Steep Reference Angle Holography: Analysis and Applications

by

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Abstract

Contemporary display holography uses two standard recording geometries, reflection and transmission. In both of these geometries, refraction at the air-emulsion interface places an upper limit on the steepness of the reference beam angle within the hologram. This thesis discusses the new "glass block" recording geometry, a recording geometry that uses a glass block to allow steep reference beam angles and thus create holograms with whose diffraction properties differ from those of standard holograms. Several applications of steep reference angle holograms are described. These include steep reference angle dispersion compensation and a compact, self-contained, edge-lit, white-light hologram display.
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1by the Nigerian author Chinua Achebe: A Man of the People, The Awakening, and Things Fall Apart; let me know if you'd like to borrow them.
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Chapter 1: Introduction

1.1 Limits of Standard Recording Geometries

Contemporary display holography uses two standard recording geometries, reflection and transmission. In both of these geometries, the steepness of the reference beam angle inside the hologram is limited by refraction at the emulsion-air interface. An angle of incidence of 45° in air becomes 25.7° within the emulsion, and the largest possible angle in air, 90°, corresponds to only 37.8° within the emulsion. Refraction defines a range of reference beam angles (between 37.8° and 217.8°) that is inaccessible through standard recording geometries. This thesis discusses the "glass block" recording geometry, a new geometry that partially opens up the previously inaccessible zone, allowing steeper reference angles and a wider range of diffraction properties.

1.2 The Glass Block Recording Geometry

The glass block recording geometry was introduced by Juris Upatnieks at the January 1988 SPIE conference [UPAT88]. Upatnieks' method involves index-matching the holographic plate to a glass block, and then sending the reference beam onto the hologram through the edge of the glass block. The reference beam will reach the plate at a steep angle; in this study, angles on the order of 66° (within the emulsion) were routinely obtained.

1.3 Applications

A steep angle hologram can be reconstructed through its edge. Two applications of the edge-lit illumination are explored in this thesis: a steep-angle dispersion compensation system, and a self-contained, compact, edge-lit, white-light hologram display.

1.4 Scope of this Thesis

Chapter 2 provides an overview of the differences between reflection and transmission holograms, and develops the concept of the inaccessible zone. Chapter 3 offers the fruit of a literature search, and situates edge-lit holography in the context of other evolutions in holography. Chapter 4 is a practical guide to making edge-lit holograms. The remainder of the thesis describes the implementation of two

---

1 In the course of this research, the glass block recording geometry was used to produce a few simple edge-lit holographic optical elements (HOEs). Because of the straightforward nature of the HOEs (a linear diffraction grating and a Fresnel lens), these experiments will not be discussed in this paper. Suffice it to say that the glass block recording geometry offers the potential for a new class of HOEs: edge-lit HOEs.
applications of the edge-lit hologram. Chapter 5 proposes a steep reference angle viewing device as a solution to the problem of dispersion in white light illumination of laser transmission holograms. Chapter 6 introduces the edge-lit display hologram. Chapter 7 describes a method for recording an edge-lit white-light transmission hologram and provides a guide for constructing a display unit for the hologram. The final chapter offers reflections on the research conducted and on possible future directions of research in edge-lit holography.
Chapter 2: Reflection vs.
transmission holograms

2.1 IN PRACTICE: TWO DISTINCT TYPES OF HOLOGRAM

Standard display holograms are made according to one of two fundamental recording geometries: transmission or reflection. Each of these recording geometries leads the laser to carve a different type of interference fringe pattern in the emulsion. The fringe patterns determine the optical properties of the hologram, in particular the hologram's sensitivity to the illumination angle and wavelength at which it will reconstruct. The recording geometry also determines the viewing specifications of the hologram. This section briefly catalogs principal differences between reflection and transmission holograms.

2.1.1 Different set-ups

Reflection and transmission hologram set-ups differ in the direction of the reference beam relative to the object beam (see Fig. 3.1a). In a reflection set-up, the reference and object beams travel towards the plate from opposite sides of the film plane. If instead the reference beam comes from the same side of the plate as the object beam, a transmission hologram can be recorded. In either case, the reference beam is usually directed at the plate from an angle of 30° to 60° (in air) from the perpendicular to the plate. These angles are convenient for later display of the hologram.

In both reflection and transmission display hologram set-ups, the object is usually placed on or near the perpendicular to the center of the plate. If the object is placed too far off the perpendicular axis, the view zone goes off axis as well. This leads to the awkward constraint of having to peer sideways into the hologram in order to see the image. If the object is on axis, the view zone is comfortably centered on the plate.

2.1.2 Different interference fringe structure

A standing interference fringe pattern forms along the bisector of the reference and object beams (see [HARI84], p. 44). The emulsion layer records the fringes that it intersects. Reflection and transmission set-ups lend different fringe structures to the emulsion. As shown in Figure 2.1b, a reflection hologram's fringes run nearly parallel to the film plane; in the transmission case, the fringes run approximately perpendicular to the film plane.
2.1.3 Different optical properties

The inclination of the fringes relative to the film plane determines several of a hologram's optical properties. In particular, wavelength selectivity depends on fringe orientation (see sections 2.2 and 2.3). Holograms whose fringes run perpendicular to the emulsion (transmission holograms) are not usually very wavelength selective. When a transmission hologram is illuminated with white light, each point in the object reconstructs a full spectrum. The image of the object becomes a collection of small overlapping spectral smears in which the object is no
longer recognizable. Though a first-generation transmission hologram is not immediately white-light viewable, a two-step a white-light viewable "transfer" transmission hologram can be made from an appropriate "master" transmission hologram. Chapters 6 and 7 deal with issues concerning white-light viewable transmission holograms.

Holograms with fringes parallel to the emulsion (reflection holograms) are much more wavelength selective: they will only reconstruct within a relatively small band of wavelengths. The width of this band depends on the fringe angle. The band is usually centered at the recording wavelength\(^1\). Because they only reconstruct over a narrow band of wavelengths, reflection holograms suffer much less from spectral smearing, so that an image several centimeters deep can be viewed in white light.

2.1.4 Different viewing geometry

A hologram's recording geometry governs its viewing specifications. A reflection hologram creates an image by diffracting light as it reflects off the emulsion; the viewer and the light source must be on the same side of the hologram. A transmission hologram bends light as it travels through the emulsion towards the viewer. Its illumination source should be placed behind the hologram, so that the hologram hangs between the viewer and the light source.

A reflection hologram can be simply hung on a wall for easy display in a home or gallery, provided that there are facilities (such as track lighting or -more awkward- a tripod) for hanging a point source illumination. Transmission holograms are more difficult to display: as they must be backlit, they cannot be hung on a wall. They must instead be suspended or supported away from the wall, between the viewer and the light source (see Fig 2.1c). Display issues are further discussed in Chapter 6.

2.2 UNDERSTANDING A TRANSMISSION HOLOGRAM: THE DIFFRACTION MODEL

This section provides a microscopic-level analysis of a transmission hologram's fringe structure and of the ways in which this structure determines the hologram's behavior.

2.2.1 An example of transmission hologram fringe formation

Let's model the fringes of a typical transmission display hologram. Our object is a single point source, placed along the central normal to the plate. The reference

\(^1\)If the hologram neither shrinks nor swells between exposure and viewing, the image will reconstruct in the color of the laser light in which it was recorded. The color of a reconstructed reflection hologram depends on the amount of emulsion shrinkage between the exposed and the processed hologram. Some developers and bleaches shrink the film, so that a hologram recorded in 633nm red would appear greenish. Holographers often swell the emulsion before or after exposure in order to control the color of the image.
beam is directed towards the plate at a $225^\circ$ angle$^1$ (see transmission recording geometry in Fig. 2.1a). The hologram's fringes will lie parallel to the bisector of the angle formed by the two beams.

### 2.2.2 Fringe inclination

As we will see later, it is essential that our model take into account the change in beam angle due to refraction at the air-emulsion boundary. Snell's law states that a light wave travelling through two media of different refractive indices, $n_1$ and $n_2$, is refracted (see Fig. 2.2) at the boundary of the two media according to the equation:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2. \quad (2.1)$$

Taking the refractive index of air as 1, and the refractive index of the emulsion of Agfa-Gevaert 8E75 plates as 1.63 [BENT88], the angles of the reference and object beam within the emulsion are calculated as follows.

$$\theta_{\text{obj-air}} = 180^\circ,$$

$$\theta_{\text{obj-emulsion}} = \sin^{-1}\left(\frac{n_{\text{air}} \sin \theta_{\text{ref-air}}}{n_{\text{emulsion}}}\right) = 180^\circ \quad (\text{no change in the object beam})$$

$$\theta_{\text{ref-air}} = 225^\circ,$$

$$\theta_{\text{ref-emulsion}} = \sin^{-1}\left(\frac{n_{\text{air}} \sin \theta_{\text{ref-air}}}{n_{\text{emulsion}}}\right) = 205.70^\circ$$

The bisector of the beams forms an angle of $\frac{180 + 205.7}{2} = 192.85^\circ$ with the perpendicular to film plane.

![Figure 2.2: Fringe formation in a transmission hologram.](image)

---

$^1$An angle's sign is determined as follows: a positive angle rotated clockwise will cross the normal to the plate. Additionally, angles are measured “downstream” of the beam. This allows the direction of the beam to be taken into account: note that in the transmission case, the reference beam has an angle of $225^\circ$, but in the reflection case, the angle is $45^\circ$. 

2.2.3 Fringe spacing

The fringe spacing depends on the angle between the reference and object beams. The distance \( d \) (see Fig 2.2) between fringes, as measured parallel to the film plane will be

\[
d = \frac{\lambda_1}{|\sin\theta_{\text{obj-emulsion}} - \sin\theta_{\text{ref-emulsion}}|}
\]

(2.2)

where \( \lambda_1 \) is the recording wavelength. In our sample case, the average fringe spacing \( d \) is 1.4\( \mu \); the spatial frequency is \( \frac{1}{d} \) or 685 lines per millimeter.

