

For $\Lambda = 2.5$ μm, and for a typical thick volume hologram, T can be 20 μm to 40 μm, so that the number of holographic waveguide layers $N_n = T/\Lambda = 8$ to 16. In this case multiple layers of holographic multilayer waveguide are required to achieve the resolution required in a display. Again, if Δn is higher, Λ can be smaller (~ 1 μm), and N_n can be 20 to 40.

Another important characteristic of a useful waveguide is that the absorption should be low, so that enough light is transmitted for the display to be bright. It should be noted that current LCD devices are only about 14% light efficient. In the HOWARD, although the absorption of the waveguide material is substantially higher than that of pure materials such as glass or plastic fiber, the distance of transmission is short (~meter) and the use of a powerful laser source compensates for the losses.

3.1.2   Computer Modeling of General Hologram/Dielectric Multilayer Structure

To compute the intensity distribution in any layer of a multilayer structure (see Figure 3-2), we make the following assumptions:

1.   The media are homogeneous, isotropic, and linear to transverse electric (TE) plane waves (e.g., this would be true of a polymer with no birefringence).

2.   The total time-harmonic electric field of angular frequency ω in any layer is in the form

$$\bar{E}_t(x,y,z,t) = \mathrm{Re}\left[\bar{E}(x,y,z)\exp\{j\omega t\}\right] , \qquad (3\text{-}1)$$

where $j = \sqrt{-1}$, Re[ ] means the real part of a function, and $\bar{E}(x,y,z)$ is a vector phasor that contains information on direction, magnitude, and phase. Phasors are, in general, complex quantities. Each layer has a different $\bar{E}(x,y,z)$.

3.   The tangential components of the fields are continuous at the interfaces.

4.   Snell's law of refraction holds for any layer, regardless of whether it is lossless or lossy; i.e.,

$$n_i \sin\theta_i = \hat{n}_L \sin\theta_L, \quad L = 1,2,....,m,m+1 \qquad (3\text{-}2)$$

where the subscript i is used by variables in the incident medium, the subscript m is used to indicate the last layer (i.e., m^{th} layer) of thickness d_m, the subscript m+1 is used to indicate the semi-infinite transmission medium after the last layer; n_i and θ_i are the respective real refractive index and incidence angle about normal in the medium on which the light is incident, $\hat{n}_L$ and θ_L are the respective complex refractive index and transmission angle in layer L, and $\hat{n}_L$ ($= n_L - j\, M_L$) is a complex number for a lossy medium, or a real number for a lossless medium.

5.   The intensity in any layer can be defined as

$$I = 2\left\langle \vec{E}_t(x,y,z,t) \cdot \vec{E}_t(x,y,z,t) \right\rangle$$

$$= \frac{2}{2T} \int_{-T}^{T} \vec{E}_t(x,y,z,t) \cdot \vec{E}_t(x,y,z,t)\, dt, \qquad (3\text{-}3)$$

where 2T is the time over which the average is taken. By substituting Eq. (3-1) into Eq. (3-3), we obtain

$$I = \vec{E}(x,y,z) \cdot \vec{E}^*(x,y,z) \quad \text{for } T \gg \frac{2\pi}{\omega}, \qquad (3\text{-}4)$$

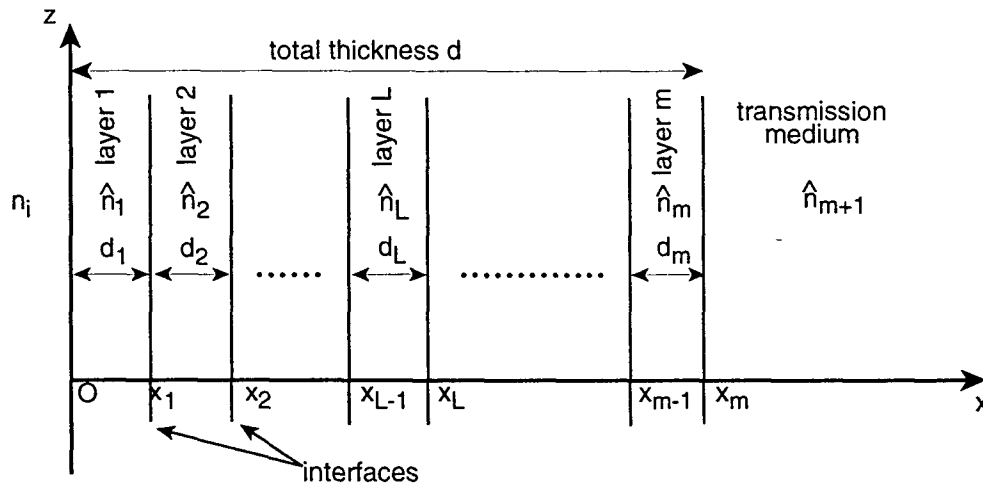where the notation (*) represents the complex conjugate.

Figure 3-2
Schematic representation of a multilayer thin film. Oxy is the plane of incidence. The Oy-axis is normal to the plane of the paper. For transverse electric (TE) plane waves, the only electric field component is along the negative direction of the Oy-axis.

In the step-index case, $n_1 = n_3 = n_5 = \ldots = \bar{n} - \Delta n/2$, and $n_2 = n_4 = n_6 = \ldots = \bar{n} + \Delta n/2$. This model can also represent any form of index modulation, such as the graded index structure. This can be done by further dividing layers into a gradually varying step-index structure to the lower limit of sublayer thickness. POC has developed this model in our previous designs of nonuniform holographic filters, in which these multilayer index structures are generated by Lippmann holographic recording in a single thick volume holographic film.

3.1.3   Computer Simulation

Using the multiplanar computer model described above, we carried out a computer simulation to study light propagation in a simple multiplanar waveguide structure. We assume a simple step-index structure with practical waveguide parameters, n_1, n_2, T_1, T_2, (see Figure 3-3). The n_1 and n_2 values are those of commercially available polymer materials, and range between 1.5 and 1.64, while T_1 and T_2 range from 1 μm to 3 μm. The total thickness for a display with a vertical resolution of 1024 would be no more than a few millimeters. We studied the light propagation properties of two waveguides and buffer layers by determining their possible modes of propagation at 457, 514, and 633 nm wavelengths corresponding to blue, green, and red colors. From these mode characteristics, we determined the minimum waveguide and buffer layer thickness that allow three-color light propagation with negligible cross-talk, and with sufficient range in the propagation angles θ (i.e., $\theta = 90° - \theta_2$). Figures 3-4 through 3-8 show the results of the simulation for two polymer waveguide and buffer thicknesses ($T_1 = T_2 = 1$ μm, 2 μm, and 3 μm) with refractive indices $n_1 = 1.5$, $n_2 = 1.56$ and $n_1 = 1.56$, $n_2 = 1.64$. The possible modes of propagation and the intensity distribution across the waveguide layer, one instance of time (valid for all values of z) are plotted. The results show that three colors of light (RGB) can propagate simultaneously through a thin (~1 - 2 μm) polymer waveguide structure without appreciable cross-talk and at a relatively large acceptance angle (i.e., $\Delta\theta \simeq 4° - 16°$).
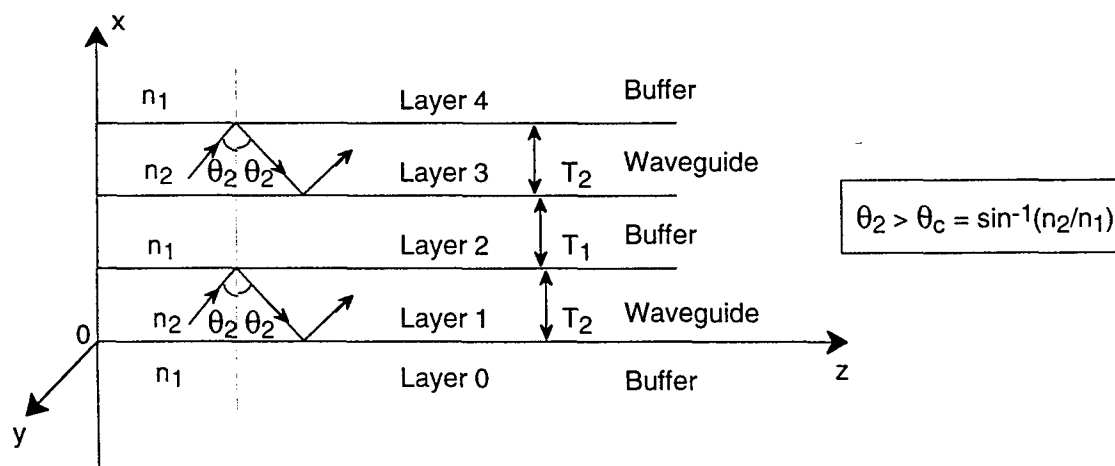
Figure 3-3
Multiplanar step-index waveguide structure used in the computer simulation.

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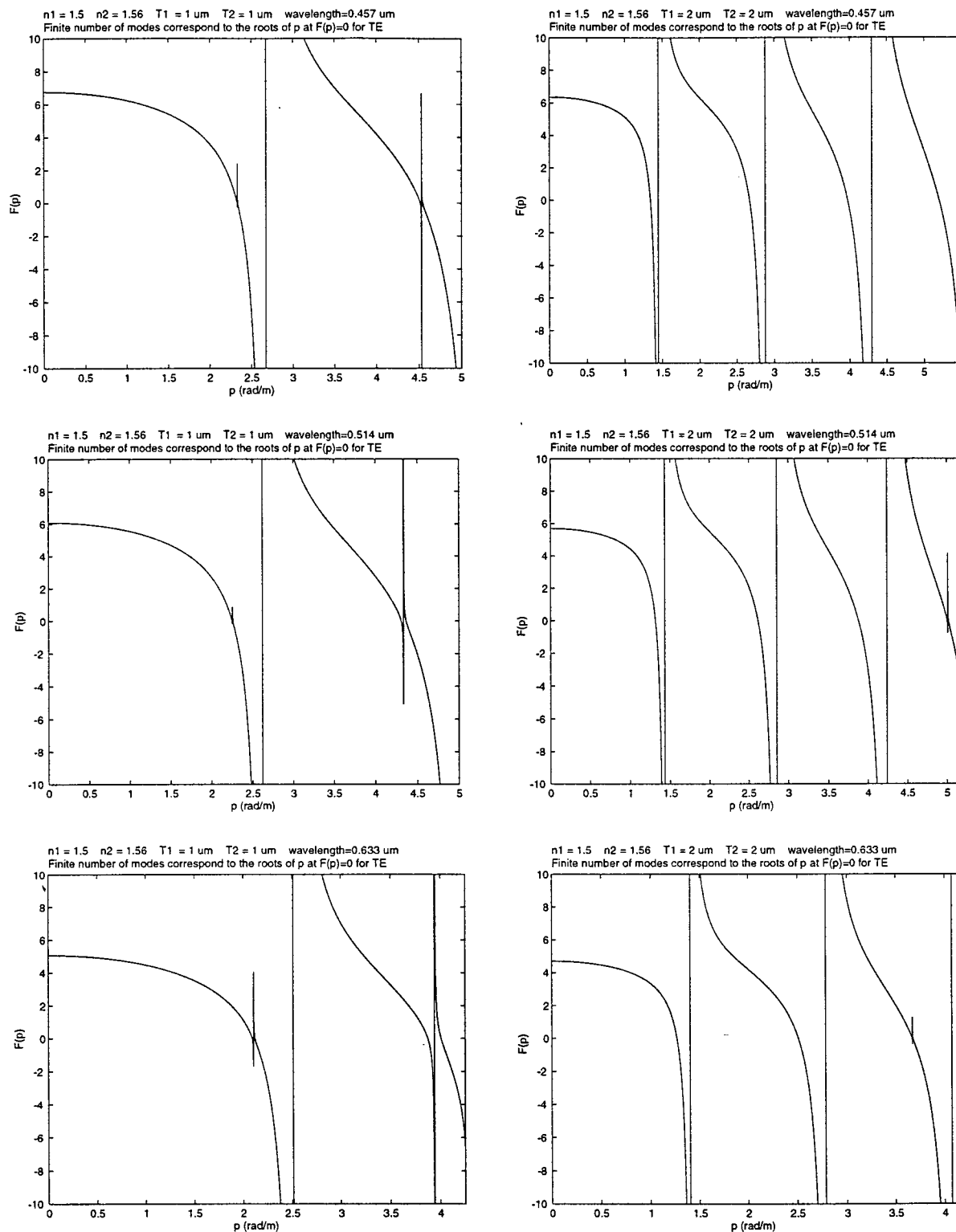
Figure 3-4
The possible modes of propagation of light in a multiplanar waveguide
structure at two waveguide thicknesses of 1 μm (left) and 2 μm (right) and for
three RGB wavelengths: 457 nm (blue), 514 nm (green), and 633 nm (red).
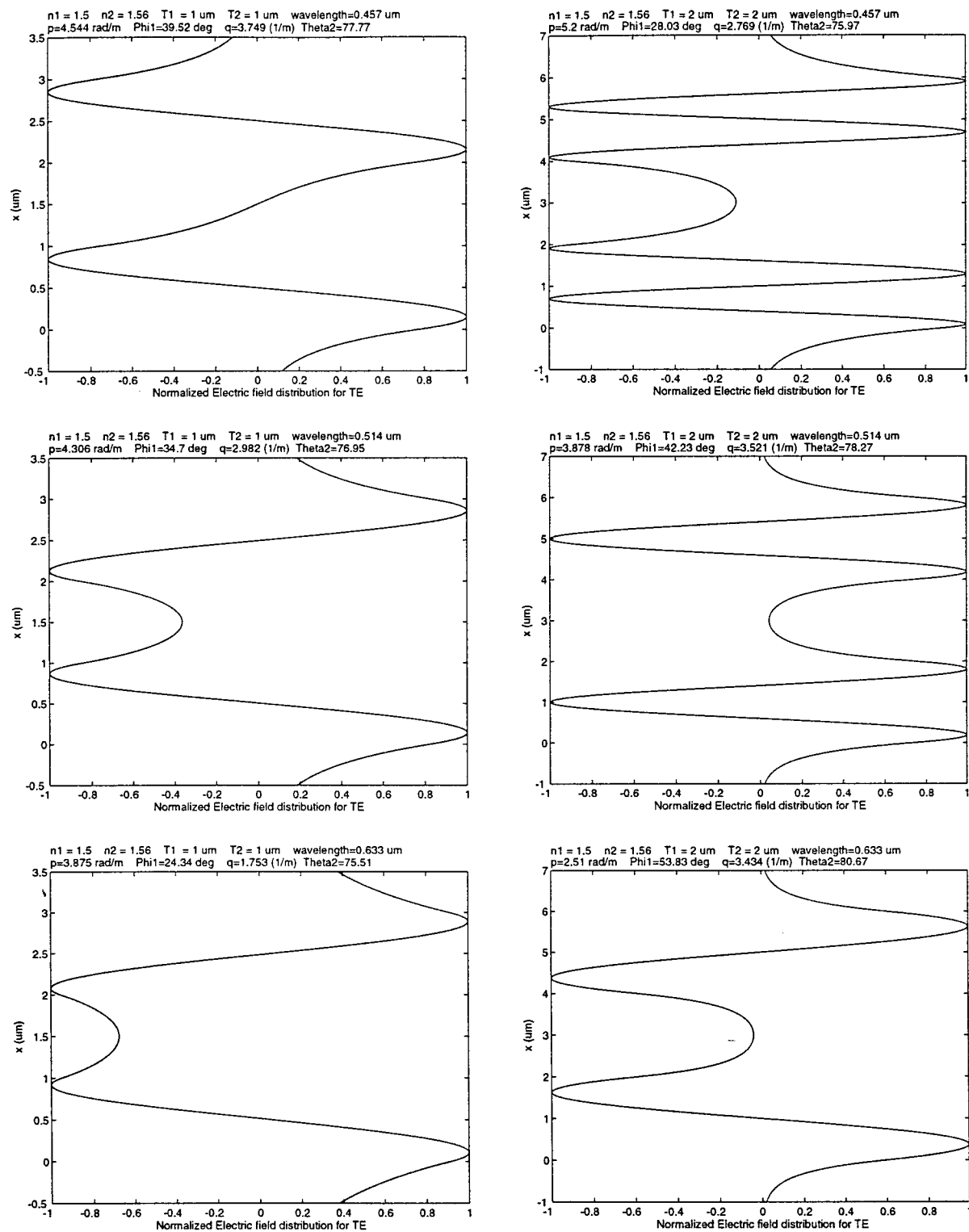
Figure 3-5
The electric field intensity across the multiplanar waveguides for the highest mode of propagation
in waveguides with parameters corresponding to those in Figure 3-4.