2.2.4 Diffraction properties

Any hologram, including the one we are describing, can be described as a sum of diffraction gratings. A diffraction grating is a structure ruled so tightly that it diffracts light, bending it and separating it into its component spectral colors. A holographic diffraction grating can bend light in a much more complex manner than a mechanically ruled grating; in fact, a hologram can be modeled as a grating/lens pair [BENT82] as it both bends and focuses light. This section and the following section will make use of diffraction principles to explain a hologram's ability to bend light.

Our fringe structure will bend and separate light according to the laws of diffraction:

\[
\sin\theta_{\text{out-air}} - \sin\theta_{\text{ill-air}} = \frac{m\lambda_2}{d},
\]

(2.3)

where \( m \) is the order of diffraction, \( \lambda_2 \) is the illumination wavelength, and \( d \) is the hologram's fringe spacing; \( \theta_{\text{out}} \) and \( \theta_{\text{ill}} \) are measured in air.

Equations (2.2) and (2.3) can be combined into one master equation that predicts the diffracted beam angle as a function of the illumination angle and the reference and object beam separation:

\[
\sin\theta_{\text{out}} = \frac{m\lambda_2}{\lambda_1} (\sin\theta_{\text{obj}} - \sin\theta_{\text{ref}}) + \sin\theta_{\text{ill}}.
\]

(2.4)

Display holographers commonly use this equation to guide them in designing their set-ups ([BENT82], [STCYR84]). A companion equation predicts the distance at which the image will focus; this equation will not be dealt with here.

2.2.5 Viewing transmission holograms in white light

The diffraction model helps us understand the properties of a transmission hologram. Equation (2.4) shows that the hologram bends red light (longer wavelength) more steeply than blue light (shorter wavelength). If a transmission hologram is illuminated in laser light, it will reconstruct an image of the object. If
the illuminating laser's wavelength differs from the recording wavelength, the image observed will be slightly displaced from the original object location, as per equation (2.4). When the hologram is illuminated in white light, the image will be reconstructed in every component spectral color, and each reconstruction will appear at a slightly different position from the next. The result, as mentioned in section 2.1, is a confused forest of spectral smears in which the original image is indistinct.

2.3 UNDERSTANDING A REFLECTION HOLOGRAM: BRAGG SELECTION

2.3.1 An example of reflection hologram fringe formation

Now let's model the fringes of a typical reflection hologram. As with our transmission hologram, the object beam is a single point source placed along the normal to the plate. The reference beam comes from the opposite side of the plate, at a 45° angle (see Fig. 2.1a).

2.3.2 Fringe inclination

We can calculate the intra-emulsion beam angles as follows:

\[ \theta_{\text{obj-air}} = 180^\circ, \]
\[ \theta_{\text{obj-emulsion}} = 180^\circ \text{ (from section 2.2)} \]

\[ \theta_{\text{ref-air}} = 45^\circ, \]
\[ \theta_{\text{ref-emulsion}} = \sin^{-1}\left(\frac{n_{\text{air}} \sin \theta_{\text{ref-air}}}{n_{\text{emulsion}}}\right) = 25.70^\circ \]

Fringes will form along the bisector of the reference and object beams, at an inclination of \( \frac{180 + 25.7}{2} = 102.85^\circ \) to the perpendicular to the film plane.
2.3.3 Fringe spacing

The fringe spacing $d$ of our reflection hologram can be calculated according to equation (2.1).

$$d = \frac{\lambda_1}{|\sin \theta_{\text{obj-emulsion}} - \sin \theta_{\text{ref-emulsion}}|} = \frac{633 \times 10^{-6}}{|\sin 180^\circ - \sin 25.71^\circ|} = 1.4 \mu \text{m}.$$ 

This gives us the distance $d$ between the fringes as measured parallel to the film plane. Let us denote by $s$ the separation between the fringes, as measured normal to the fringe planes (see Fig. 2.3). Before processing, this separation is equal to one-half of the exposing wavelength, $0.316 \mu \text{m}$ for HeNe red. If the film shrinks during processing, as is most often the case, the final fringe separation will be less than $\frac{\lambda_1}{2}$.

2.3.4 A thick hologram

The emulsion thickness of the plates used is 6\mu. With a fringe separation $s$ of approximately 0.2\mu, we can fit about 30 layers of fringes across a single emulsion layer. A reflection hologram is thought of as having a "thick" emulsion, because the layers of parallel fringes build up in the thickness of the emulsion.

---

1In a transmission hologram, the layers of fringes are perpendicular to the film plane and so do not depend on the thickness of the emulsion. Hariharan [HARI84] defines a criterion for determining whether a hologram is thick or thin. This is the Q-factor, given as

$$Q = \frac{2\pi \lambda_1 t}{n_1 d^2},$$

where $t$ is the emulsion thickness. A thick hologram has a $Q$ factor greater than 10.
2.3.5 Bragg selection

A reflection hologram produces a monochromatic image. This can be explained by closely considering the effects of the fringes' inclination within the thickness of the emulsion. The fringes are partially reflecting surfaces. In the case of an amplitude (unbleached) hologram, the fringes are layers of silver. The fringes in a phase (bleached) hologram are marked by local variations of the refractive index.

Let's follow the path of a beam of white light as it travels through the emulsion and is reflected back towards the viewer (see Fig. 2.4, and also [KASP85]). When white light reaches the first fringe surface, part of the light is reflected, and part of it is transmitted through to the next layer. There again, part of the light is reflected out towards the viewer, and part continues to travel through the hologram. This reflecting process persists through all the fringe layers.

The light that is reflected off any particular fringe has a phase delay of \( \frac{2\pi}{\lambda} \times 2s \) with respect to the light reflected off the neighboring fringe. \( S \) is the fringe separation described above as approximately \( \frac{\lambda_1}{2} \). Light of a wavelength near \( \lambda_1 \) will emerge from any fringe layer in phase with light emerging from the neighboring layer, and will constructively interfere. Other wavelengths will emerge from the hologram sufficiently out of phase with each other to destructively interfere. They effectively cancel each other out, and only the remaining reflected light, a band of colors centered at \( \lambda_1 \), is diffracted out towards the viewer. The reflection hologram acts as a color selector or interference filter; this is referred to as Bragg selection. Thanks to this built-in interference filter, reflection holograms can be directly viewed in white light.

Figure 2.4: Light reflecting off Bragg planes in a reflection hologram, LEFT: light of wavelength equal to twice the fringe spacing reflects in phase, resulting in constructive interference, RIGHT: light of other wavelengths suffers destructive interference (from [SAXB88]).
2.4 THEORETICAL CONTINUITY BETWEEN REFLECTION AND TRANSMISSION HOLOGRAMS

Thus far we have compared reflection and transmission holograms and found many differences between the two. They have disparate recording geometries, fringe structures, optical properties and display characteristics. We have discussed the wavelength selectivity of two typical reflection and transmission holograms and found a big difference between them; the reflection holograms is quite wavelength selective, the transmission hologram is not. E. Leith et al. undertook a rigorous theoretical study of holograms' wavelength and angular selectivity [LEITH66]. Their findings are summed up in the graphs in Figs. 2.6 and 2.7. The graphs predict a smooth transition in angle and wavelength selectivity between reflection and transmission holograms. This smooth transition occurs in a region that is not accessible by standard recording geometries.

2.4.1 The inaccessible zone

A quick examination of Leith's graphs shows that each has three regions: a hatched central area and a region to the left and right of this area. The authors explain that

"the hatched area represents a region that is not readily accessible, that is, an angle of 41° within the emulsion [of Kodak 649F plates] corresponds to an angle of 90° for the beam in air. [LEITH66, p 13061]"

Their statement presents a fundamental limitation of traditional recording geometries. As such, it deserves to be expanded upon. Leith et al. give the refractive index of the emulsion of the Kodak 649F plates they used as 1.52. For this refractive index, the steepest possible intra-emulsion reference beam angle is 41°. Let us determine the limit that refraction places on the intra-emulsion reference beam angle for Agfa-Gevaert 8E75 plates. We have already seen that an angle of 0° is not affected by refraction, and that an angle of 45° in air refracts towards the normal to become 25.7° within the emulsion. What happens to a beam directed towards the film at the steepest possible angle in air, 90°? Snell's law states

\[ \theta_{\text{steep-air}} = 90°, \theta_{\text{steep-emulsion}} = ? \]

\[ \theta_{\text{steep-emulsion}} = \sin^{-1} \left( \frac{n_{\text{air}} \sin \theta_{\text{ref-air}}}{n_{\text{emulsion}}} \right) = 37.85° \]

This means that the steepest possible fringes lie at an angle of 17° off normal, for a transmission hologram, or 17° off the parallel to the film plane in the reflection case. This is only a difference of 5° from the average cases seen in sections 2.2 and 2.3. With a standard recording geometry, fringes of 45° to 18° off axis cannot

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1This seems improbably low, as the refractive index of gelatin is around 1.54, and other emulsions have been measured at 1.62.
occur. This constrains holograms to fall into either the transmission regime (left of the hatched zone) or the reflection regime (right of the hatched zone). As Figure 2.4 shows, about a two thirds of all possible fringe configurations fall in the inaccessible zone. Leith et al.'s paper offers a theoretical prediction of the optical properties of a steep reference beam angle hologram, a hologram whose intra-emulsion reference beam angle is higher than 38°. 

![Diagram of hologram configurations](image)

**Figure 2.5: The inaccessible zone.**

### 2.4.2 Angular selectivity

Figure 2.6 is a plot of a hologram's predicted angular sensitivity as a function of its fringe tilt, as reported in [LEITH66]. The holograms they modeled were recorded in 633nm light, with an object beam fixed at 0° and a reference beam that varied from 0° to 180°, as measured within the emulsion. The graph shows that reflection and transmission holograms have similar angular selectivity. The farther off normal their reference beam goes, the more angular selective they become. Overall, angular selectivity varies from 11° to 2.5°.

Angular selectivity in the inaccessible zone varies only by 1°. It is 2.5° as it nears the reflection or transmission zones, and hovers at 1.5° when the fringes form at around 45°. In terms of angular sensitivity, access to this zone offers the potential to make fine-tuned highly-angle selective holograms.
2.4.3 Wavelength selectivity

Figure 2.7 is the hologram wavelength selectivity graph. The plot represents a theoretical calculation of the wavelength change $\Delta \lambda$ needed to extinguish the diffracted wave, while maintaining a constant angle of illumination. As with Figure 2.6, the plot was calculated for holograms made on Kodak 649F plates in 633nm light, with an on-axis object beam.

The left of the graph, up to the hatched region, represents the transmission regime. A transmission hologram is shown to diffract a wide range of illuminating wavelengths. However, as the fringes veer off normal, the hologram begins to be more wavelength selective. $\Delta \lambda$ varies from a bit above 150nm, for nearly perpendicular fringes, to around 65nm, for fringes that lie nearly parallel to the plate.

The right side of the graph shows that reflection holograms have a consistently narrow range of reconstruction wavelengths: they only diffract light whose wavelength falls within a 10nm spread around their favored reconstruction wavelength. In other words, reflection holograms are highly wavelength selective.

The central portion of the graph depicts the hologram's predicted behavior in the inaccessible zone. Wavelength selectivity in this zone varies from the...
transmission hologram’s low end of 55nm to the reflection narrow band extreme of 10nm. Access to this zone would offer control over a hologram’s wavelength selectivity.

Figure 2.7: A Hologram’s wavelength selectivity as a function of reference beam angle, (from [LEITH66]).

2.4.4 Opening up the inaccessible zone

Leith et al.’s paper shows that there is a theoretical continuity between the optical properties of reflection and transmission holograms. In practice, refraction in standard recording geometries has imposed a discontinuity on these two hologram types. However, recording in the “inaccessible zone” could offer holographers a new, intermediate type of hologram, replete with its distinguishing recording geometry, fringe structure, optical characteristics, and display geometry. The following chapter introduces a method for opening up the inaccessible zone.
CHAPTER 3: EDGE-LIT HOLOGRAMS: BACKGROUND AND RELATED WORK

3.1 THE GLASS BLOCK METHOD FOR OPENING UP THE INACCESSIBLE ZONE

3.1.1 Upatnieks' "glass blocks"

At the January, 1988 S.P.I.E. conference, Juris Upatnieks presented a talk entitled "Compact Holographic Sight". In the accompanying paper [UPAT88] he briefly outlines a method for making edge-illuminated HOEs (Holographic Optical Elements) for HUDs (Head-Up Displays). He couples a 15mm thick glass cover plate to the holographic plate and introduces the reference beam into the emulsion through a polished edge of this cover plate. The image is reconstructed when the hologram is illuminated through its edge. This new "glass block" recording geometry is a means of reaching the inaccessible zone.

3.1.2 How the glass block opens the inaccessible zone

The glass block (see Fig. 3.1) is a simple means of coaxing the reference beam into traveling through the emulsion at a very steep angle. The holographic plate is index-matched onto a thick glass block whose edges are polished. The plate becomes effectively as thick as the block; a reference beam is easily introduced through the edge of this thickened plate. At the glass-air interface, the beam is refracted towards the plane of the plate. The refracted beam continues to travel through the glass block to the plate and then to the emulsion. At the plate-emulsion interface the beam is again slightly refracted. At the emulsion-air interface, the reference beam is totally internally reflected, and it travels back through the plate and out the opposite edge of the block. The object beam travels normal to the emulsion, as in any standard display hologram.
3.1.3 Practice: what sort of angles were obtained?

The glass block† used for this study was 12"x12"x2" (30cm x 30cm x 4.9cm). It supported a 4"x5" (10cm x 12.5cm) holographic plate braced by a shim on the center of the block. The reference beam was introduced from an edge of the block and directed towards the center of the plate, as shown in Figure 3.1. A typical reference beam angle can be calculated through simple trigonometry. Figure 3.1 shows the dimensions and positions of the block, the plate, and the reference beam. The reference beam angle \( \theta_{\text{emulsion}} \) is can be found by first determining the angle of the beam in the block, and then applying Snell's law at the various interfaces between

†The block used was not a solid glass block, but rather a plexiglass block to which a thin sheet of glass had been laminated on all sides. See Chapter 4, section 4.2.2 for more details on the assembly of the "glass" block.

Figure 3.1: Glass block recording geometry for obtaining steep angle reference beam.
the block and the emulsion. The beam's angle within the block is obtained through simple trigonometry (see Fig. 3.1). The

$$\theta_{\text{glass}} = 90° - \left(\tan^{-1}\left(\frac{1}{6}\right)\right) = 80.54°$$

The intra-emulsion reference beam angle is $64.3°$.

or, according to the angle convention established in Chapter 2, Section 2.2.1, the reference angle $\theta_{\text{ref}} = 90° + 64.3° = 154.3°$. This is clearly within the inaccessible zone! With an on-axis object beam, fringes will form at $32°$ off normal. The glass-emulsion interface prevents the intra-emulsion reference beam from getting much steeper: a beam incident on the emulsion from $90°$ in glass will have an angle of only $68°$. The new reduced inaccessible zone is depicted in Figure 3.2.

![Diagram](image)

**Figure 3.2:** The glass block recording geometry has a smaller inaccessible zone than standard recording geometries.

### 3.2 Related Work

Aside from Upatniek's paper, I have uncovered only one other paper [LIN70] bearing directly on the issue of edge-illuminated holograms. Research has been conducted on two neighboring topics, holography with totally internally reflected light and evanescent-wave holography.

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1This takes into account refraction from the following boundaries: plexiglass(r.i. 1.49, beam angle 80.54°) to epoxy (r.i. 1.54, beam angle 72.6°) to glass (r.i. 1.51, beam angle 76.7°) to xylene (r.i. 1.5, beam angle 78.4°) to glass (r.i. 1.51, beam angle 76.7°) to emulsion (r.i. 1.63, beam angle 64.3°). See Chapter 4, section 4.5.1 for more details on the effects of the various refractive index mismatches.
3.2.1 Lin's work on edge-illuminated holograms

In April of 1970, Lawrence H. Lin, a co-author of the technical reference text *Optical Holography* [COLL71], presented a talk to the annual meeting of the Optical Society of America entitled "Edge-Illuminated Holograms". The talk was abstracted in the Society's Journal [LIN70], but no paper ensued. In a personal communication, Lin explained that he had obtained commercially made 1/4" (.6cm) thick holographic plates for his edge-lit research. He recorded holograms whose reference beam was sent to the emulsion through the edges of these thick plates. He was discouraged because all the internal reflections made it very difficult to obtain a reference beam of even intensity. His research on edge-illuminated holograms never went beyond this initial exploration; other higher-priority research concerns led him to abandon his edge-lit work. He does not know of any researcher having followed up on his edge-lit work.

3.2.2 Stetson's analysis of Total Internal Reflection (TIR) holograms

In 1969, K. A. Stetson published a technically oriented paper entitled "An Analysis of the Properties of Total Internal Reflection Holograms" [STET69]. He used the set-up shown in fig. 3.3 to introduce a totally internally reflected reference beam into the emulsion. He was interested in this technique because it enabled him to record a transmission hologram of an object placed very close to the plate. Stetson notes that in general, coherence requirements during recording, third order aberrations, and degradations of the reconstructed image due to illumination source size and spectrum are all proportional to the object's distance to the holographic film. He then points out that by minimizing that distance with a TIR reference beam, the holographer can limit image degradation. This is most relevant for holograms of shallow objects very close to the plate.

![Figure 3.3: Stetson's set-up for recording holograms with totally internally reflected light (from STET69).](image)

3.2.3 Nassenstein's Evanescent Wave Holography

The German researcher H. Nassenstein published a rigorous theoretical investigation of evanescent-wave holography [NASS69 1, 2]. Evanescent waves occur when light is totally internally reflected at the boundary between two media having different refractive indices (see Fig. 3.4). A small amount of energy is not
totally internally reflected and escapes through the surface boundary to propagate through the plane of the adjoining (lower refractive index) medium before returning. This energy is called the evanescent wave. It decreases exponentially with distance to the original surface. In order to make a hologram with an evanescent wave, the holographic recording medium must have a lower refractive index than the substrate onto which it is coated. Nassenstein found that evanescent-wave transmission holograms were more efficient and had higher resolution than standard transmission holograms.

Had Nassenstein coated his emulsion onto plates whose refractive index was lower than that of the emulsion, he would have recorded edge-lit holograms instead of evanescent-wave holograms.

![Figure 3.4: Nassenstein's set-up for recording holograms with evanescent waves (from [NASS69]).](image)

### 3.3 OTHER TYPES OF HOLOGRAMS

#### 3.3.1 A map of the holographic recording space

The diagram in Figure 3.5 is used in many books and articles to depict the interference fringes in the space around the reference and object beams. The diagram is a simple tool for predicting the fringe structure for a given recording geometry. Points A and B in the diagram represent the object and reference beams, both point sources emitting spherical wavefronts. Each hyperbola is a slice of the three-dimensional hyperboloids of revolution formed by the standing interference pattern between the two point beams. Destructive interference occurs along the lines traced by these hyperbolae. Note that the diagram does not take into account refraction at the emulsion surface. Nevertheless, the diagram helps in understanding how the fringes' position depends on the set-up configuration.