n1 = 1.5   n2 = 1.56   T1 = 1 um   T2 = 1 um   wavelength=0.457 um
p=2.326 rad/m   Phi1=66.74 deg   q=5.412 (1/m) Theta2=83.77

n1 = 1.5   n2 = 1.56   T1 = 1 um   T2 = 1 um   wavelength=0.457 um
p=4.544 rad/m   Phi1=39.52 deg   q=3.749 (1/m) Theta2=77.77

n1 = 1.5   n2 = 1.56   T1 = 1 um   T2 = 1 um   wavelength=0.514 um
p=2.248 rad/m   Phi1=64.59 deg   q=4.731 (1/m) Theta2=83.23

n1 = 1.5   n2 = 1.56   T1 = 1 um   T2 = 1 um   wavelength=0.514 um
p=4.306 rad/m   Phi1=34.7 deg   q=2.982 (1/m) Theta2=76.95

n1 = 1.5   n2 = 1.56   T1 = 1 um   T2 = 1 um   wavelength=0.633 um
p=2.092 rad/m   Phi1=60.54 deg   q=3.703 (1/m) Theta2=82.24

n1 = 1.5   n2 = 1.56   T1 = 1 um   T2 = 1 um   wavelength=0.633 um
p=3.875 rad/m   Phi1=24.34 deg   q=1.753 (1/m) Theta2=75.51

Lowest Mode   Highest Mode

Figure 3-6

Intensity distribution across a pair of planar waveguides (n_2 = 1.56) with a buffer layer (n_1 = 1.5): $T_1 = T_2 = 1$ µm. Wavelengths: 457 nm (blue), 514 nm (green), and 633 nm (red).

n1 = 1.5   n2 = 1.56   T1 = 2 um   T2 = 2 um   wavelength=0.457 um
p=1.341 rad/m   Phi1≈76.84 deg   q=5.736 (1/m)   Theta2=86.42

n1 = 1.5   n2 = 1.56   T1 = 2 um   T2 = 2 um   wavelength=0.457 um
p=5.2 rad/m   Phi1=28.03 deg   q=2.769 (1/m)   Theta2=75.97

n1 = 1.5   n2 = 1.56   T1 = 2 um   T2 = 2 um   wavelength=0.514 um
p=1.317 rad/m   Phi1≈75.44 deg   q=5.07 (1/m)   Theta2=86.04

n1 = 1.5   n2 = 1.56   T1 = 2 um   T2 = 2 um   wavelength=0.514 um
p=3.878 rad/m   Phi1=42.23 deg   q=3.521 (1/m)   Theta2=78.27

n1 = 1.5   n2 = 1.56   T1 = 2 um   T2 = 2 um   wavelength=0.633 um
p=1.268 rad/m   Phi1≈72.65 deg   q=4.06 (1/m)   Theta2=85.3

n1 = 1.5   n2 = 1.56   T1 = 2 um   T2 = 2 um   wavelength=0.633 um
p=2.51 rad/m   Phi1=53.83 deg   q=3.434 (1/m)   Theta2=80.67
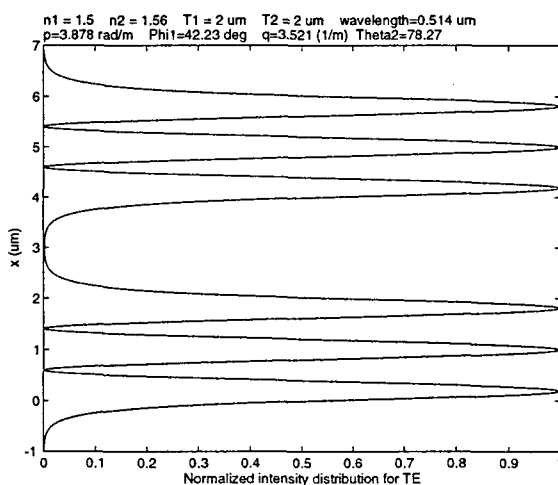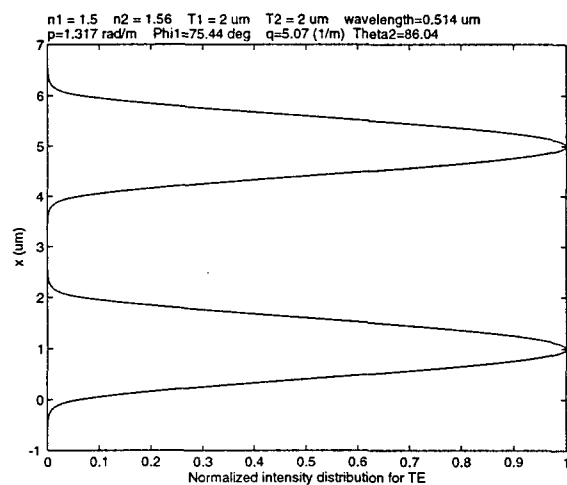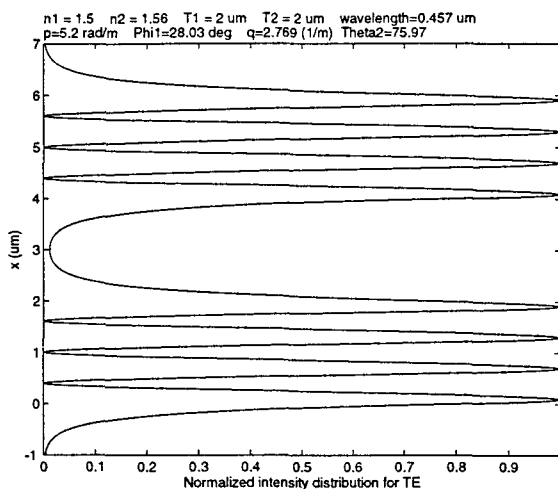
Lowest Mode   Highest Mode

Figure 3-7
Intensity distribution across a pair of planar waveguides (n_2 = 1.56) with a buffer layer (n_1 = 1.5):
T_1 = T_2 = 2 μm. Wavelengths: 457 nm (blue), 514 nm (green), 633 nm (red).

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n1 = 1.56   n2 = 1.64   T1 = 1 um   T2 = 1 um   wavelength=0.633 um
p=2.218 rad/m   Phi1=63.79 deg   q=4.506 (1/m) Theta2=82.17

n1 = 1.56   n2 = 1.64   T1 = 1 um   T2 = 1 um   wavelength=0.633 um
p=4.297 rad/m   Phi1=31.16 deg   q=2.599 (1/m) Theta2=74.69

n1 = 1.56   n2 = 1.64   T1 = 2 um   T2 = 2 um   wavelength=0.633 um
p=1.307 rad/m   Phi1=74.91 deg   q=4.849 (1/m) Theta2=85.39

n1 ≈ 1.56   n2 ≈ 1.64   T1 = 2 um   T2 = 2 um   wavelength=0.633 um
p=4.933 rad/m   Phi1=10.79 deg   q=0.9404 (1/m) Theta2=72.36

n1 = 1.56   n2 = 1.64   T1 = 3 um   T2 = 3 um   wavelength=0.633 um
p=0.9239 rad/m   Phi1=79.4 deg   q=4.937 (1/m) Theta2=86.75

n1 = 1.56   n2 = 1.64   T1 = 3 um   T2 = 3 um   wavelength=0.633 um
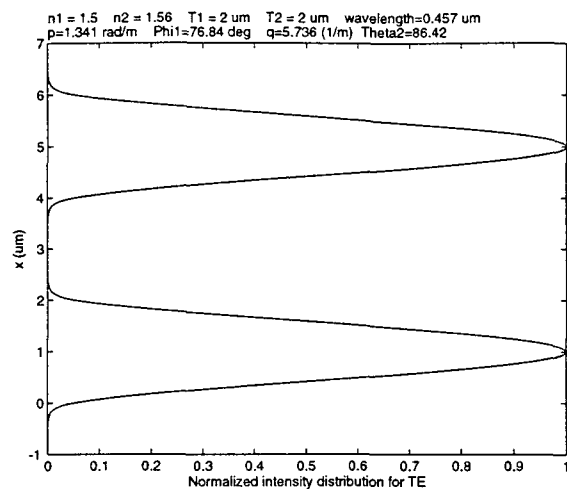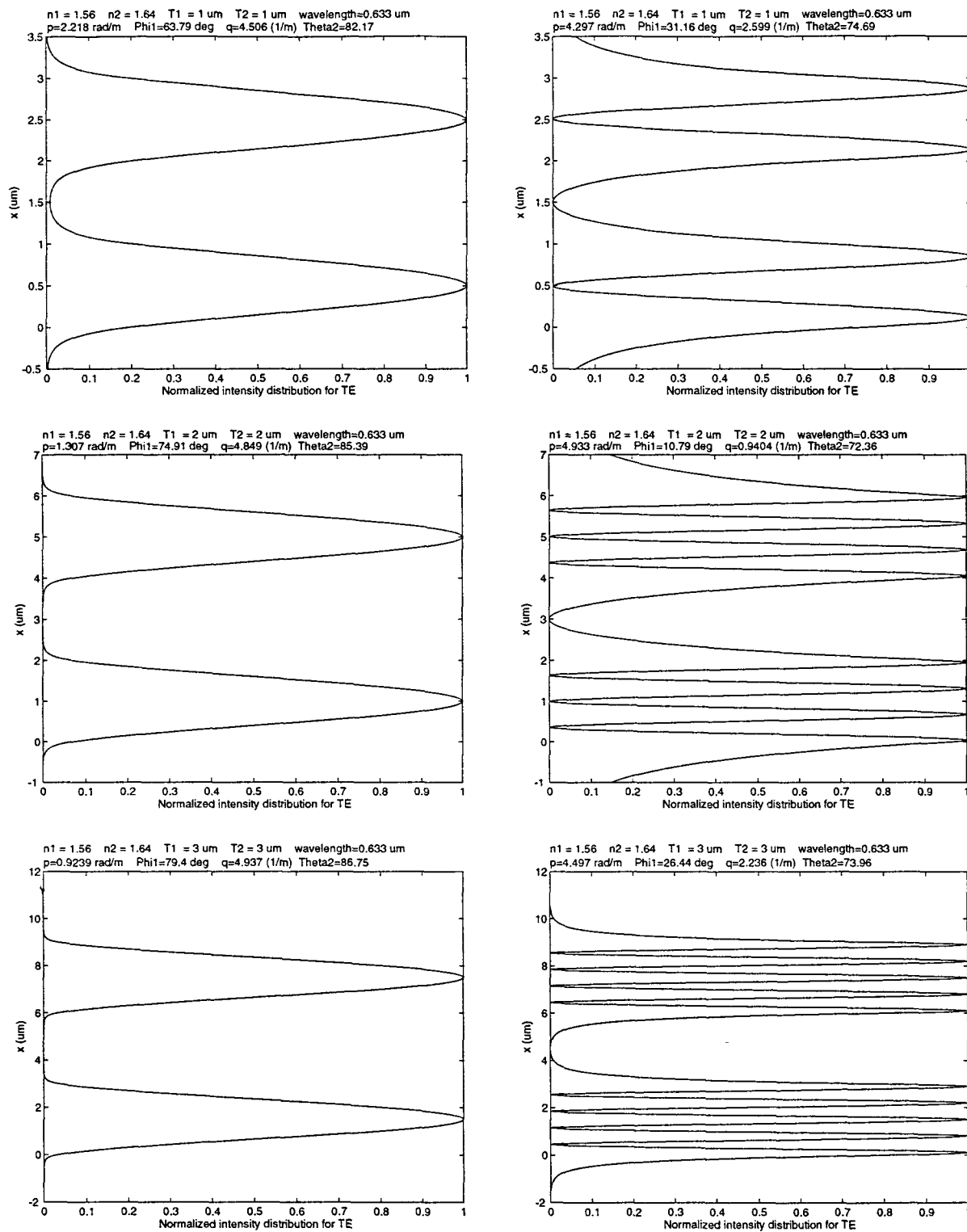p=4.497 rad/m   Phi1=26.44 deg   q=2.236 (1/m) Theta2=73.96

Lowest Mode

Highest Mode

Figure 3-8

Intensity distribution across a pair of planar waveguides ($n_2 = 1.64$) with a buffer layer ($n_1 = 1.56$): $T_1 = T_2 = 1\ \mu m$, $2\ \mu m$, and $3\ \mu m$. Wavelength: 633 nm (red).