The diagram is an effective map of the holographic recording space. This map is often used to present common recording configurations.
R x

Figure 3.5: The diagram of holographic recording space (from [SAXB88]).
(1): In-line hologram; (2): Off-axis transmission hologram; (3) reflection hologram; (4) Lensless Fourier transform hologram; (5) "glass block" or steep reference angle hologram.

3.3.2 In-line holograms

In 1947 Dennis Gabor recorded the first holograms. These were "in-line" holograms, in which the reference and object beams are on the same axis. In-line holograms present a number of inconveniences: the zero-order beam shines in the viewer's eyes, a spurious real image hovers around the virtual image (the "halo" effect), and the hologram is not white-light viewable. Nevertheless, a variation of Gabor's original in-line, called the Fraunhofer hologram, remains a useful technique for taking a three-dimensional snapshot of tiny particles. The particles are illuminated by a pulsed, collimated beam. The light they diffract serves as an object beam; the collimated beam is the reference beam. Tiny particles, such as fog or aerosol particles, can be studied with this method.

3.3.3 Off-axis transmission holograms

Leith and Upatnieks sought to improve a hologram's viewing conditions and image quality. To this end, they separated the object and reference beams and moved the reference beam off axis. This change moved the zeroth-order beam away from the viewer and eliminated the halo effect. In 1963, they published a paper describing this "off-axis" holography technique [LEITH63].

Leith and Upatnieks' off-axis hologram was still not white light viewable. In 1969 [BENT69] Stephen Benton invented the "rainbow" or white light transmission hologram. His two-step recording process results in a hologram that is white-light viewable but has limited vertical parallax. This invention did much to open the field of display holography.

3.3.4 Reflection holograms

Reflection holograms are by nature white light viewable. In 1962, Soviet holographer Yuri Denisyuk developed the first technique for recording reflection
holograms. His simple one-beam approach does not allow control of the object/reference beam ratio. Though Denisyuk holograms are often quite dim, their rugged and simple set-up keeps them a favorite for quick holography demonstrations.

The reflection hologram has been much improved upon since its invention. The two-beam reflection set-up is part of most holographers' repertoire. It offers control over the beam ratio and can therefore produce brighter holograms than the Denisyuk set-up. The two-beam reflection set-up also allows recording a reflection hologram from a real image projected by a transmission master. This lets the holographer freely position the hologram plane with respect to the image. This two-step reflection hologram technique is essential to advanced color control techniques.

3.3.5 Lensless Fourier transform holograms

Stroke, in 1965, wrote about the so-called lensless Fourier transform hologram [STRO65]. These are holograms whose reference beam is a point source in the same plane as the object. With such a geometry, the waves that interfere at the hologram plane are the Fourier transform of the object and reference waves. This technique works best for planar objects oriented parallel to the plate. These holograms are not sensitive to fine fringes; they are useful for recording in a medium that has a low resolving power.

3.3.6 New to the map: steep reference angle holograms

The steep reference angle or edge-lit hologram's recording geometry is different from that of other holograms on the map; note that none of the other holograms points steeply towards the reference beam. The steep reference beam yields a hologram with unique optical properties and with a new display configuration. The edge-lit hologram does not fit into any of the existing hologram categories. It is a new addition to the holograms traditionally depicted in the diagram of the holographic recording space.

In the remainder of this thesis a detailed practical guide to using the new glass block recording geometry is presented, and two novel applications of the glass block recording geometry are introduced: a new method of dispersion compensation (Chapter 5) and a new edge-lit hologram display (Chapters 6 and 7).
Chapter 4: A Practicum

4.1 STANDARD HARDWARE AND PROCESSING

The only special equipment required for making a steep reference angle hologram is a thick transparent glass or plexiglass block and an index-matching fluid. The block serves as a plateholder and as a guide for the steep angle reference beam. The fluid index-matches the plate to the plateholder. The remaining set-up hardware and processing conform to standard holographic practices.

4.1.1 Table

Like any hologram, steep reference angle holograms must be recorded in a stable, vibration-isolated environment. The MIT Spatial Imaging Group's 4'x10' steel-top optical table, floating on pneumatic pillars, satisfied these stability requirements.

4.1.2 Laser

A short exposure time helps ensure stability during recording. The duration of the exposure depends somewhat on the set-up, but mostly on the power of the laser. The set-up for a HOE (holographic optical element) is very economical in terms of light: most of the laser's light is sent directly towards the plate. A 12 mW Helium-Neon (HeNe) laser was sufficiently powerful to produce bright steep reference angle 4"x5" (10 cm x12.5 cm) HOEs, while keeping exposure time under 3 seconds. Recording a steep reference angle display hologram requires a more powerful laser, because in this case much of the laser's light gets strongly diverged or directed away from the plate. Our lab's 50mW HeNe was an appropriate laser for this application. Steep reference angle display holograms produced for this thesis had exposure times on the order of 5 seconds.

4.1.3 Optics

The optics set-up for steep reference angle holograms contains elements familiar from standard display holography set-ups. A holographer wishing to successfully embark on steep reference angle production would do well to have on hand the following equipment:

- a number of different beamsplitters (50/50, 70/30, 96/4) and/or a stable variable beamsplitter
- several small front surface mirrors, for guiding the undiverged beam
- microscope objectives, in 20x, 30x, and 40x, and a 60x objective for the steep reference beam
- lens-pinhole spatial filters (LPSF), usually only 2 per set-up
• a cylindrical lens, for making edge-lit white light transmission holograms

• a collimating lens or mirror for making HOEs and edge-lit white light transmission holograms.

• a 4"x5" (the size of the holographic plate) piece of ground glass that can be index-matched to the block while setting up. It is helpful for seeing what light will reach the plate.

The optics must be stably secured to the table. The optics used in this study screw into a pole that is clamped into a magnetic base.

4.1.4 Film

The steep reference angle holograms produced for this thesis were all recorded on Agfa-Gevaert 8E75 4"x5" glass plates. The display holograms were created in a three-step process that required using two larger master holograms. These were shot on 8"x10" (20cm x 24.5cm) Agfa-Gevaert 8E75 plates.

4.1.5 Processing

The holograms made for this study were initially processed as follows. They were developed in Ilford 50/50 developer\(^1\) for three minutes, placed in a stop bath for 15 seconds, rinsed briefly in water, and then bleached in ferric sodium EDTA (ethylene-diamino-tetra-acetic acid\(^2\)) until clear. This chemistry minimizes scatter and emulsion shrinkage. Its big disadvantage for this application is that the EDTA bleach does not leave the plate completely clear. The plate overall turns a transparent brownish color, and heavily exposed areas turn quite dark, leaving unsightly scars on the plate.

4.1.6 Use of bromine

The EDTA bleach is a physical transfer bleach. A physical transfer bleach does not extract material from the emulsion, nor does it add to it. It bleaches the plate by transferring material from one part of the emulsion to another. It attacks the metallic silver, which, once dissolved, plates onto transparent silver halide crystals. The brown stains on the plate result from residual silver that the EDTA did not dislodge. A bromine bath following the EDTA bath will turn this remaining silver into crystals of silver bromide. This faintly tints the plate a creamy yellow but leaves

\(^{1}\) Ilford Publication 15718.GB, May 1986, Section 4 provides information on Ilford holographic processing chemistry. The developer used for this research was mixed as follows: for solution A, mix 24g of pyrogallol with 24 g of ascorbic acid in 2 liters of water; for solution B, dilute 120g of sodium carbonate in 2 liters of water. Mix equal parts of solution A and B, just prior to developing. Used developer is toxic waste and should be disposed of accordingly. Refer to the Appendix for more information on the health hazards of holographic chemistry.

\(^{2}\) Refer to the Appendix for information on the health hazards of EDTA.
it otherwise uniformly clean and transparent. Bromine bleaching generally produces a hologram that is brighter than an EDTA-bleached hologram, but that has more image scatter. In the experiments for this thesis, the extra bromine bath did not perceptibly alter the quality of the image.

The plate should be left in the bromine for twice the time it takes for the plate to clear. It should then be rinsed only briefly, in a low pH solution. This helps prevent photolysis, or printout. Bromine liquid and vapor are extremely dangerous; bromine should always be used under a hood and handled with very thick impermeable gloves. The reader is referred to the Appendix for more information on the health hazards of holographic processing chemicals.

4.2 THE TRANSPARENT BLOCK

The transparent block is the innovative and crucial piece of hardware necessary for making steep reference angle holograms. It serves both as a guide for the reference beam and as a plateholder. It is essential that the block be flat, clean, and mechanically stable. The block's size, material, and support are critical to successful steep reference angle holograms.

4.2.1 Block dimensions and material

In the initial development stages of this project, it was decided that the block would be two inches (5cm) thick. That thickness made it possible to build a simple set-up that would allow a beam to pass comfortably through the block's edge and fully illuminate a 4"x5" plate on the face of the block. In determining the length of the block, the position of the plate was taken into account; it seemed useful to have some latitude in the separation between the plate and the edge of the block. A 12" (30cm) long block offers sufficient flexibility. The block used in all the experiments for this thesis was therefore 12"x12"x2". This proved to be appropriate dimensions for making 4"x5" steep reference angle holograms.

4.2.2 Protective glass coating

The first block used for the steep reference angle work was made of plexiglass with polished edges. The plexiglass used was Lucite™, whose refractive index is 1.491, close to that of glass (1.51). The plexiglass scratched easily and was soon so scuffed that even abrasive polish could not clean it. The xylene used for index-matching the plate to the block (see Section 4.3) seemed to dissolve the plexiglass, leaving a trail of big milky patches in its wake. Within a few weeks, the block was unusable. I looked into replacing the dirty plexiglass block with a more durable solid glass block and found that the cost of such a large, clean, flat, solid glass block was prohibitive. Instead, a second plexiglass block was obtained, and this time, its faces and edges were protected by a thin (1/8" or .3 cm) sheet of glass. The glass was laminated onto the block with an optically clear index-matching epoxy, Norland Optical Adhesive #68, whose refractive index is 1.54. Reader be warned! This is a

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1 Two-inch thick glass is not a standard product. A 2" thick block would have to be factory-ordered, at a minimum cost of $80.
tedious operation, requiring strict meticulousness and much patience. Dirt or bubbles captured in the laminate may happen to fall in the path of the reference or object beam and get recorded in the hologram. Take particular care when laminating the edges any bubble or dirt in the path of the reference beam will scar the hologram.

4.2.3 A practical block holder

The block holder should be stable. It should not block the reference or object beam. A flexible design will allow the plate to be placed on either side of the block. The following figure illustrates the block holder used for all the work presented in this thesis. The holder is made of aluminum that has been anodized black. A glass shim can be affixed, with tape or hot glue, at any height and to either side of the block. The holder has been impeccably stable. It was designed and built at MIT by Terry Maxedon.

![Figure 4.1: a practical block holder (drawing by Terry Maxedon).](image)

4.3 INDEX-MATCHING

In order for the reference beam to travel through the face of the block to the holographic plate, there must be a close index match between the two surfaces. If the glass plate and the glass face of the block are joined by a substance whose refractive index is close enough to that of glass, the light waves will travel through the block, through the index-matching substance, through the plate, and finally reach the emulsion, having been slightly refracted at each boundary. However, if
the two surfaces are joined by a substance whose refractive index is lower than that of glass, the light will remain totally internally reflected within the block. It will not be transmitted through to the plate.

Through capillary action, the index-matching substance forms a temporary bond between the plate and the block, holding the plate to the block for the exposure. This lets the block act as a plateholder. The bond between the plate and the block must be stable, so that the plate is immobile during exposure, and easily undone, so that after the exposure the plate can be removed without harm to it or to the block.

4.3.1 Xylene as an index-matcher

Many holographers use xylene as an index-matcher and as a bonder. Its index of refraction is 1.4971, which is quite close to that of plate glass (1.51). It is a very volatile liquid. It has the advantage of evaporating quickly, seemingly without residue. Xylene is a mild narcotic, and some people have adverse reactions to it: it can make them lightheaded or give them a headache.

4.3.2 Using xylene

If the xylene is improperly applied, small bubbles or air pockets will fleck the bond between the block and the plateholder. If a beam traveling through the block encounters such an air pocket, it will remain totally internally reflected within the block. Air pockets prevent light from reaching the plate; they will manifest themselves on the processed hologram as regions where there is no image.

The key to avoiding the formation of air pockets is to make certain that both glass surfaces are clean and dust-free. Then the plate should be placed against the block, resting on a previously affixed shim. Now a brief squirt on a squeeze bottle filled with xylene will provide enough fluid to hold the plate. If the xylene is not applied in a smooth, continuous stream, small air bubbles may form. The bubbles will either remain in the xylene and be imaged on the hologram, or they will slowly make their way out from under the plate, possibly causing the plate to move during exposure. It is a good idea to have a safelight on hand, and to examine the xylene layer for bubbles. If any are present, it is best to remove the plate, dry the plate and the block, and start over. Experienced holographers know that they must at this point wait 5 minutes or so before exposing the plate. This gives the xylene and the plate time to settle, so that they will be still during exposure.

4.4 SENDING THE REFERENCE BEAM

4.4.1 Using ground glass to see the reference beam during set-up

In the course of this research, I have used the two most common types of reference beam: a collimated beam, to produce a plane wavefront, and a point source, to produce a spherical wavefront. Both were simple to obtain. To ensure a hologram of constant brightness, the reference beam should be even across the plate.

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1CRC Handbook of Chemistry and Physics (56th edition), average of meta- and para- xylene.
When making standard holograms, one places a white card in the plateholder to check the evenness of the reference beam across the card. This won't work with the block set-up: the reference beam stays totally internally reflected. A simple trick to make the reference beam apparent is to index-match a piece of ground glass to the block. Light travels through the index-matcher and falls on the ground glass. The ground glass diffuses the reference beam and its light can readily be seen.

4.4.2 Sine qua non: a clean edge

The block edge through which the reference beam will be sent must be clean. Any dust, fingerprint, or even cleaning detergent residue in the path of the beam will leave its footprint on the plate. The footprint appears clearly on the unbleached plate. It takes the form of a slanted bullseye, whose concentric rings are fringes of destructive interference between the light scattered by the dirt and the surrounding light. The size of the defect is magnified if the reference beam is a diverging wavefront (point source beam).

4.4.3 The collimated reference beam

Figure 4.2 illustrates a set-up for a steep angle collimated reference beam. Note the placement of baffles to keep unwanted reference light away from the block.
4.4.4 The point source reference beam

Basic set-up

Figure 4.3 illustrates the basic set-up for a steep angle spherical reference beam.
Figure 4.3: setup for steep angle spherical reference beam.

Set-up with diverging lens
In the course of making steep reference angle display holograms, I explored a variation of the basic point source set-up mentioned above. The variation involves bringing the point source right up to the edge of the block, and index-matching a diverging (negative) lens to the edge, so that the beam spreads enough to cover the 4"x5" plate. The motivation behind this change, and a modus operandi, are detailed in Chapter 7, Section 7.1.7.

4.5 THREE PROBLEMS DUE TO UNWANTED REFLECTIONS: WOOD GRAIN, SPURIOUS GRATINGS, AND A "RASTER" EFFECT

4.5.1 A description of reflections from surfaces in the recording system
The Fresnel reflection and transmission equations can be used to calculate the amount of light that is reflected at every interface of two media of different refractive index. The proportion of light reflected at such an interface is given by

\[ r_t = \left( \frac{n_i \cos \theta_i - n_t \cos \theta_t}{n_i \cos \theta_i + n_t \cos \theta_t} \right)^2. \]  

(4.1)
where the subscripts "i" and "t" denotes the incident and transmitted beams respectively, and "n" refers to the refractive index of the medium considered. As the number obtained represents the amplitude of the reflected wave, it must be squared in order to express intensity. This equation can be used to determine how much light is reflected at every relevant interface during a typical glass block recording. Figure 4.5 shows the reflections considered. Table 4.1 presents the results obtained.

![Figure 4.5: Schematic representation of the reflections at boundaries between media of different refractive indices in the glass block plate holder. NOTE: in the interest of a clear illustration, refraction has not been taken into account in this figure.](image-url)
Table 4.1: Refractive index differences and reflection at boundaries between media in the glass block plate holder.

The index mismatch between the emulsion and the plate contributes the most back reflections to the hologram, though one should remember that because of heterodyne gain, even the feeble back reflections can interfere significantly with the reference beam and produce unwanted noise on the hologram.

4.5.2 Wood grain
An unbleached steep reference angle hologram can exhibit more or less prominent lines of "wood grain". Wood grain is the colloquial name given to the dark lines that can be seen on a developed, unbleached plate; these lines do indeed resemble wood grain. They are engendered by light back-reflected from the glass side of the plate interfering with other beams. The interference lines appear on the developed plate, forming a pattern reminiscent of wood grain. Once the plate is bleached, these lines are no longer visible, but they do affect the reconstruction of the image; their pattern appears in the image, on the plane of the plate. Wood grain also occurs in standard reference beam holograms; it is usually reduced by anti-helation dyes on the back of the plate, by painting the back of the plate, or by index-matching the plate to dark glass. Steep reference angle holograms can have particularly accentuated wood grain, and as the reference beam's angle grows steeper, the wood grain becomes even more pronounced. This is borne out by equation (4.1), which shows that the reflection at the emulsion-glass interface intensifies as the reference beam angle grows steeper.
A piece of ground glass index matched to the block is helpful for seeing the object and reference light that will reach the plate; however, though the wood grain is quite noticeable on a developed plate, it does not manifest itself on the ground glass. The ground glass diffuses light too much for the fringes to be apparent. Fortunately, there is a way to use a prism to see some of the fringes without having to expose and develop a plate. The prism is index-matched to the block, in the plate area. The prism receives and deflects the light that would reach the plate. Wood grain that would appear on the film is revealed in the light projected by the prism. This method only reveals the wood grain that is due to an index mismatch between the block and the plate; it cannot show the wood grain arising from index mismatch between the emulsion and the plate.

4.5.3 Spurious gratings

Even when it does not cause pronounced wood grain, totally internally reflected light affects the emulsion by creating spurious gratings. Figure 4.6 shows the path of an undiverged beam. Typically, a beam will be reflected within the block for a good number of bounces before escaping through an edge or simply losing intensity. Any of this internally reflected light that reaches the plate will interfere with the object beam, the reference beam, and perhaps with some other internally reflected beam. Any two beams that interfere will create a grating. These spurious gratings lower the efficiency of a hologram.
reflected beam. Any two beams that interfere will create a grating. These spurious gratings lower the efficiency of a hologram.

![Diagram of totally internally reflected beam](image)

*Figure 4.6: example of path of totally internally reflected beam, inside glass block.*

4.5.4 "Raster" effect on image

The edge lit holograms made for this thesis all have a slight raster or digitized appearance. The image appears to be made up of distinct points, as on a CRT monitor, rather than seeming continuous, as on a photographic slide. This so called raster effect is caused by internal reflections. The .12 refractive index mismatch between the glass support plate and the emulsion creates a boundary that reflects 10% of light back towards the emulsion. The other refractive index boundaries (glass-xylene, xylene-glass, glass-epoxy, and epoxy-plexiglass) contribute feeble back reflections as well. The apparent raster points are defined by the very fine lines produced by all these interfering back reflections. In the following section, I propose two methods for attenuating wood grain and spurious gratings. Unfortunately, those methods cannot deal with the raster effect problem. To effectively eliminate the raster effect, one would have to use a support plate and a block made of glass whose refractive index is significantly closer to that of the emulsion. Alternately, one could attempt to make an emulsion with a refractive index closer to that of glass.