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3.2   Investigation of Display System Architecture (Task 2)

Two HOWARD architectures were proposed (see Figure 3-9), based on two input/output coupling approaches: holographically formed multiplanar polymer structure with wedge waveguide coupling; and laminated multilayer polymer structure with waveguide hologram coupling. We investigated the holographic multiplanar architecture with wedge coupling first because of its simplicity. This concept is illustrated in Figure 3-10. Using POC dichromated gelatin polymer material, we cast the wedged film. After trying several techniques to produce a smooth wedged DCG film on a glass substrate, we settled on a method in which a thin plastic sheet between the glass substrate and the DCG film makes casting and peeling simple.
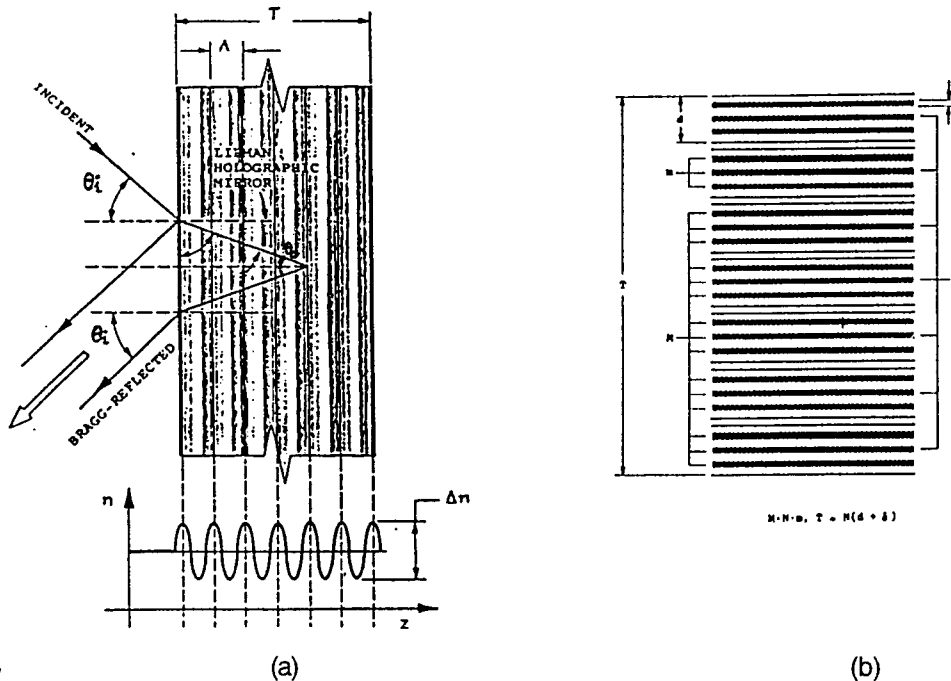

(a)   (b)

Figure 3-9
Two basic HOWARD architectures: (a) Holographically formed multiplanar polymer structure;
(b) Laminated multilayer polymer structure.

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(a) Polymer Casting

Flat Glass Substrate

Holographic Polymer

Wedge Glass Substrate

(b) Lippmann Holographic Exposure

Wedge

Index Matching Fluid

Collimated Laser Beam

(c) Lithographic Mask Printing
UV Exposure

Lithographic Mask with
Channel Waveguide
Pattern

(d) Polymer Waveguide Release
Thin Backing
Rollable Substrate

Peel Off

Epoxy

Wedge Mold

(e) Diffuser Replication

Master LSD
Flexible Substrate

Epoxy

LSD Replica

(f) Display of Injected Light

Elliptical Diffusion

Injected
Beam

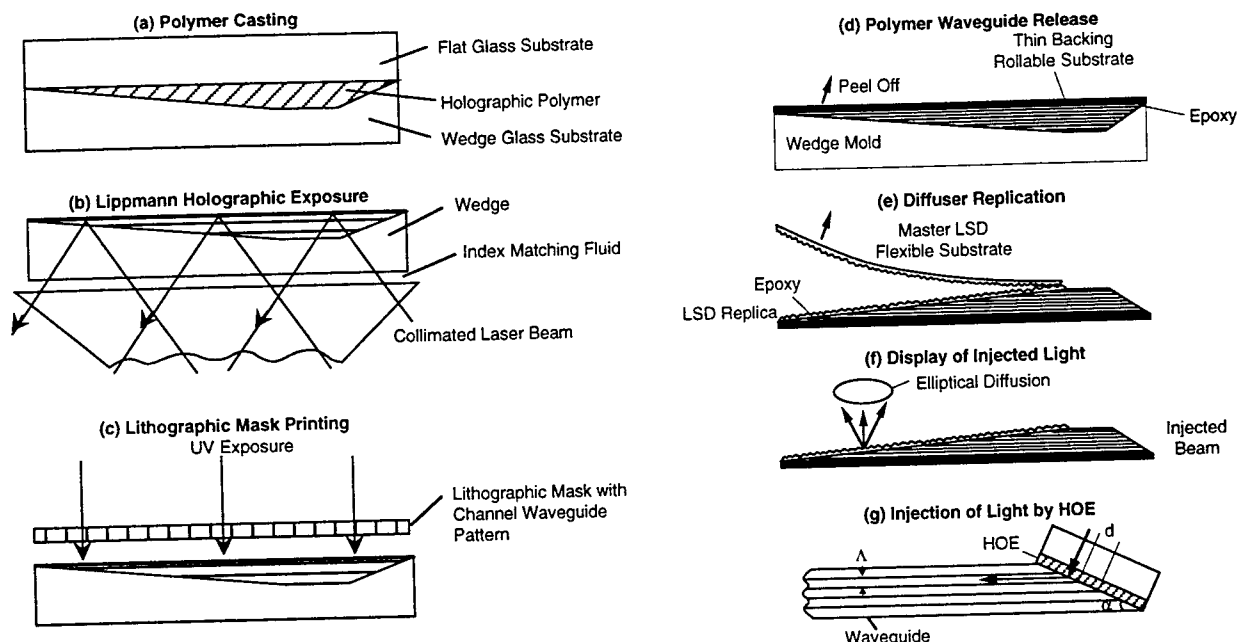**(g) Injection of Light by HOE**

HOE

Waveguide

Figure 3-10
Proposed fabrication process for holographic multiplanar polymer wedged substrate.

3.2.1 Fabrication of Holographic DCG Polymer Wedges

The DCG solution was prepared with a relatively low concentration of ammonium dichromate sensitizer, and filtered in a warm bath at ~55°C. The glass substrate was cleaned thoroughly, and a spacer of the required thickness (made from layers of plastic tape) was placed on one side of the glass (see Figure 3-11). Next, a cover plate was prepared using a glass substrate and a thin plastic sheet attached using methanol. The gelatin solution was poured onto the substrate, and the cover plate was placed on top of the solution. After 30 minutes, the glass cover was removed, leaving the plastic behind. After 7 to 8 hours, the plastic sheet was removed, leaving a small DCG wedge film on the glass substrate. The same method can also be used on the substrate side to cast the film required there when the final holographic multilayer structure is fabricated.

Many samples were fabricated using this method. The thickness and the wedge structure are directly observable as fringes by using a monochromatic sodium light source. The thickness variation was also measured with a profilometer. The results shown in Figure 3-12 clearly show a smooth variation of the film surface, forming a uniform wedge over a 12 cm length.
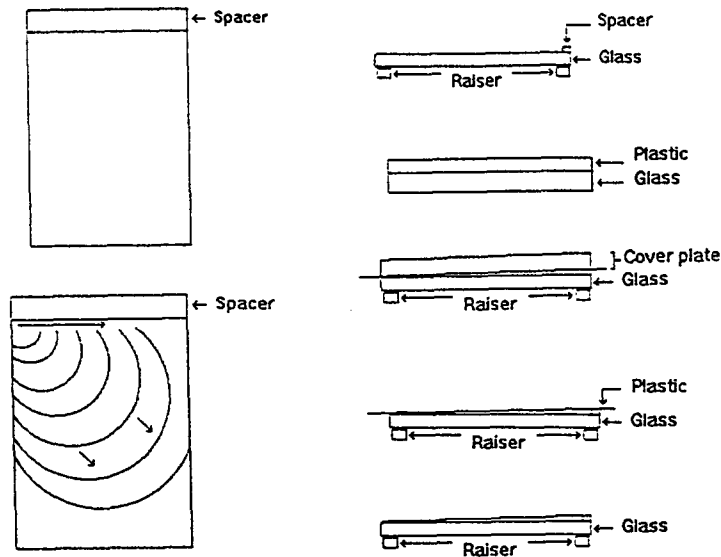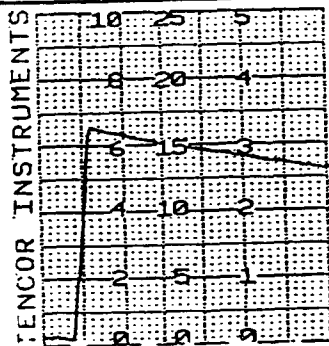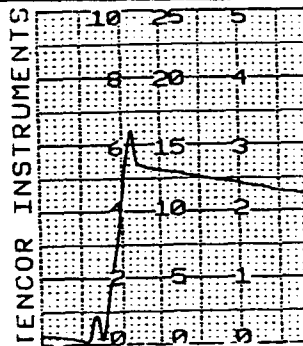
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Figure 3-11
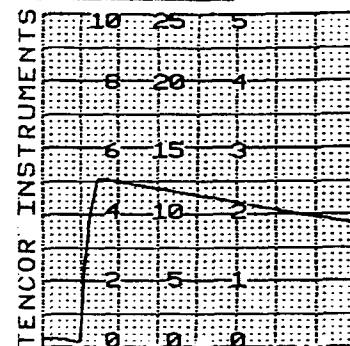DCG wedge fabrication process developed in Phase I.

Measurement #1

Thick end of wedge 30 mm down
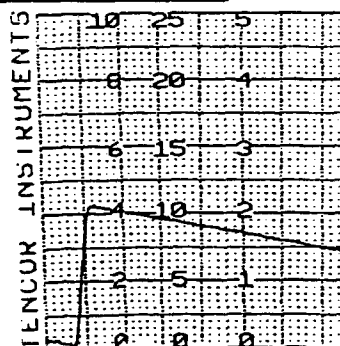from top of plate ≈ 16 μm thick

Measurement #2

60 mm down from top of plate
≈ 13 μm thick

Measurement #3

90 mm down from top of plate
≈ 11 μm thick

Measurement #4

102 mm down from top of plate ≈ 9 μm
thick

Measurement #5
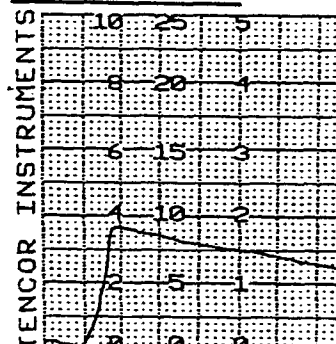
Thin end of wedge 120 mm down from
top of plate ≈ 6 μm thick and decreasing

Figure 3-12
Thickness data for a wedged DCG film, recorded using a profilometer. Total of five measurements,
taken 30 mm apart down the plate. Each graph shows a decrease in the thickness of the gelatin.

This casting method was used to fabricate a polymeric substrate with an input and output wedge. The next step in the fabrication of the waveguide structure in the wedge polymer films involved Lippman holographic recording at a large incidence angle. The large angle is required in order to produce graded index layers ~1-2 μm thick. The precise angle used for recording is determined by the required waveguide thickness and the refractive index modulation Δn producible by the volume holographic material (i.e., DCG or DPP). The maximum achievable Δn in these materials was determined through systematic material characterization as described in the following Task 3 description, Section 3.3.

3.2.2 Polymer Waveguide Input/Output Coupling

Three basic input/output (I/O) coupling approaches were considered. These approaches are:

1. Wedge coupling
2. Prismatic coupling
3. Holographic grating coupling.

3.2.2.1 Wedge Coupling

As shown in Figure 3-13, wedge coupling involves directly injecting either a single pixel of the input image (represented by a single thin light beam) or a line image (consisting of an array of parallel beams) through beam forming optics such as a cylindrical lens. The wedged input and output structures expand the width of the waveguide layers in a way that is simple and has potentially high coupling efficiency. However, the thinness of the waveguide layers limits the angle of injection, and thus also the coupling efficiency. This makes it necessary to use additional coupling elements on the wedged input and output, and to ensure that the wedge-to-air interface is of good optical quality in order to maintain good image quality, image uniformity, and low cross-talk between pixels. The wedged holographic multiplanar polymer approach has the advantage of automatically creating the wedged I/O area without the physical alignment required in the other two techniques.
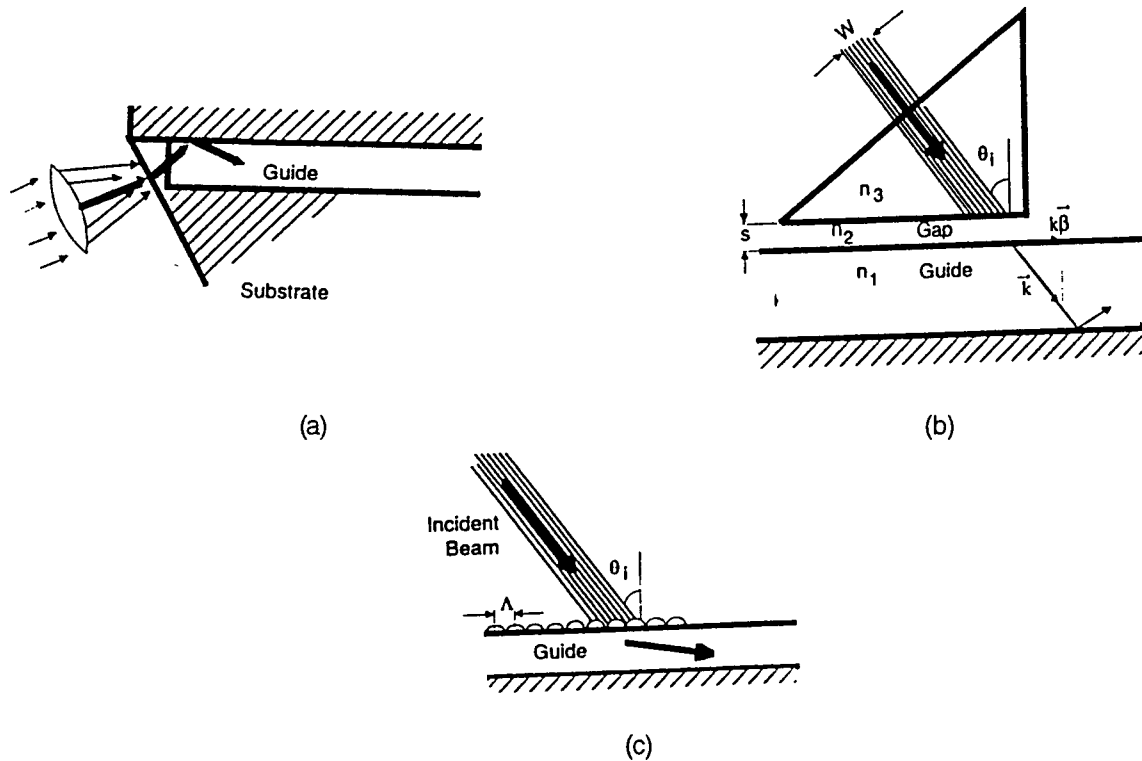
Guide

Substrate

(a)

W

θ_i

n_3

n_2 Gap $\vec{k\beta}$

s

n_1 Guide

$\vec{k}$

(b)

Incident
Beam

θ_i

Λ

Guide

(c)

Figure 3-13
Polymer waveguide I/O coupling approaches: (a) Wedge coupling; (b) Prismatic coupling;
(c) Holographic grating coupling.