4.6 SOLUTIONS TO TOTAL INTERNAL REFLECTION PROBLEMS: INDEX-MATCHED BAFFLING WITH HIGH PRECISION INDEX-MATCHING

4.6.1 Index-matched baffling

To minimize wood grain and spurious gratings, one must limit internally reflected light. This can be done by index-matching light-absorbing glass, such as thick dark glass, to the block. Two types of absorbing glass were used: black Kodalith plates and thick transparent grey glass.

The block was covered with index-matched pieces of 1/16" (.15cm) thick, exposed and developed black Kodalith 8"x10" plates. When making a reflection hologram, only the reference beam edge and a 4"x5" area for the plate were left uncovered. When recording a transmission hologram, a clear area was left on the opposite side of the plate, so the object beam could reach the plate (see Figure 4.7).
A 1/4" (.6cm) thick transparent grey glass was expected to be particularly useful for recording a transmission hologram. Because the glass is transparent, the object beam can pass through it to reach the plate. The grey glass could be index-matched to the front of the block, where the object beam passes, and it would let the object beam in while attenuating internal reflections. In practice it was found that though the glass did attenuate internal reflections, it also cut down the intensity of the incoming object beam. To keep proper beam ratios, the reference beam intensity had to be decreased, and this lengthened the exposure time. In the interest of a shorter exposure, the transparent grey glass baffling was not retained.

Neither grey glass nor Kodalith were index-matched to the emulsion side of the plate, because this caused wood grain to appear, especially when the reference beam angle approached 90°. Without the benefit of index-matched baffling, the transmission hologram's reference beam is totally internally reflected at the air-emulsion interface, and it forms a reflection hologram. This unintentioned hologram brings down the overall efficiency of the hologram being deliberately recorded. The ideal baffling material for eliminating the additional hologram would be a dark glass that offered an exact index match with the emulsion.

For practical reasons, grey glass was not placed on the edge of the block through which the reference beam passed. It was difficult to obtain a sufficiently clean bond between the grey glass and the glass edge. The tiny impurities inevitably sandwiched between the two surfaces scarred the reference beam.
4.6.2 Special index-matching oils

Holographers may want to use special index-matching oils instead of xylene. Special purpose oils offer the advantage of having a refractive index closer to that of glass. This helps inhibit back reflections. It was found that the steeper the reference beam, the more sensitive it is to subtle changes in the refractive index. At nearly 90° incidence, the emulsion bore dark stripes of destructive interference, several mm. thick. An index-match with Dow Corning's 550 fluid, whose refractive index is 1.495, lessened the stripes. A drawback to using index-matching oils is that like any oils, they can be quite messy.

4.6.3 Using index-matching oils

Applying oil to the plate can be quite a messy operation. A syringe was very effective for applying the oil to the plate. The oil should be applied to the glass side of the plate. Oil on the emulsion slightly distorts and dims the hologram, and attracts dust besides. Not much oil is needed to form a thin layer between the two
glass surfaces. Good results were obtained from syringing a bead in the shape of an upside-down T out onto the plate, resting the bottom edge of the plate against the shim of the block, and then slowly bringing the top of the plate up against the block. This is illustrated in Figure 4.8.

Figure 4.8: using mineral oil to index-match the plate to the block. LEFT: first pour a pool of mineral oil on the glass side of the plate in the shape of an upside-down "T". RIGHT: lean bottom edge of plate against shim and slowly bring face of plate towards block.
Chapter 5: A steep angle dispersion compensation system

This chapter relates an experiment in which the glass block recording and display geometry were applied to the problem of dispersion compensation. The chapter begins by introducing the phenomenon of dispersion. Two existing approaches to dispersion compensation are recounted. Then the steep-angle dispersion compensation experiment is described, and the phenomena observed are presented¹.

5.1 THE DISPERSION PROBLEM, AND THREE PREVIOUS SOLUTIONS

5.1.1 Dispersion in white light viewing of one-step laser transmission holograms

When a one-step laser transmission hologram is illuminated in white light, each of the various component wavelengths reconstructs an image at a different angle and distance. The image appears spectrally smeared, or dispersed, such that the original object is indistinct (see Chapter 2, Section 2.2.5).

Two-step rainbow transmission holograms are white light viewable. However, a rainbow hologram has no vertical parallax, only horizontal parallax. In the interest of obtaining a full-parallax, white-light viewable transmission hologram, efforts have been made to develop dispersion compensating viewing systems.

5.1.2 Dispersion compensation by color filtering

There is a simple way around the problem of dispersion. A narrow-band color filter placed in front of the illumination source will provide the hologram with near-monochromatic illumination. Dispersion in the reconstructed image is limited by the effective narrow reconstruction bandwidth. This method makes inefficient use of the full intensity of the illuminating light, in that it only uses a portion of the light’s spectrum.

5.1.3 De Bitetto’s method for achromatized viewing of laser transmission holograms

In 1966, De Bitetto introduced a dispersion compensation method that made use of the full spectrum of the illumination source to reconstruct an undispersed, achromatic image [DeBIT66] [KATYL72]. He recorded a diffraction grating and a hologram with the same average spatial frequency; when flipped, the grating diffracted the light with an angular dispersion equal but opposite to that of the hologram (see Fig 5.1). When the grating was placed in the dispersed beam

¹The term "direct illumination" is used throughout this chapter to denote an illumination source coming from the same angle and distance as the reference beam.
diffracted by the hologram, it compensated for the hologram's dispersion, and the observed image was achromatic and undispersed, within limits that will be set forth in the next paragraph. The hologram and the grating are held next to each other, with a piece of louver film\(^1\) sandwiched between them to block the zeroth order beam.

![Diagram of De Bitetto's dispersion compensation system](image)

**Figure 5.1:** De Bitetto's dispersion compensation system [DeBIT66].

The dispersion compensation principle can be modelled with the help of equation 2.4 (see Chapter 2, Section 2.2.4 for derivation) to predict the angle at which the hologram projects an image, and a companion equation that predicts the image's distance. The angle and distance equations are, respectively:

\[
\sin \theta_{\text{out}} = \frac{m \lambda_2}{\lambda_1} (\sin \theta_{\text{obj}} - \sin \theta_{\text{ref}}) + \sin \theta_{\text{ill}}, \quad \text{and} \quad
\]

\[
\frac{1}{R_{\text{out}}} = \frac{m \lambda_2}{\lambda_1} \left( \frac{1}{R_{\text{obj}}} - \frac{1}{R_{\text{ref}}} \right) + \frac{1}{R_{\text{ill}}}, \tag{5.1}
\]

where the subscripts -out, -obj, -ref and-ill designated the output, object, reference and illumination beam, \(m\) refers to the order of the diffracted beam, and \(R\) is the distance, or radius of curvature, of the projected image.

We can use these equations to determine the angle at which a red (633nm), green(550nm), and blue(480nm) illumination beam must reach a hologram, in order for each color to reconstruct an on-axis image. For a hologram made with an an-axis object 60cm away and a collimated reference beam incident at 225°, the prescribed illumination angles as calculated with equation (2.4) are 225° for red, 217.9° for green, and 212.4° for blue. These illumination angles can be obtained from

---

\(^1\)Louver film is a thin film which supports a miniature venetian blind-like structure. The film is manufactured with the slats of the "blinds" set to a specified angle. Light reaching the film at that angle can travel through the film; other light is blocked by the slats. The film is made by 3M.
a grating of the same spatial frequency as the hologram. If the hologram is illuminated with the spectrum projected by such a grating, the red, green, and blue (and intermediate) images will all be projected on-axis. They will overlap to form an achromatic image.

The sharpness of this image depends on the distances at which the various images are projected. If all the image points are projected at the same distance by every wavelength, then the image points will overlap to form a sharp image. If the image points are projected at different distances, the image will appear blurred. As one considers image points away from the center of the object (i.e. image points that are off-axis) one finds that they reconstruct at a different distance for different wavelengths. The limits of De Bitetto's dispersion compensation system are therefore that it reconstructs a sharp image only near the center of the object; the image becomes blurred for off-axis image points.

5.1.4 Bazargan's dispersion compensated hologram viewer

Kaveh Bazargan designed a hologram viewing system based on De Bitetto's dispersion compensation method [BAZ86]. He combined a diffraction grating, a compact light source, a collimator, and louver filters into a compact (11"x11"x12") unit that provided dispersed illumination for hologram reconstruction (see Fig. 5.2). His system can be configured to produce full-color holographic images. In order to do this, he mounts three holograms into his viewer. The holograms are recorded such that when illuminated in the viewer, each reconstructs a full-size, on-axis image, and these overlap to form one full color image.

![Diagram of Bazargan's dispersion compensated hologram viewer](image)

Figure 5.2: Bazargan's dispersion compensated hologram viewer [BAZ86].

5.2 The steep reference angle approach to dispersion compensation

As part of the glass block research, a series of experiments were conducted on a steep-angle dispersion compensation system (see Fig. 5.3). This section describes a
steep reference angle dispersion compensation system, offers qualitative data on the
system's color, depth, and resolution characteristics, and proposes an analysis of the
system's behavior.

5.2.1 A description of the viewing system

The edge-lit, dispersion compensated viewing system requires a matched
hologram and reflection grating. The reflection grating and the transmission
hologram are both recorded on a glass block, using the recording techniques
described in Chapter 4. The beam designated as the grating's reference beam is an
on-axis point source\(^1\). The grating's object beam is a collimated steep-angle beam
sent through the edge of the glass block. The hologram's steep-angle reference beam
is also collimated, so that the hologram's reference beam is identical to the grating's
object beam. The objects imaged for this study were masks on a backlit ground glass
screen. They were placed such that the object-hologram distance was the same as
the grating-reference beam distance. As in De Bitetto's and Bazargan's methods, the
hologram and the grating have the same average spatial frequency.