3.2.2.2   Prismatic Coupling

For prismatic coupling, POC fabricated a microprism array ($\leq 100\mu m$), with one microprism for each planar waveguide, using standard waveguide technology. The coupling efficiency is determined by the waveguide thickness and the refractive indices of the microprism (n_3), waveguide (n_1) and buffer (n_2). It is required that $n_3 > n_1 > n_2$ in order for light to be coupled into the waveguide layers. In contrast to conventional prism coupling, a polymer microprism array can be fabricated directly onto the multilayer polymer waveguide substrate by UV polymer replication. By optimizing the choice of n_1, n_2 and n_3 (note that the refractive indices of commercial polymer and plastic materials cover the broad ranges from 1.48 to 1.68), this could achieve ~80% efficient coupling, only limited by the geometrical fill factor of the microprism structure. One drawback would be the noise due to the edges of the microprisms.

For our Phase I effort, only two types of optical-quality polymer material were readily available with which to demonstrate this coupling concept: Mylar (n = 1.64) from DuPont and UV epoxy (n = 1.54) from Norland. Other types of polymer were found to be of poor quality (they are simply not manufactured to optical quality, although according to the manufacturers they could be). To demonstrate this coupling concept, we replicated an epoxy microprism array (n = 1.54) onto 50 μm thickness glass (n = 1.51). Figure 3-14 shows the high quality of the replicated epoxy microprism array. Very high efficiency coupling was demonstrated using a red laser beam at

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633 nm and green at 514 nm. We concluded that this method would require a Mylar-type high index polymer in liquid form, similar to a UV epoxy, that could be cured by UV exposure.
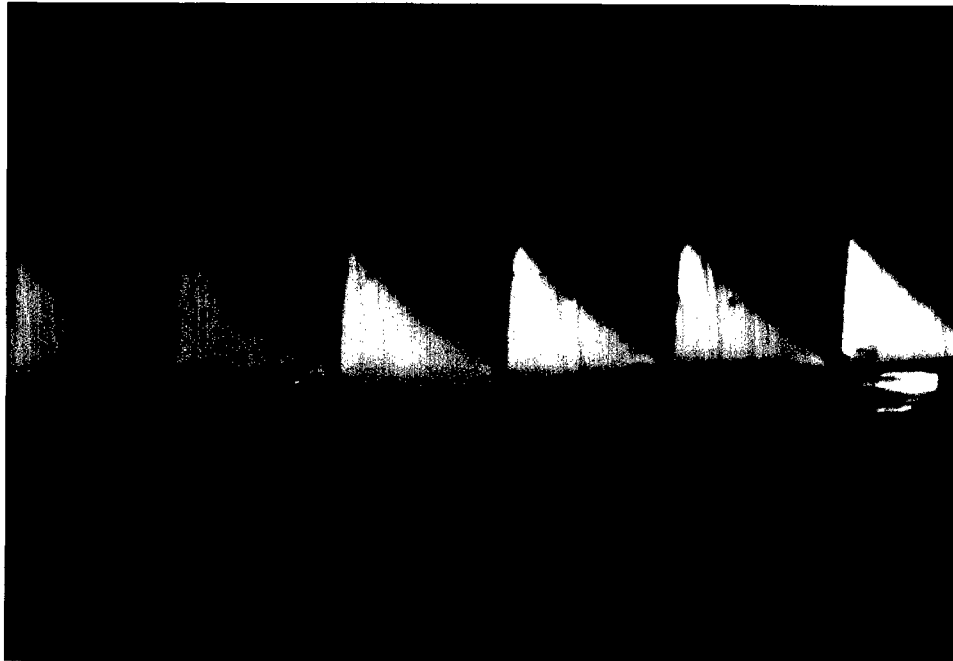

Figure 3-14
Epoxy microprism array fabricated on thin waveguide (50 μm glass microsheet) using POC's polymer replication technique.

3.2.2.3   Holographic Grating Coupling

Using dichromated gelatin (DCG) and DuPont photopolymer (DPP) volume holography materials, we investigated the design, fabrication and performance of volume holographic grating couplers (HGC). Two HGC approaches were considered.

1. *Symmetric grating*, which is easy to fabricate and has a large coupling angle and wavelength tolerance, but low coupling efficiency (<30%).

2. *Slanted (Bragg) grating*, which affords single order high efficiency coupling (efficiency >80%), but requires special fabrication techniques and is less tolerant of coupling angle and wavelength variations.

Using the standard holographic optical element design equations, the HGC recording geometries for a desired input and the diffraction angles for a selected wavelength can be determined. Figure 3-15 shows the recording geometries for the two cases. The holographic film is first coated on the polymer substrates, and the HGC is recorded using an argon ion laser at 514 nm. The optimum recording exposure was determined to maximize the diffraction efficiency of the HGCs.
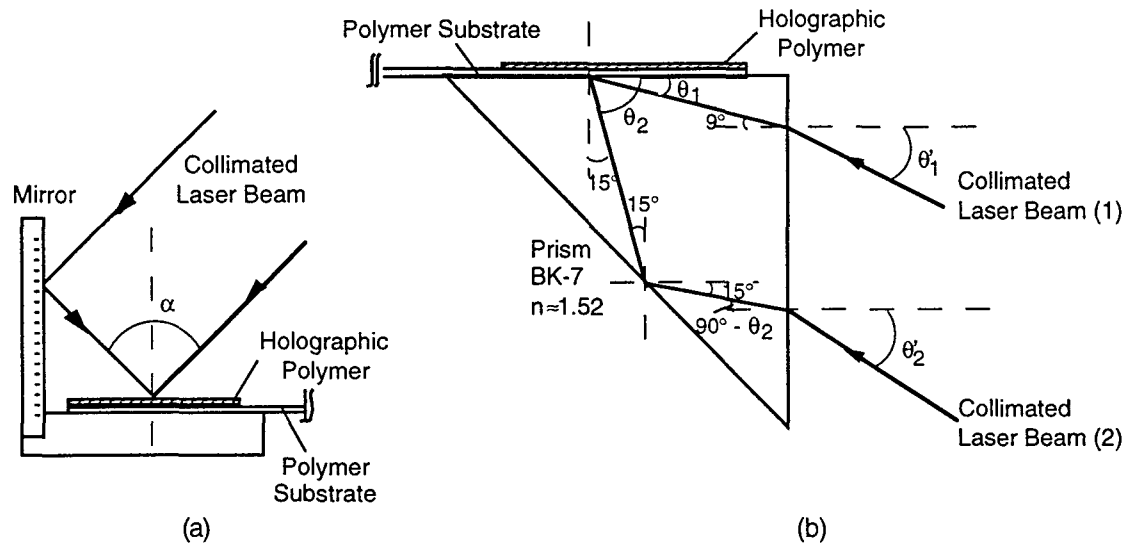
Figure 3-15
Holographic grating coupler recording geometries for (a) symmetric grating, and (b) slanted (Bragg) grating.

The advantage of using an HGC is that the incidence angle of the input light beam can be normal to the polymer substrate, and the coupling efficiency is independent of the refractive indices of the HGC and the polymer substrate. It can also be designed to couple light into the waveguide accurately and within the waveguide acceptance angle; i.e., $\Delta\theta \approx 0.4°$ for a 2 μm thick polymer waveguide. Unlike prism coupling, this image coupling can have a high fill factor, avoiding the substantial area of dead zones inherent in microprism coupling. The HGC couples the whole image into the polymer waveguide array without requiring precise alignment of the coupler to the multiplanar waveguide.

Initially, symmetric HGC samples were fabricated using both DCG and DPP, and their coupling efficiencies were determined at 633 nm and 514 nm. The coupling efficiency was found to be very low (~20% maximum) as expected. However, these samples did demonstrate coupling of two laser colors simultaneously into thin polymer waveguides. These experiments were conducted using DuPont Mylar polymer film 2.5 μm to 23 μm thick.

In order to increase coupling efficiency, slanted volume HGC samples were fabricated using the prism recording setup illustrated in Figures 3-15(b). We used DPP film on Mylar substrate to record HGCs for the same two laser colors. The test samples were recorded with a 514 nm laser beam at various exposure levels. The DPP was UV cured for ~1 minute, and then heated in a convention oven at 100°C for 2 hours. Because heating warped the plastics, we reduced the temperature to ~80°C and sandwiched the samples between two glass plates. This prevented the HGCs from warping. The experimental test results on the angular response of slanted HGC samples for red (633 nm) and green (514 nm) laser beams show high coupling efficiency and good angular tolerance (see Figures 3-16, 3-17, 3-18).

Below measurements taken at 632.8 nm

θ₁	It (mW)	Io (mW)	Ir (mW)	Id (mW)	n(Eff.) %
3.5	8.273	11.631	1.4172	1.9408	19.0
4.0	7.641	11.625	1.2978	2.6862	26.0
4.5	7.532	11.638	.9854	3.1706	29.6
5.0	7.169	11.632	.8957	3.567	33.2
5.5	7.291	11.641	.5328	3.8172	34.4
6.0	7.146	11.627	.3675	4.1185	36.6
6.5	6.563	11.646	.7428	4.3402	39.8
7.0	6.001	11.621	1.3325	4.2875	41.7
7.5	5.935	11.627	1.1804	4.5116	43.2
8.0	6.100	11.634	.5248	5.0092	45.1
8.5	6.285	11.629	.2496	5.0944	44.8
9.0	6.543	11.626	1.0909	3.9921	37.9
9.5	6.641	11.624	1.5857	3.3973	33.8
10.0	6.813	11.627	1.6321	3.1819	31.8
10.5	7.137	11.634	1.7819	2.7151	27.6
11.0	7.472	11.629	1.997	2.16	22.4

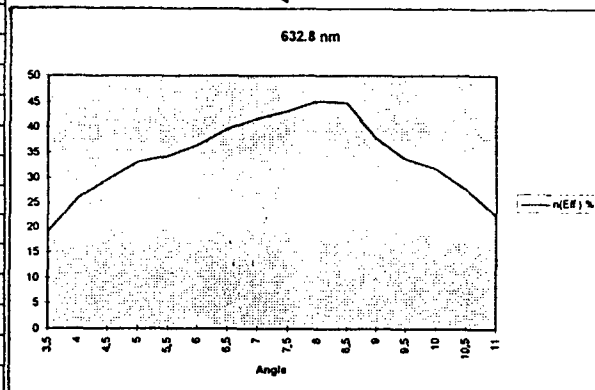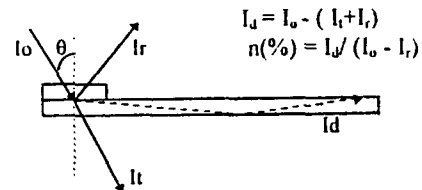$$I_d = I_o - (I_t + I_r)$$
$$n(\%) = I_d / (I_o - I_r)$$

632.8 nm

Figure 3-16
Slanted holographic grating coupler (DuPont photopolymer) angular response at 632.8 nm wavelength.

Below Measurements taken at 514.5 nm

| θ₁	It (mW)	Io (mW)	Ir (mW)	Id (mW)	n(Eff.) %
16.5	11.843	16.187	1.417	2.927	19.8
17.0	11.712	16.201	1.038	3.451	22.8
17.5	11.241	16.209	.9943	3.9737	26.1
18.0	10.711	16.214	.9839	4.5191	29.7
18.5	9.634	16.104	1.0761	5.3939	35.9
19.0	9.039	16.178	.9794	6.1596	40.5
19.5	7.534	16.238	1.9541	6.7499	47.3
20.0	7.509	16.143	.5398	8.0942	51.9
20.5	6.857	16.198	1.4939	7.8471	53.4
21.0	7.529	16.268	.5367	8.2023	52.1
21.5	8.022	16.254	.9004	7.3316	47.8
22.0	8.601	16.218	1.967	5.6603	39.7
22.5	10.778	16.243	.6607	4.8043	30.8
23.0	11.447	16.205	.5341	4.2239	26.9
23.5	11.699	16.253	.5812	3.9728	25.3
24.0	11.912	16.208	.6474	3.6486	23.4
24.5	12.314	16.187	.6538	3.2192	20.7

$$I_d = I_o - (I_t + I_r)$$
$$n(\%) = I_d / (I_o - I_r)$$
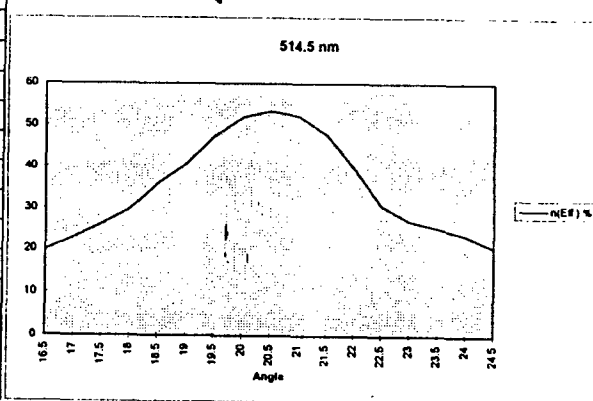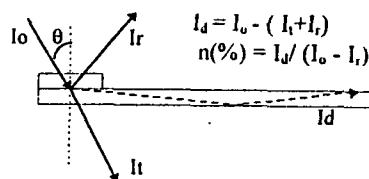
514.5 nm

Figure 3-17
Slanted holographic grating coupler (DuPont photopolymer) angular response
at 514.5 nm wavelength.

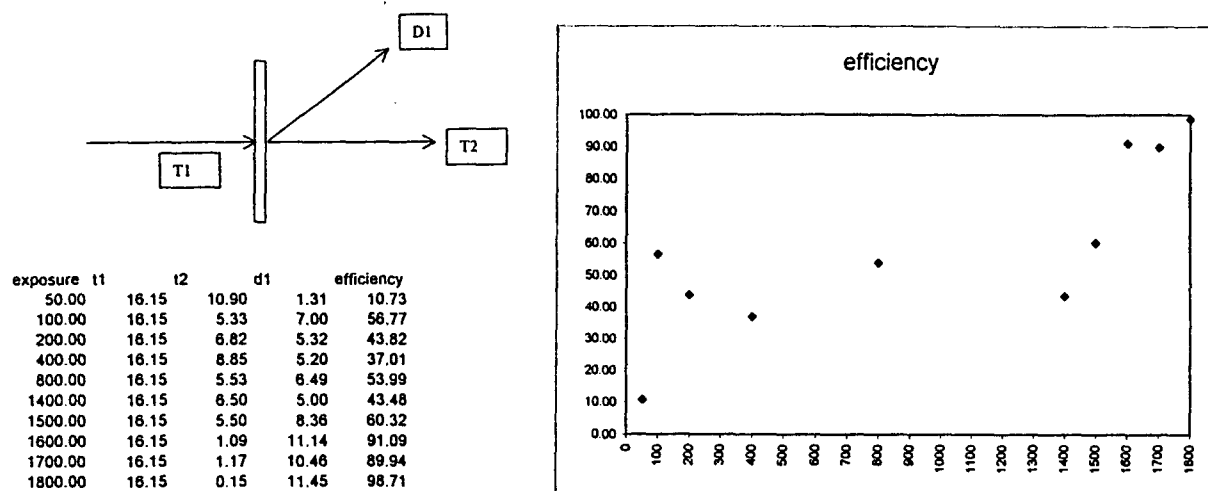| exposure	t1	t2	d1	efficiency
50.00	16.15	10.90	1.31	10.73
100.00	16.15	5.33	7.00	56.77
200.00	16.15	6.82	5.32	43.82
400.00	16.15	8.85	5.20	37.01
800.00	16.15	5.53	6.49	53.99
1400.00	16.15	6.50	5.00	43.48
1500.00	16.15	5.50	8.36	60.32
1600.00	16.15	1.09	11.14	91.09
1700.00	16.15	1.17	10.46	89.94
1800.00	16.15	0.15	11.45	98.71

Figure 3-18
Holographic grating coupler exposure characteristics.

3.2.3 Image Formation

The following approaches were considered for image formation in the HOWARD system:

1. Sequential point-by-point 2-D scanning
2. Parallel 1-D scanning of a 1-D line image
3. Parallel 2-D image projection.

Our design goal is to develop a compact, lightweight, rugged, plug-and-play display system that is easily portable. This requires that the image forming device be directly attached to the HOWARD substrate, and that it be attached through a standard cable to an image source such as a VCR or a computer. We analyzed the above three approaches (see Figure 3-19) in light of these packaging requirements, in terms of their brightness, resolution, color purity, light efficiency and power, and refresh rate.
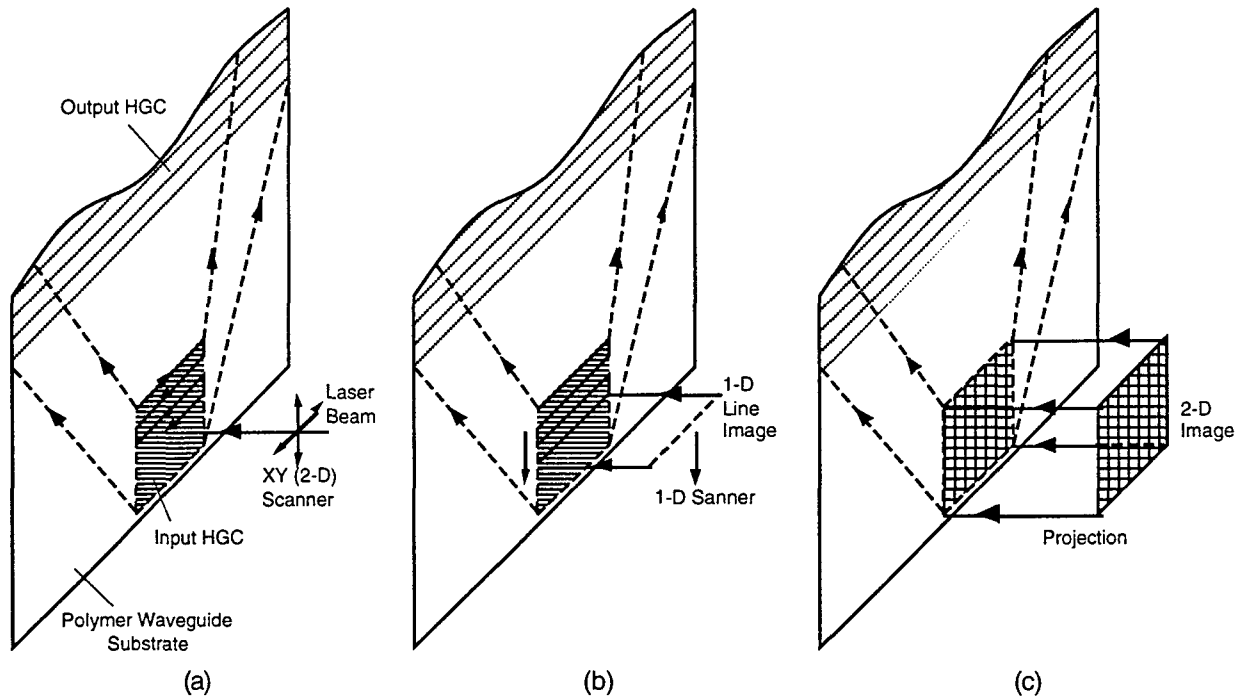
Figure 3-19
Three image forming approaches: (a) 2-D line scanning of a laser beam; (b) 1-D scanning of 1-D
line Image (1-D LD array, linear LCD); and (c) 2-D image projection using laser beam or white light
(LCD or DMD, miniature CMOS-SLM)

3.2.3.1   2-D Scanning

2-D scanning by mechanical mirrors and acousto-optic (AO) deflectors is a well developed, mature technology, and scanners are commercially available that can be applied to HOWARD image formation. For 2-D image scanning, several recent application have demonstrated high resolution laser scanned images with high brightness and color purity. For high resolution displays such as HDTV, horizontal scanning requires speeds >10 kHz and precision beam control. This calls for complex driving electronics and a bulky system. Additionally, the scanning optics can be complex and difficult to align. This approach offers high brightness, full color, high resolution, and light efficiency, but suffers from a potentially slow refresh rate, bulky hardware, and potential alignment problems.
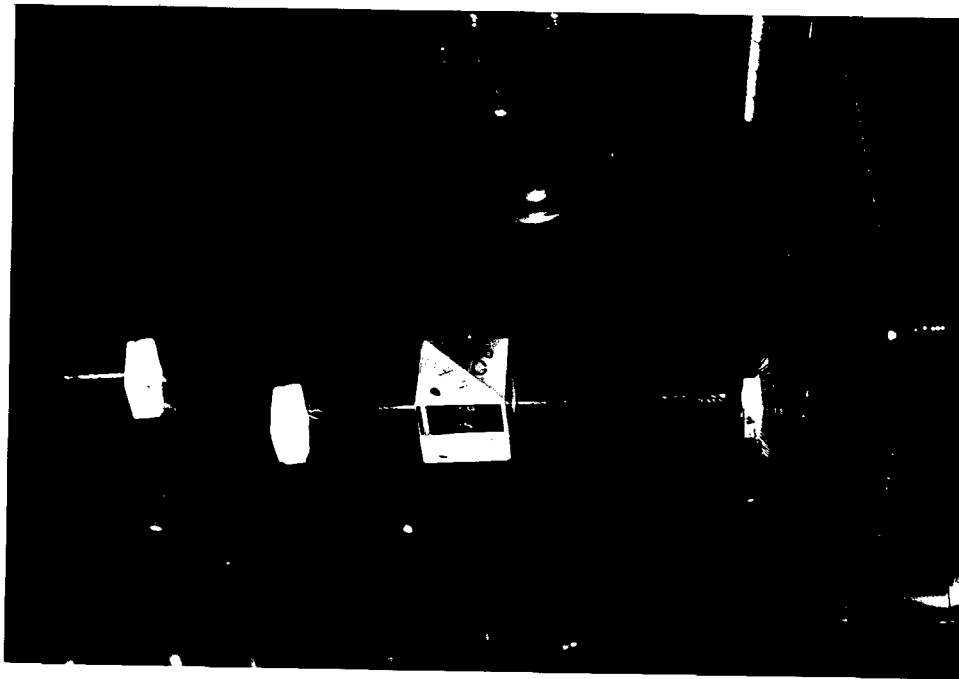
3.2.3.2   1-D Line Image Scanning

In this approach, a line image is first formed by an array of laser diodes or a 1-D LCD array, and then scanned in the vertical direction only, at a relative low speed such as the standard video display rate of 30 Hz. This approach avoids several problems associated with 2-D scanning. Since the horizontal image resolution is independent of the scanner, it can be very high (e.g., >2048). Also, because the individual pixels of the line image source can be modulated in parallel, the laser source need not support a high modulation speed. Devices available for this application include high resolution linear arrays of LDs, a ferroelectric liquid crystal spatial light modulator

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(FLC-SLM) from Display Tech, Boulder, CO, and a 1-D array of digital micromirrors (DMD) from Texas Instruments. The linear format permits simple driving electronics and high speed image refresh. One dimensional scanning also eliminates the synchronization requirement of 2-D scanners, and therefore improves input alignment.

For an RGB display, three line images, one for each color, can be modulated in parallel and combined into a composite full color line image by using a high efficiency color combining holographic (CCH) optical element. Figure 3-20 shows the CCH fabricated at POC for this project to demonstrate full color line-image formation. This holographic optical element (HOE) consists of a conjugate volume DCG holographic grating that combines the three colors into a single collinear line image beam. A compact line image forming unit was set up to demonstrate this approach with POC's high speed (10 kHz frame rate) CMOS-LCD device (see Figure 3-21). This experiment successfully demonstrated three important features of this image forming approach:

1. Line image generation in a miniature high speed LCD device
2. Combining of three (RGB) colors into single full-color composite line image
3. 1-D line image scanning to form 2-D images.

(a)
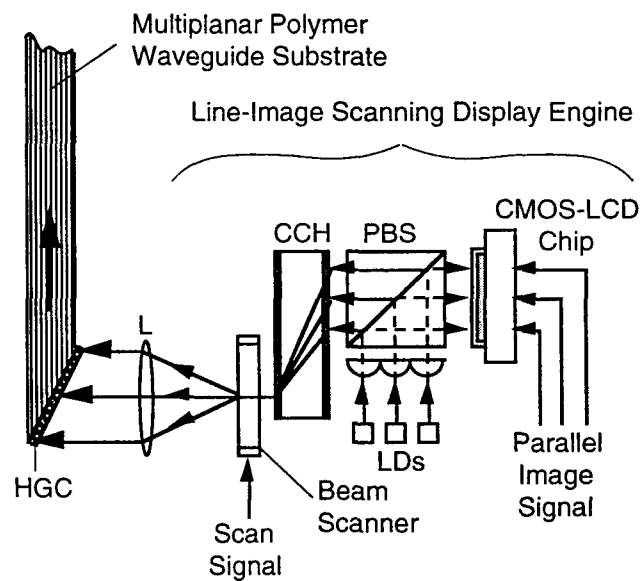
(b)

Figure 3-20
(a) A color combiner hologram (CCH) consisting of two high-efficiency conjugate volume
holographic gratings; and (b) Line-image scanning display engine using a high speed CMOS-LCD
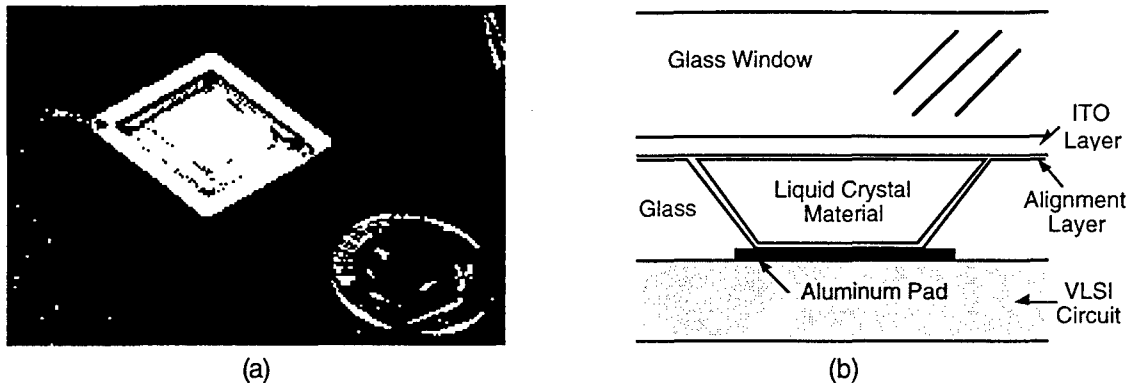chip.

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Figure 3-21
(a) POC'S 128 x 128 CMOS-LCD with 20 μm pixel size and 10 kHz frame rate [8].
(b) Construction of FLC/VLSI LCD. Aluminum pads on the IC surface define reflective pixels.
Underlying circuitry applies pad voltage to switch the FLC, confined to a micron-thick gap.

3.2.3.3   2-D Image Projection

A 2-D image can be projected directly onto the input coupler using a 2-D image forming device such as a high resolution LCD, TI's DMD, or a CMOS-SLM. A collimated laser beaming (combine three colors) or a collimated white light beam from a high intensity halogen lamp can be projected through these imaging devices onto the input HGC. Such a monolithic device can be very compact, without any moving parts. Since 2-D image forming devices can be attached directly to the input HGC, the pixel alignment problem is totally eliminated. It is also compatible with current projection display technologies based on LCDs, DMDs, and miniature CMOS-SLMs, so that no special image display formatting is necessary. However, for a compact system using LCDs, light throughput is very poor because of the use of polarizers, which reduce the brightness of the display. A DMD with laser illumination could be very light efficient. However, since the DMD is a reflective device that modulates light by scanning, such a device could be rather bulky.