The finished grating and hologram are index-matched one above the other
onto a glass block of the same thickness as the one on which they were recorded\(^2\).
When the grating receives direct illumination\(^3\), it projects a narrow-band beam up
through the glass block onto the hologram. This beam functions as the hologram's
playback beam. It reconstructs a full-parallax virtual image in a saturated spectral
hue.

---

\(^1\)In this experiment, the grating's reference beam was placed 60 cm away from the plate.
\(^2\)The blocks used were 2" thick.
\(^3\)The grating was illuminated with light from a xenon arc lamp, channeled through a fiber-
optic cable.
A novel feature of this system is that there is no zeroth-order beam present in the hologram's reconstruction. When a standard transmission hologram is reconstructed, the undiffracted part of its illumination beam passes straight through the plate in the direction of the viewer; this is called the zeroth-order beam. The reconstruction angle is usually chosen such that this beam avoids the viewer's eyes; nevertheless, this zeroth-order beam is unnecessary and potentially distracting light. In the glass block dispersion compensation system, the hologram's illumination source is the steep-angle beam projected through the glass block by the grating. This beam remains totally internally reflected at the hologram-air interface, such that no zeroth-order beam escapes from the hologram. If the back of the grating were painted black, the zeroth-order light from the grating illumination beam would be masked off as well, and no stray light at all could escape from the system.

Another interesting characteristic of the system is that because the hologram is a full-parallax laser transmission hologram, it has no set viewing distance. The image stays undistorted regardless of the observer's distance. This is not the case with white-light transmission holograms, where the image has a limited viewing distance. If a white-light transmission hologram is viewed astray from the intended viewing zone, the colors in the image migrate away from the desired reconstruction color, and the image distorts.

5.2.2 Color

When the grating receives direct playback, it reconstructs a spectrum. The top of the spectrum is a near-collimated beam of red light. If the hologram is illuminated by this portion of the projected spectrum, the original image appears, in full size, focused, and in red. The image's color, distance, and focus will change if the hologram is illuminated by light of a different color. If the hologram is slid down towards the grating, it will be illuminated by a narrow band of light centered about a color of a shorter wavelength, such as orange or green. Alternately, if the hologram stays in place, but the grating illumination is angled slightly downwards, the color illuminating the grating will shift towards a shorter wavelength. It is still possible to reconstruct a sharp image in a shorter wavelength. However, for shorter wavelengths, the focal distance of the grating illumination moves farther back; the image appears smaller and farther away, and it sinks off axis. The distance of the grating illumination does not affect the reconstruction color.

5.2.3 Resolution

The holographic image is affected by the distance of the grating's playback beam. There is a certain illumination distance (designated as the focal distance) at which the system will reconstruct a sharp image. This distance varies with wavelength. As the light source moves closer to the grating, the reconstructed image appears vertically blurred, and smaller. As the light source moves away from the grating, the image appears vertically blurred and larger, and it suffers from a spherical distortion: the object looks as though it were wrapped around a ball. The system tolerates about 2cm of displacement forwards or backwards of the focal distance, beyond which the image becomes noticeably blurry.
The focal distance recedes as the illuminating wavelength gets shorter. The focal distance for red was 68.5cm from the grating; for green, the distance grew to 76cm. A distance for blue could not be determined, because the blue image travelled so far down off-axis as to be superimposed onto the grating illumination.

The variation in focal distance can be explained by the fact the grating was made in 633nm red light, and so in direct playback it reconstructs a collimated beam only in a red wavelength. Other wavelengths will reconstruct a curved wavefront. However, when the playback distance grows, red light reconstructs a curved wavefront whereas some other wavelength can reconstruct a collimated beam. Because the hologram expects a collimated beam, it reconstructs a focused image when offered collimated light. The focal distance is a distance for which the narrow band of illuminating wavelengths reconstruct an image at nearly the same distance, creating a sharp image. When the reconstructing wavelength is shorter than the recording wavelength, the image appears farther away, hence smaller.

5.2.4 Depth
Tests were made to determine the range of image depths the system could sharply reconstruct. The system was tested on planar images whose distance from the plate varied from 71cm to 12.25cm. So long as the grating was illuminated from the focal distance, the system played back a sharp image. So as to better compare reconstruction quality for objects at different depths, a triple exposure was made of three air force resolution tests plates, placed at 22cm, 41.5cm, and 60cm away from the plate. When offered direct reconstruction, they appeared in focus. However, the resolution test plate farthest away was not as sharply focused as the others. Its slight fuzziness can be explained by the narrow-band illumination it was receiving. The several wavelengths within that narrow band diffract at different angles. The deeper the image, the more pronounced the spread between the various diffracted wavelengths becomes, and the more blurred the image appears.

5.2.5 Analysis
It has been empirically determined that the glass block dispersion compensation system has a so-called focal distance, i.e. that there is a particular point source distance, for a given narrow band of reconstruction wavelengths, which will cause the grating to reconstruct a sharp image in the hologram. The present analysis attempts to explain this behavior. The analysis first concerns itself with the effect of the point source distance on the divergence (or distance) of the reconstructed image; it then notes the variation of this effect with wavelength.

The effect of the point source distance on the reconstructed image must be calculated in two steps. First, the divergence of the projected spectrum is calculated. Then, taking light from that spectrum as the illumination source, the distance of the reconstructed image is calculated. A pair of companion equations are used. The first one predicts the effect of the point source distance on the divergence of any given wavelength projected by the grating. The second one predicts the distance at which the hologram will reconstruct an image at a particular wavelength, given the
divergence of the illumination coming from the grating. When considering the
divergence of light coming from the grating, one must take into account the
separation between the grating and the hologram. This is done in the last term of
equation (5.4). The refractive index of the plexiglass block is also taken into account,
as it affects the divergence of the steep-angle beam (but not that of a normal-
incidence beam).

\[
\frac{n_{\text{plexiglass}}}{d_{\text{out-grating}}} = \frac{\lambda_2}{\lambda_1} \left( \frac{n_{\text{plexiglass}}}{d_{\text{steep-beam}}} - \frac{1}{d_{\text{point-source-beam}}} \right) + \frac{1}{d_{\text{ill}}} \quad (5.3)
\]

\[
\frac{1}{d_{\text{out-image}}} = \frac{\lambda_2}{\lambda_1} \left( \frac{1}{d_{\text{obj-image}}} - \frac{n_{\text{plexiglass}}}{d_{\text{ref-image}}} \right) + \frac{1}{d_{\text{out-grating}} + d_{\text{grating-hologram}}} \quad (5.4)
\]

Table 5.1 offers a theoretical prediction of the image distances for two close
pairs of wavelengths, red (633nm) and orangeish-red (623nm), and greenish-
blue(490nm) and blue(480nm), corresponding to various positions of the
illuminating source. The table indicates that shorter wavelengths will reconstruct
an image farther back than a longer wavelength. This coincides with observed
phenomenon. The table also suggests that the image distance moves in and out
with the point source distance moving slightly more for blue (22.2 cm image
displacement between 45cm and 75cm illumination distance) than for red (only
20cm image displacement for same light source translation).

<table>
<thead>
<tr>
<th>wavelength (nm)</th>
<th>633</th>
<th>623</th>
<th>490</th>
<th>480</th>
</tr>
</thead>
<tbody>
<tr>
<td>point source distance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45cm</td>
<td>49.5cm</td>
<td>49.8cm</td>
<td>53.8cm</td>
<td>54.1cm</td>
</tr>
<tr>
<td>59cm</td>
<td>59.3cm</td>
<td>59.6cm</td>
<td>64.5cm</td>
<td>64.9cm</td>
</tr>
<tr>
<td>60cm</td>
<td>70cm</td>
<td>60.3cm</td>
<td>65.2cm</td>
<td>65.6cm</td>
</tr>
<tr>
<td>61cm</td>
<td>60.6cm</td>
<td>60.9cm</td>
<td>65.9cm</td>
<td>66.4cm</td>
</tr>
<tr>
<td>75cm</td>
<td>69.7cm</td>
<td>70.0cm</td>
<td>75.8cm</td>
<td>76.3cm</td>
</tr>
</tbody>
</table>

5.2.6 Future modifications

The present system is inefficient in that it uses only a portion of the spectrum
to illuminate the image. If there were three gratings in the system, each one
reconstructing an image in one of the three primary colors (red, green, and blue),
then the system would make fuller use of the spectrum. The divergence of the
gratings' object and reference beams should be such that when they all received
illumination from the same set distance, each would create a sharp, full-size, on-axis
image. The superposition of these three image could result in either a full-color image or an achromatic image¹.

5.2.7 Conclusion

These experiments have shown that dispersion compensation within the steep-angle range is possible. A reflection grating and a hologram both having the same spatial frequency were recorded on a glass block with a steep-angle beam, and then mounted on an identical block for viewing. When the grating was illuminated, it diffracted a steep-angle narrow-band beam that travelled through the glass block to the hologram. A image in a saturated spectral color was observed. The sharpness of this image is a function of the distance of the grating's illumination source. The image's size and distance depends on the color projected onto the hologram by the grating. Images with depths ranging from 12.25cm to 71cm were sharply reconstructed, though a slight blur was noticed in the 71cm deep images.

¹A full-color image could be obtained by having a triple-exposure master where each of the exposures corresponds to a different color separation of the image. Each exposure should be recorded such that it will reconstruct on-axis in the appropriate color.
Chapter 6: The edge-lit display

This chapter describes a new type of hologram display, the edge-lit display. The chapter begins with a review of the standard hologram display formats. The problems inherent to them are pointed out, and the display requirements of future applications of holography are surmised. The edge-lit display is then introduced and its advantages over existing display formats are argued.