A possible way to strengthen this approach is to couple a high power laser diode to the display substrate through a fiber optic light pipe, and to use a high efficiency polarizer (such as a polarizing beam splitter). Figure 3-22 illustrates this configuration, using high power miniature laser diodes such as, diode pumped Nd:YAG lasers for blue and green wavelengths and an optical fiber light delivery system connected to the HOWARD through a standard fiber coupler.
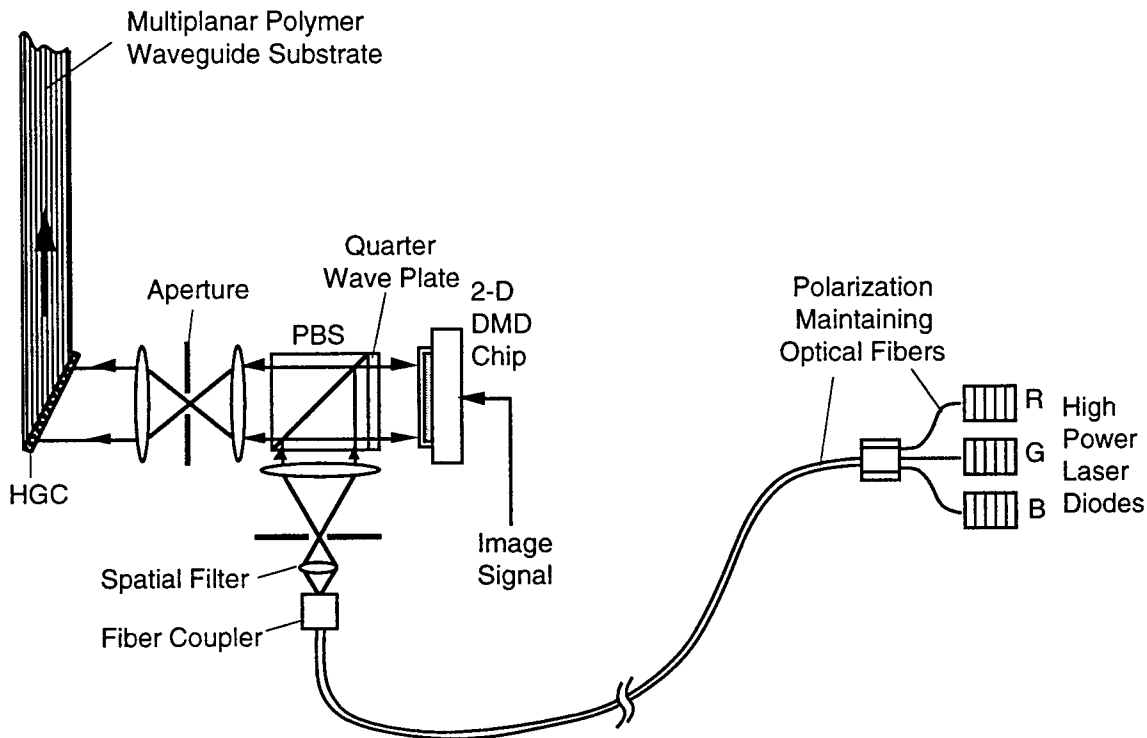
Figure 3-22
2-D Image projection system for HOWARD using a TI DMD and fiber optic laser diode light delivery.

3.3 Characterization and Selection of Polymer Materials (Task 3)

POC investigated three types of holographic photopolymer materials: bleached silver halide, DCG, and DPP. The goal of this task was to characterize the index modulation and exposure characteristics of the materials in order to achieve the nonlinear modulation necessary for the waveguide graded index profile.

3.3.1 Refractive Index Modulation by Laser Exposure

Using standard silver halide material, we analyzed its characteristics for a high γ film (γ is a measure of the slope of optical density vs. the log of the exposure energy curve). Using current bleaching processes, we found that the bleached silver halide film can barely take on the required Δn profile. This led us to look at DCG and DPP.

Not depending upon any previously claimed Δn for these two materials, we proceeded to independently characterize their Δn vs. exposure properties. We prepared samples of DCG and DPP films on glass substrates, and recorded reflection holograms using a single beam method at multiple exposure levels. This method allowed us to eliminate other factors such as vibration and thermal drift that could affect the results. The holograms were developed under the same conditions, and their diffraction efficiencies were measured. Using Kogelnik's volume hologram model, the index modulation Δn can be calculated from the formula

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$$\text{Diffraction efficiency } \eta = \tanh^{-1}\left(\frac{\pi \Delta nT}{\lambda \cos\theta}\right) , \qquad (3\text{-}5)$$

where T = thickness of the hologram, λ = recording wavelength, and θ = Bragg angle of reflection.

Figure 3-23 shows Δn vs. exposure (or fluence) for several samples. Several series of experiments were conducted using DCG films differing in hardness or age (one to seven days) before exposure. The results show that susceptibility to index modulation decreases as the film ages. In the case of DPP, a 10 μm thick HRF-200 film was used. A series of experiments was conducted in which heating time was varied. These films were exposed to a collimated 514 nm argon ion laser beam. It can be seen that the maximum index modulation achievable with DCG is about 0.06, and with DPP about 0.02.

The holograms were also analyzed to determine the Δn profile. By observing their spectral characteristics, the reflection peaks at the fundamental frequency, and their harmonic content, the harmonics of Δn, and thus their profiles, could be determined.
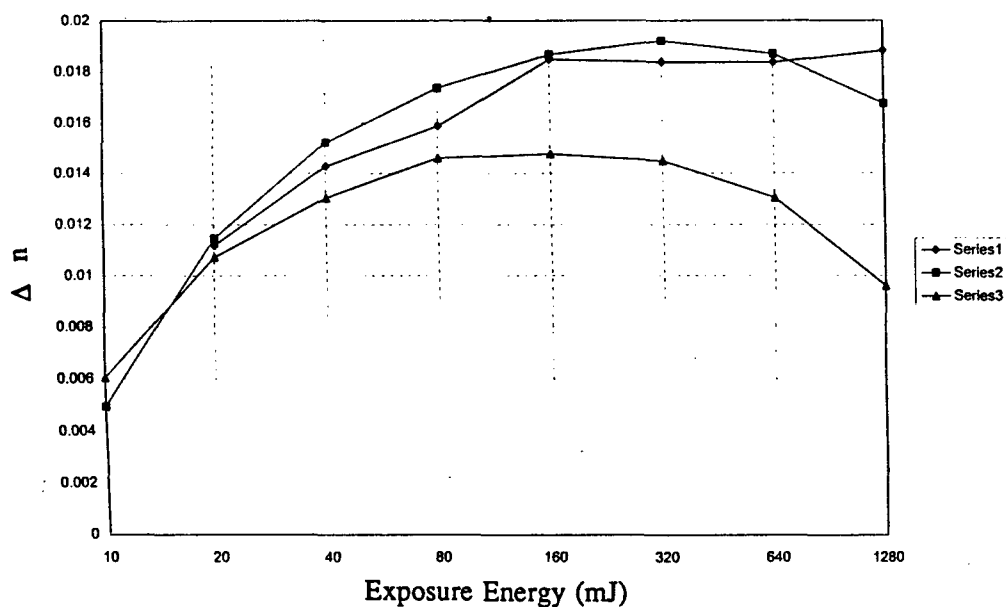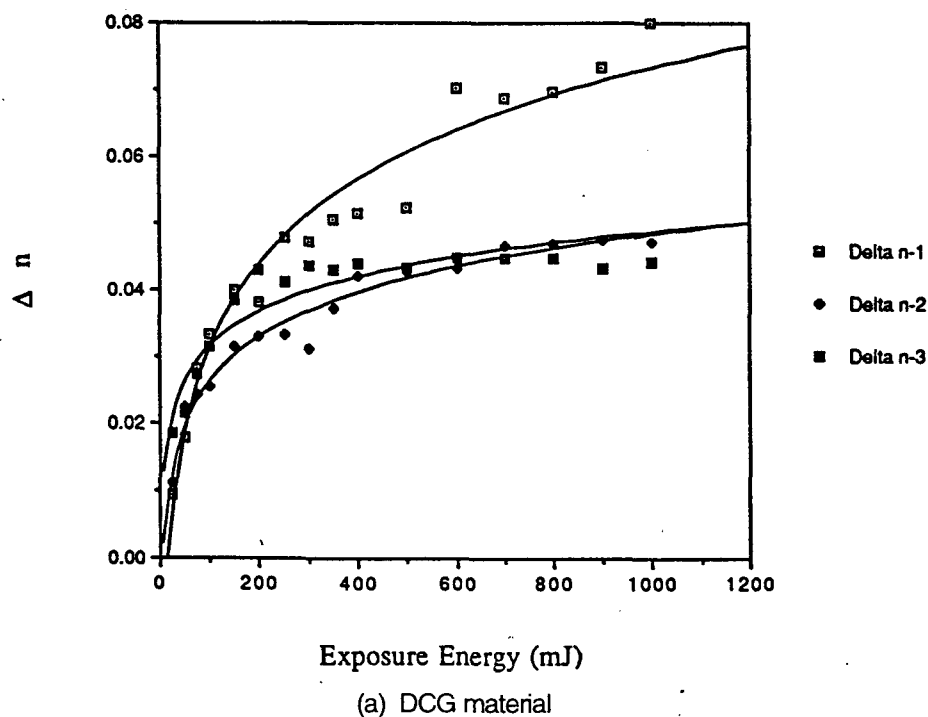
(a) DCG material

Figure 3-23
Experimental data on index modulation Δn vs. exposure energy (or fluence) for DCG and DPP materials.

3.3.2 Absorption Characteristics

The light absorption characteristics of DCG and DPP films were studied to determine the light propagation efficiency of the holographically formed multi-planar waveguides. Samples of DCG

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and DPP films ~ 10 μm thick were prepared and thoroughly processed to eliminate the sensitizer dye from the material.

For DCG, we employed our standard hologram development procedure, consisting of a fixing process using Kodak fixer, a water wash, followed by a series of isopropyl alcohol and water rinses. The film was dried and scanned with a spectrophotometer.

For DPP film, we employed the standard development procedure of UV exposure for 1 minute, followed by heating at 100°C for 2 hours. Additional UV exposure bleached out the remaining sensitizer from the film. The results, shown in Figure 3-24, show that the material absorption is very low for wavelengths above 600 nm, while showing substantial absorption (a few percent) in the blue and green regions especially in DPP material. Therefore, for a large display format the absorption in the holographically formed waveguides need to be further reduced. For DPP material the intrinsic material absorption must be reduced by optimization of material composition while for DCG, due to its wet processibility, which include water washing, the material absorption can be further reduced by carefully optimizing its processing.
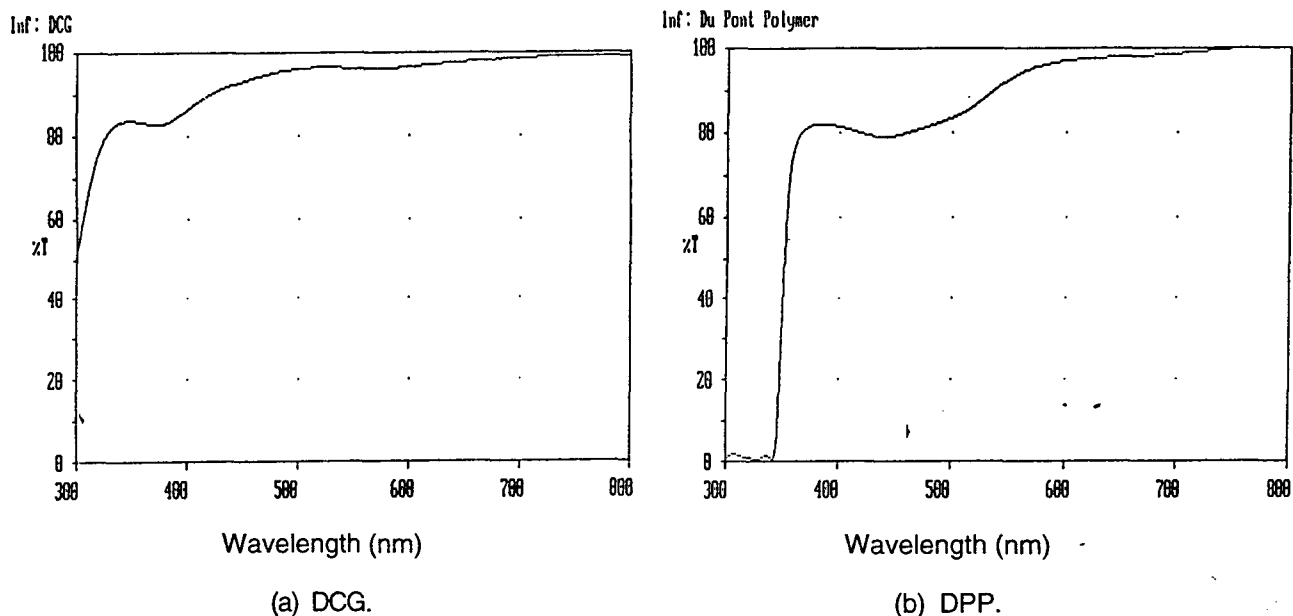

(a) DCG.   (b) DPP.

Figure 3-24
Absorption characteristics of DCG and DPP
photopolymer materials (Fresnel reflection correction 4%).

3.4   Demonstration of the Proposed Fabrication Method (Task 4)

3.4.1   Holographic Generation of Multiplanar Waveguide Structures

The multiplanar waveguide structure was generated by means of "Lippmann hologram recording," in which a plane wave laser beam is reflected from a suitable surface such as a mirror, and an

optical field of standing waves is generated in the region where the direct and reflected beams overlap. This standing wave pattern can be recorded in a volume holographic material as phase or refractive index modulation (Δn) in the bulk of the material. If the material exposure characteristic is linear, the recorded Δn pattern will be in a sinusoidal form with period Λ given by the Bragg condition [9]:

$$2\Lambda \cos \theta_0 = \lambda_0 , \qquad (3-6)$$

where λ is the wavelength and θ is the angle of incidence of the laser beam (Figure 3-26).

However, for present purposes we require a high Δn value and nonlinearity in recording, so that the Bragg planes essentially approximate multilayer thin graded-index planar waveguides with period Λ (Figure 3-25). In order to achieve this condition, we need to create a standing wave with very high contrast (i.e., zero bias) and high intensity, taking full advantage of the nonlinearity of the material. The result is a "clipped" sinusoidal Δn pattern with high modulation depth approaching the maximum Δn achievable with the material [10].
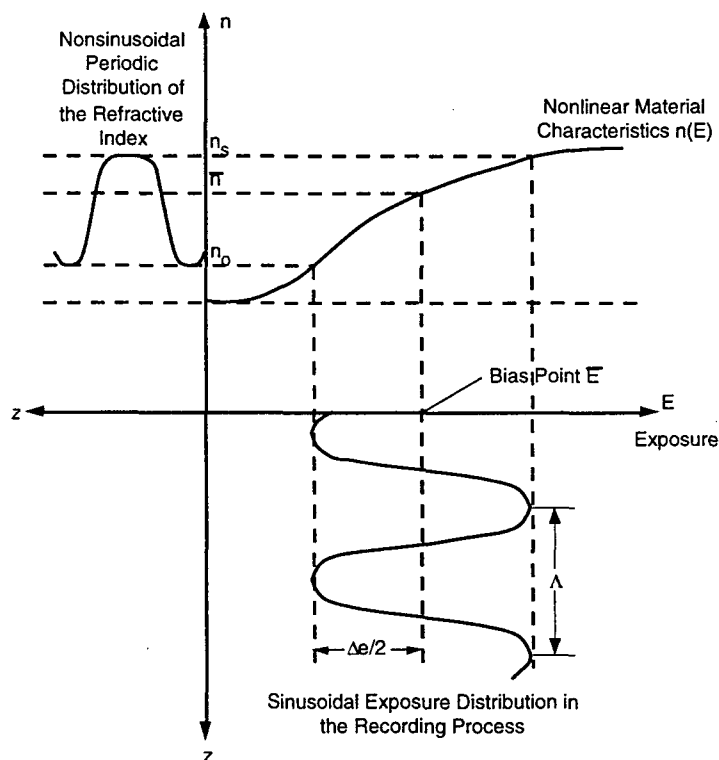

Figure 3-25
Multiplanar graded-index waveguide generation using non-linear Lippmann hologram recording technique.

The recording geometry to achieve this condition is shown in Figure 3-26, where the incidence angle θ must be greater than the critical angle θ_c of the laser beam in the medium ($\leq 45°$). This

geometry automatically produces high-contrast interference patterns, since the incident and reflected beam are almost equal in intensity. With this geometry, a large polymer substrate can be fabricated by a simple process requiring no interferometric stability or fine alignment.
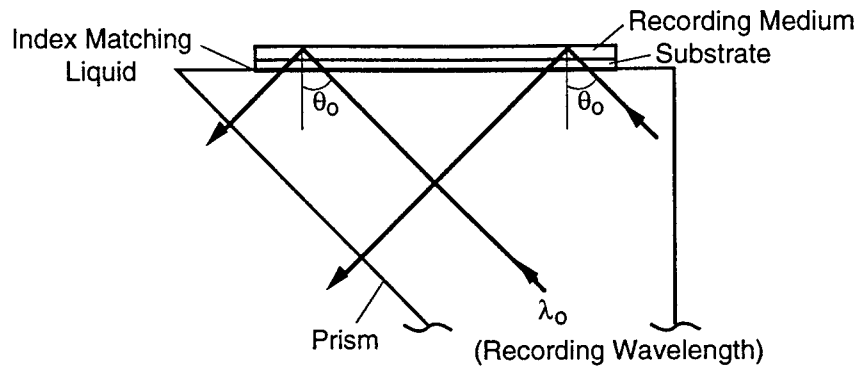

Figure 3-26
Multiplanar graded-index waveguide fabrication using the total internal reflection geometry of Lippmann hologram recording.

3.4.2   Demonstration of Graded Index Multiplanar Formation

Samples of DCG wedge films were fabricated using the wedge coating technique described in Section 3.2.1. Sensitizer concentration and film hardness were adjusted to maximize Δn consistent with maintaining the uniformity of the grating layers and the low absorption of the processed holograms. Figure 3-27 illustrates the recording setup using a large (8 in. $\times$ 10 in.) prism. The prism is required to achieve the high recording angle θ necessary to create a large Λ. The preliminary experiments were conducted using $\theta = 60°$ and $\theta = 80°$. The results show that a nonsinusoidal (i.e., squarer) Δn profile was indeed produced, which represents the first demonstration of fabricating a graded index waveguide multilayer structure in a single DCG film.

Figure 3-28 (a) is a photomicrograph of the cross-section of a DCG multilayer holographic Bragg plane structure. Because of the high angle of incidence of the recording beam, the absorption of the material (which is about 5% - 10% at 514 nm wavelength) gradually reduces the laser beam power as it penetrates through the material. This effect produces nonuniform index modulation across the thickness of the film. This nonuniformity can, however, be reduced by reducing the sensitizer concentration and greatly increasing the laser exposure. The graded index profile of these Bragg planes is evident from the fact that these structures, when analyzed as Bragg reflectors, exhibit multiple resonance peaks (or valleys) in their spectral response. Figure 3-29 shows the spectral response of DCG samples recorded at a high ($\approx 78°$) incidence angles. From the spectral harmonic content observed in the figure, we can estimate the profile of Δn to approximate a step-like graded index form.
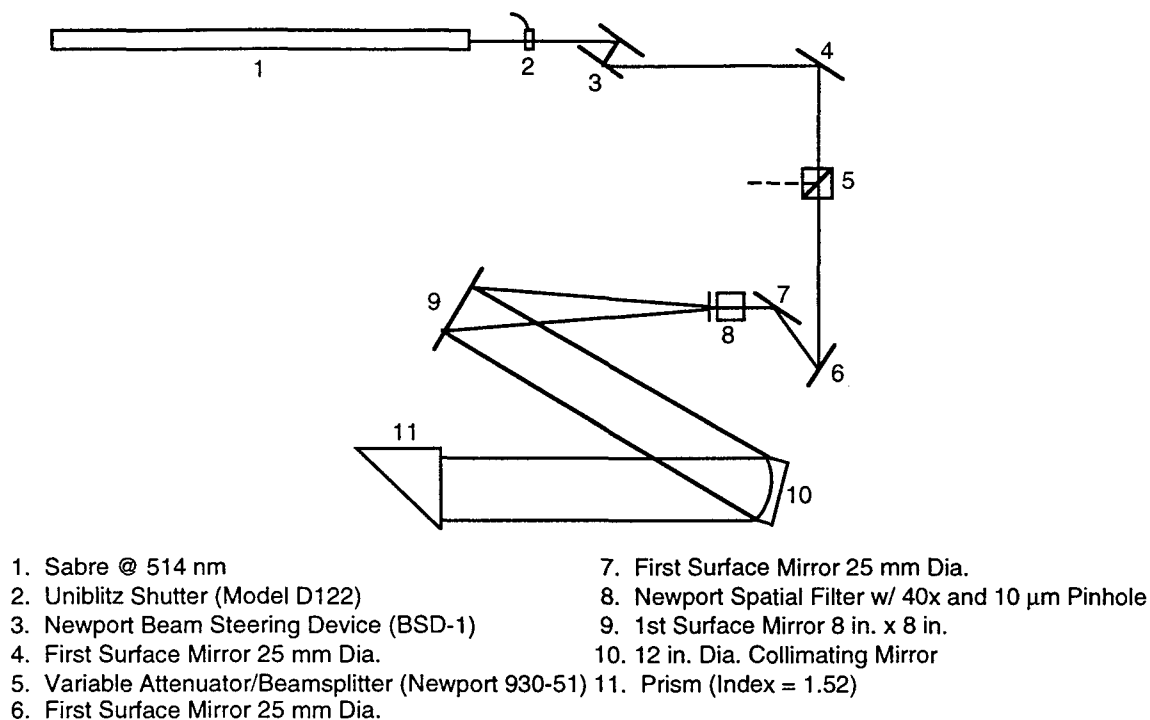
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1. Sabre @ 514 nm
2. Uniblitz Shutter (Model D122)
3. Newport Beam Steering Device (BSD-1)
4. First Surface Mirror 25 mm Dia.
5. Variable Attenuator/Beamsplitter (Newport 930-51)
6. First Surface Mirror 25 mm Dia.

7. First Surface Mirror 25 mm Dia.
8. Newport Spatial Filter w/ 40x and 10 μm Pinhole
9. 1st Surface Mirror 8 in. x 8 in.
10. 12 in. Dia. Collimating Mirror
11. Prism (Index = 1.52)

Figure 3-27
Exposure setup for fabrication of multilayer Lippmann holographic waveguide structure with graded index profile.

Vertical Grating Non-Uniformity

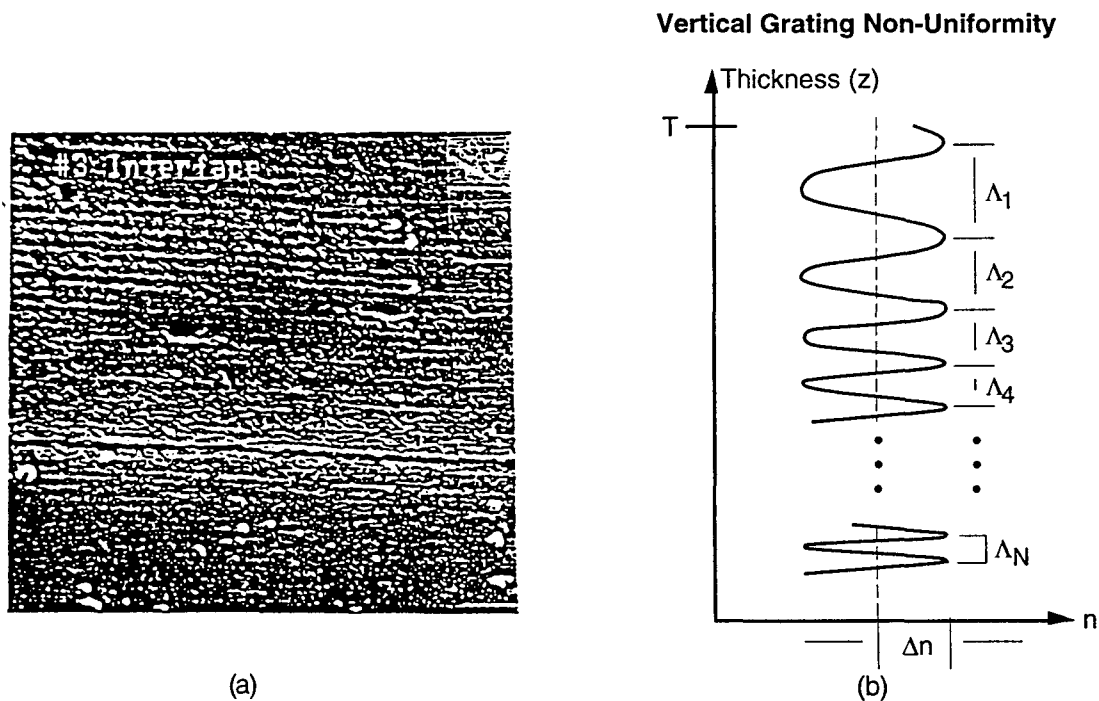(a)   (b)

Figure 3-28
(a) Cross-section of a DCG holographic Bragg plane multilayer structure; and (b) Nonuniformity of Bragg planes due to increased attenuation of recording laser power at high incidence angles.
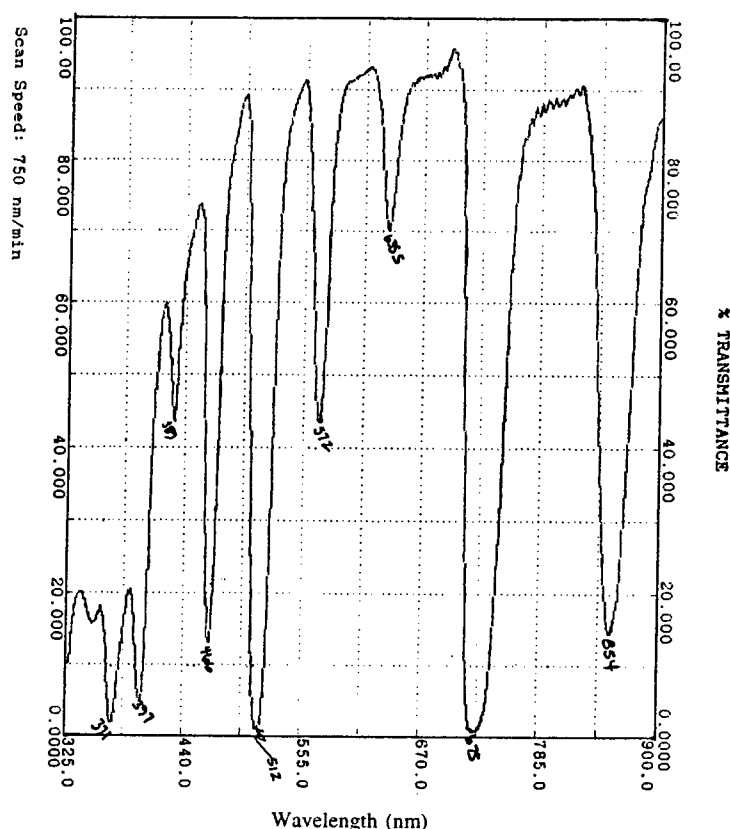
36

Figure 3-29
Spectral response of holographic Bragg plane multilayer structure, showing formation of step-like graded index multiplanar profile.

The thickness T of these graded index planes can be determined from the Bragg condition given in Eq. (3-6).

$$T = \frac{\Lambda}{2} = \frac{\lambda_o}{4n\cos\theta_o} \ . \tag{3-7}$$

In the present case, $\lambda_o = 514.5$ nm, $n = 1.5$ (average index for DCG), and $\theta_o = 78°$, which gives $T = 412.4$ nm. On the other hand, for $T = 1$ μm, we require $\theta_o = 85°$, which is difficult to obtain with current prism fabrication setup because small differences in the refractive indexes of prism ($n = 1.52$), index matching fluid ($n = 1.495$), and substrate did not allow efficient coupling of light into the film. From Eq. (3-7), it can be seen that, in order to increase T without requiring large recording angle (θ_o), the recording wavelength λ_o can be increased. For this improvement, a Krypton ion laser with $\lambda_o = 647$ nm, could be used with red sensitive DCG or DPP material. This can provide about 25% increase in the thickness T ($T \simeq 518$ nm). A

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potentially very promising approach is to use two-wavelength multiplexed recording technique which make use of the nonlinear exposure characteristics of these holographic materials. For example, by using two coherent laser wavelengths, i.e., the second and third harmonics; 532 nm and 355 nm of Nd:YAG laser, an effective wavelength of $\lambda_{eff} = \lambda_1\lambda_2/(\lambda_1-\lambda_2) \simeq 1064$ nm can be generated to record multiplanar holographic structure with T $\simeq$ 853 nm. Alternatively for two Argon ion laser wavelengths ($\lambda_1 = 514$ nm, $\lambda_2 = 488$ nm), we have $\lambda_{eff} = 9647$ nm, and we can get T up to $\simeq$7.7 μm. This method will be investigated in the future development of this technology.

3.4.3   Multiplanar Polymer Waveguide Fabrication

An alternative approach to holographic multiplanar fabrication is the multilayer lamination of two types of polymer thin films. We investigated several available polymer thin film materials, including UV curable monomers such as UV epoxy. We analyzed their optical quality in terms of their waveguiding characteristics. We used standard prism coupling and He:Ne and argon lasers. Two batches of commercial polymer films from DuPont were analyzed. In particular, DuPont Mylar films of grade D ranging in thickness from 2-5 μm to 23 μm showed excellent quality for waveguide fabrication. Since the refractive index of Mylar films is n = 1.64, the cladding or buffer layer should be a lower-index plastic material. We found that the commercial UV epoxy from Norland is optically very clear and UV curable with n = 1.56. This can be used as the cladding layer.

Using Norland 75 UV epoxy, we laminated 30 layers of 2-5 μm thick DuPont Mylar film. Because Mylar absorbs UV, making it difficult to cure all 30 layers in a single step, we tried laminating one film at a time. This process was rather time consuming and messy, since excess epoxy had to be cleaned off before UV curing. In addition, it was difficult to manually align the film layers to form stepped wedge input and output areas. However, we finally succeeded in fabricating a few samples of small area (2 in. × 6 in.) layered polymer waveguide substrates (see Figure 3-30). For production of large area polymer substrates with large numbers of layers, this fabrication technique could be automated, possibly using web coating and lamination.

During this Phase I period, we learned that there is a third approach for fabrication of multiplanar waveguide structure. This approach was recently developed by a group of researchers from Battelle, Pacific Northwest Laboratory, Washington. This method is a low cost multilayer polymer thin film fabrication using vacuum deposition technique [11]. They have demonstrated fabrication of polymer/polymer and polymer/metal multilayer structure with layer thickness of a few micron each. This method should be further explored to determine its suitability for the multiplanar polymer waveguide development.

3.5   HOWARD Concept Demonstration (Task 5)

The HOWARD concept demonstration presented a proof-of-principle of:

- Efficient coupling of light into a multiplanar polymer waveguide

- • Propagation of light through individual waveguides
- • Output coupling of light as an image pixel.

Several experiments were conducted involving 633 nm He:Ne and 514.5 nm argon laser beams, a precision rotation and translation stage assembly, volume holographic grating couplers (both DCG and DPP), microprism array couplers, holographic (elliptical) diffusers, and Mylar polymer waveguides 2.5 μm to 25 μm thick. The HOWARD concept demonstrations successfully:

- • Demonstrated integration of I/O couplers to polymer waveguides (see Figure 3-30)
  - Volume HOE couplers (DCG and DPP)
  - Surface embossed prismatic couplers

- • Demonstrated laser beam coupling, propagation and display (see Figure 3-31)
  - Single layer with multiple output pixel positions
  - Multiple layers with multiple (staggered) output pixel positions
  - Single layer with multiple (parallel) output pixels

- • Demonstrated parallel two-color laser beam coupling and propagation (see Figure 3-32)

- • Demonstrated 2-D image projection, propagation, and display in a flexible multilayer polymer substrate (see Figure 3-33).
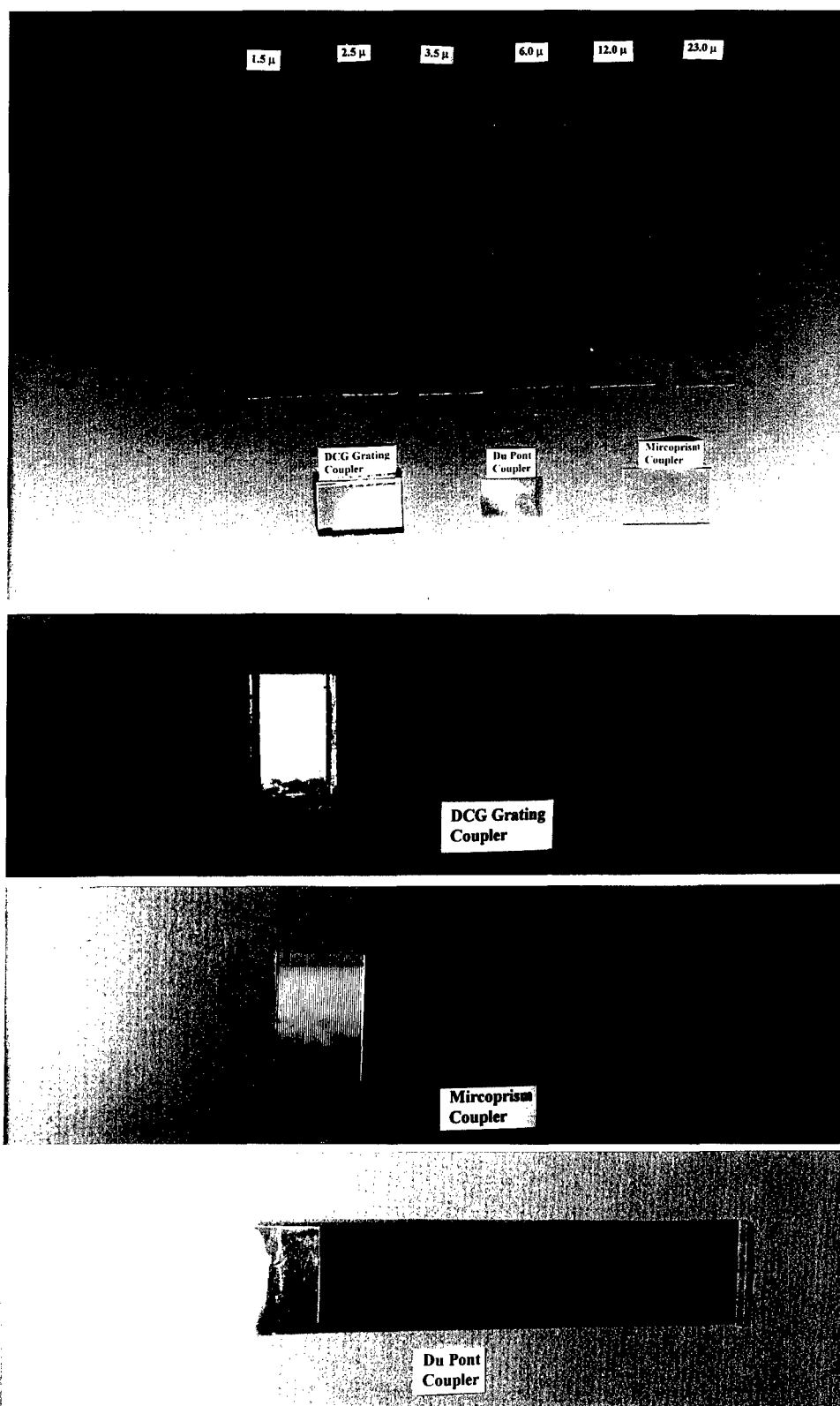
Figure 3-30
Multilayer polymer substrates integrated with volume holograph grating couplers using DCG and
DPP material and surface embossed (replicated) prismatic couplers. Samples of Mylar polymer
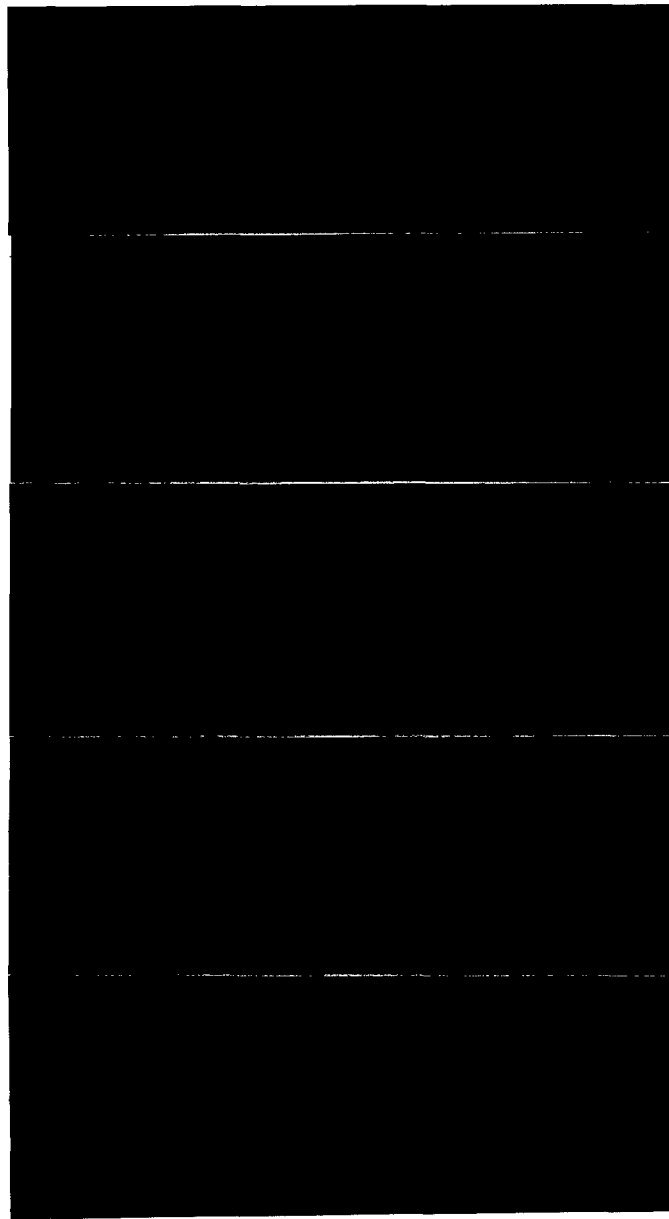microsheets are also shown.

Figure 3-31
Demonstration of HeNe laser beam coupling, propagation, and pixel display through holographic diffuser output couplers in multiplanar Mylar waveguide layer with multiple output couplers.

Figure 3-32
Demonstration of simultaneous two-color (He:Ne laser and argon laser) coupling and propagation in a single flexible (2.5 μm) polymer waveguide film.
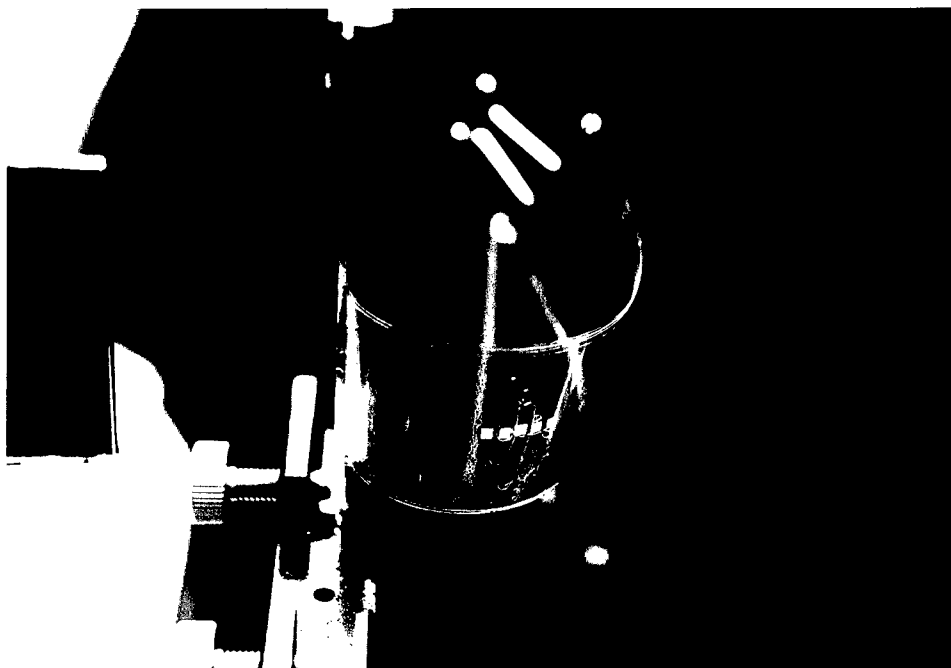

Figure 3-33
Demonstration of parallel 2-D image projection of mask pattern (simulating LCD) using a holographic grating coupler, propagation through a flexible 30-layer polymer waveguide, and display of image.

4.0 POTENTIAL APPLICATIONS

This Phase I project has demonstrated the feasibility of the HOWARD technology, which is very promising for use in a large area display for both military and commercial applications

Because the display can be rolled into a small package when not in use, it is well suited for military applications. Light weight, portability, and ease of deployment are intrinsic. A large-area version can be used in a field station, command post, or mobile station, while smaller displays can be carried by individual soldiers in the field. Flexible large area displays will be very useful for military virtual environment simulation systems, and miniaturized ones in head-mounted or helmet-mounted displays.

Commercial applications of the flexible display are numerous. It can literally replace all large-area projection TV and video projection systems both in business and in home entertainment. Since it can be hung on the wall, the display will be extremely attractive for advertising, trade shows, and conferences. Again, the display can be used as wraparound-total-immersive virtual environment system in computer game displays.

5.0 CONCLUSION

This report has presented the technical findings and results of the Phase I study feasibility of POC's holographic waveguide array rollable display (HOWARD). The investigation included: (1) Preliminary computer modeling and analysis of multiplanar polymer waveguide structure, which showed analytically the feasibility of coupling and propagating visible (RGB) laser beams through a very thin (1 - 2 μm) waveguide structure; (2) Experimental investigation of holographic photopolymer material and polymer waveguide thin films for multiplanar waveguide polymer substrates and input/output holographic grating couplers; and (3) Demonstration of the feasibility of the HOWARD concept by fabricating a small area multiplanar waveguide structure. The initial findings are very encouraging, and the Phase I study has identified the technical issues that must be specifically addressed to further develop this technology. All the Phase I technical objectives were met.

6.0 PHASE II RECOMMENDATIONS

In order to fully develop this feasible but high-risk/high-pay-off technology into a commercially viable product, POC plans to develop a fully functional HOWARD prototype system in Phase II. In order to accomplish this goal, POC recommends the following steps:

- Optimize and refine the HOWARD architecture using a fully developed multiplanar polymer waveguide model as well as 3-D HOE coupler design and ray tracing software to simulate and analyze its performance

- Extend and optimize the multiplanar polymer waveguide fabrication process using both holography and multilayer lamination techniques, including extrusion and evaporative coating

- Develop and integrate critical system components, and optimize their fabrication.

- Produce a practical, high resolution, rollable or flexible flat panel polymer display prototype

- Demonstrate and evaluate the full potential of the HOWARD prototype as a high resolution, versatile display technology

- Identity near term applications of the HOWARD system for military and commercial markets, and collaborate with commercial partners to commercialize the HOWARD product.

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