6.1 DISPLAY ISSUES

6.1.1 Review: Basic reflection and transmission display formats

A reflection hologram expects front illumination; it is usually hung on a wall, where it can be easily front-lit. The hologram should not be parallel to the wall, but angled slightly downwards; this helps ensure that people of various heights will be able to see the image (see Figure 6.1). The hologram must be lit by a precisely positioned point source, usually angled towards the hologram at between 30° and 60° and placed around 1.5m away. The exact angle and distance of the illumination source are determined by the recording geometry, and differ from one hologram to another.

Figure 6.1: Typical transmission and reflection hologram display formats.

A transmission hologram is more difficult to display. Because it must be backlit, it cannot be hung against an opaque wall. Instead, it is usually hung or supported about 1.5m away from a wall, and lit from above. The space between the hologram and the wall is usually wasted. If the hologram is hung, it must be protected from people knocking into it or causing it to swing. The alternative is to build a sturdy and attractive stand for the hologram. A transmission hologram lacks the format compatibility of reflection holograms; in other words, its format is different from that of traditional 2D media in that it cannot be hung on a wall (see
Section 6.1.4 for previous attempts to overcome the problem of format compatibility in transmission holograms).

6.1.2 Art holography and display issues

Though throughout the world there are museums and galleries dedicated to holography, the medium has yet to gain widespread acceptance by the dominant art establishment. D. Tulla Lightfoot researched the New York art establishment's attitude towards holography [LIGHT87]. She interviewed a number of curators and gallery owners. Though her firmest conclusion is that the medium would gain legitimacy if artists already established in other media were to produce holograms, display issues did figure among certain interviewee's gripes with the medium.

A few of the curators interviewed mentioned that the work and cost involved in fine-tuning a holography display discouraged them from mounting a show in the medium. Ms. Lightfoot writes that John Szarkowski, the Director of photography for the Museum of Modern Art,

is aware that an exhibition of holography could be more costly than an exhibition of drawings, or photography, where the work could virtually be placed on the wall with thumb tacks. Many display holographers insist that they be present at the hanging to tune in their work.... New lighting apparatus must be purchased and developed for the exhibition space, all contributing to an increased cost of exhibiting holography.

Szarkowski laments the exigencies and cost of a holography exhibit. He points out that not only is precise positioning of the lights crucial, but the light sources themselves must be of a specific sort. Many exhibition spaces do not have bright point sources on hand. Holographers are the first to admit (and bemoan!) the rigors of properly displaying a hologram. When James Finlay was the director of exhibition services at the Museum of Holography, in New York City, he wrote [FIN79] that

although more holograms may have been exhibited at the Museum of Holography than at any other place on earth, putting up an exhibition is still a unique, even harrowing experience, fundamentally unlike mounting an exhibition of any other art form.... Anyone who has tried to exhibit a hologram in the best way knows the difficulties involved. With every hologram there will be a particular combination of methods to match the hologram's demands. And owing to the lack of information on the subject, two people often experiment for hours to get the best image/display arrangement for a single hologram. For an exhibition, the problems increase exponentially.

Holographers and the art establishment agree that lighting a hologram is an exacting procedure. Unfortunately, display constraints dissuade some members of the art establishment from venturing to mount a holography display. They also discourage potential patrons from purchasing holograms for their homes.
6.1.3 Display issues for holography's future

What will the future of display holography bring to science and industry? The Spatial Imaging Group envisions holographic hardcopy peripherals for computers and is currently exploring the potential for this in the areas of scientific visualization and CAD-CAM. The group has also begun to research the use of holographic overlays for 3D screen displays.

Scientific visualization refers to any graphic or pictorial means of imaging the raw data (numbers) that scientists obtain from their research. Because it can convey three-dimensional information, a hologram is particularly suited for presenting data describing spatial relations and depth. The Spatial Imaging Group has produced a hologram from a scanning electron microscope’s data on aluminum. At this point the group is concentrating on investigating the use of holograms for rendering 3D medical data. Michael Halle, a graduate student who wrote his undergraduate thesis on holograms in medical imaging, pointed out that hospitals tend to have space restrictions; a hologram display for medical imaging should be compact.

Another area of research in the Spatial Imaging Group is the use of holography as part of a hardcopy peripheral to a CAD-CAM system. Research undertaken at Brown University has shown that it is possible to record a hologram of a liquid crystal screen display [GERR87]. This is an important first step in producing a holographic hardcopy machine with quick turnaround time, because it eliminates the step of having to transfer images to film. Holographic hardcopy of an object being designed would help artists and engineers perceive the spatial relationships between various elements of its design. As with any office or laboratory equipment, the holographic peripheral should be compact.

The group has also produced prototype holographic overlays for computer screens. The overlays are part of an eventual 3D screen display. We have had trouble lighting these holograms: the viewer can shadow the illumination beam by sitting too close to the screen. An ideal screen overlay would be lit in such a way that it could not be shadowed.

Holograms are beginning to appear at scientific and technical conferences, not only as novelty advertising but as a means of communicating research results. This currently requires packing a light and a tripod or two along with the hologram. A more practical conference display for holograms would be both portable and compact.

6.1.4 Early approaches to display problems

The earliest approach that I have been able to find to self-contained hologram displays is a hologram viewer invented by R.L. Kurtz, selling in 1979 for $6495 [KURTZ79]. An advertisement claimed that the unit weighed under 40 pounds. It contained a 7mW laser (which accounted for most of the unit’s cost) and optics for reconstruction.
Frequently, holographers find themselves wasting time at meetings trying to find the equipment necessary to show their holograms, hence this system.... It can accommodate 4"x5" holographic plates either horizontally or vertically and can display virtual or real images.

Kurtz hoped to capitalize on the need for a convenient display, though his display kit was not especially innovative.

Holographic artist such as Rudi Berkhout or Harriet Casdin-Silver have occasionally backed their transmission work with a mirror. The mirror allows transmission holograms to be front-illuminated, providing them with a display format that is compatible with the display standards for 2D media. The problem with this configuration is that an image of the room or even of the viewer reflects off the backing mirror towards the viewer and superimposes itself on the holographic image. Benton designed a reflection mount for transmission holograms that does not reflect room light back towards the viewer [BENT84]. He improved the simple mirror-backed mount by replacing the mirror with a prism/light trap element that reflects illumination light towards the hologram but traps ambient light. This element resembles a fresnel lens in that it is a thin, faceted composite of slices of a thicker prism. A few successful prototypes of this system were built, but the optical element has never been manufactured.

The multiplex display, invented by Lloyd Cross, is a self-contained transmission display for stereograms. The holographic film is curved around a hollow plexiglass cylinder or half-cylinder and lit from a bulb in the center of the cylinder, as shown in Figure 6.2. To produce these holograms, one records a series of 2D views of an image or scene in thin (3mm) strips on a piece of holographic film. The hologram projects a different view out into each eye of the observer, and a 3D image is perceived. As producing holograms for multiplex displays requires a considerable amount of specialized equipment and technical expertise, relatively few have been made.
6.2 THE EDGE-LIT DISPLAY

6.2.1 The edge-lit holographic display box

The glass block recording geometry (see Chapters 3 and 4) has been used to successfully record holograms that can be edge-lit in a compact and portable display unit (see Fig. 6.3). The finished hologram is index-matched to the top of a glass slab that is taller than the hologram. The extra length of the slab is inserted into a slot in the display unit. A light source housed in the unit illuminates the hologram through the edge of the glass.

The unit is compact: it need only be as wide as the hologram. Its height and depth depend on the reference beam optics, as will be explained in section 6.3. The edge-lit display prototype that I built reconstructs 4"x5" (10cm x 12.5cm) holograms. It is 18cm wide by 35cm tall (including the hologram) by 11cm deep.

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1The slab can be made of glass or plexiglass. The advantages and disadvantages of each will be discussed in Chapter 7, Section 7.2.6.
6.2.2 Virtues of the edge-lit display

Because the edge-lit display is compact, it seems a suitable component of the holographic hardcopy peripheral of the future. It also should win the favor of curators who shy away from more space-consuming displays. It could increase the sales of art holograms, as it is more convenient for home display than a traditional hologram.

The edge-lit display is self-contained; it needs no complicated instructions. No additional equipment, such as a point source of light or a tripod, is necessary for viewing the hologram. This is beneficial to those selling holograms, because it prevents the "but when I got home the image was gone!" problem by guaranteeing that the hologram will always receive proper illumination. The small self-contained display also reduces the load for people traveling with a hologram to exhibit.

The position of the light source inside the display unit needs only minimal adjustment. A knob on the outside of the base moves the light source back and forth for fine-tuning the image or demonstrating holographic reconstruction properties. The knob makes it simple to adjust the reference beam angle, relieving holographers and curators from the very time-consuming process of hanging illumination for holograms.

Figure 6.3: The edge-lit hologram display prototype.
The edge-lit display is portable. It plugs into any ordinary outlet. This is convenient for showing holograms at talks or demonstrations. The display unit could be designed to be foldable, making it even more convenient for transporting.

The glass support can be modified so that no zeroth order beam appears. Light can only leave the glass support through the edge opposite the light source; light is totally internally reflected at all other surfaces. If this edge is painted or covered, then no distracting zeroth order beam escapes from the edge-lit display. This is a feature useful to any application of the display, be it artistic, scientific, or novelty. It is interesting to note that with the light source hidden away in the base and the opposite edge of the glass covered, the edge-lit hologram appears to be a self-luminous object.

Ambient light hardly affects image reconstruction. The image is bright enough so that it can be shown in a lit room, and the reconstruction conditions are such that lights in the room do not play back a noticeable secondary image. This means that a room does not have to be specially prepared before it can receive an edge-lit hologram.

The display unit can be designed to be wall-mounted, thus offering full format compatibility. Figure 6.4 shows two possible configurations for a wall-mounted display. The first resembles an art deco lamp. The second is an edge-lit version of a picture frame.

Figure 6.4: Two possible configurations for a wall-mounted edge-lit display. The one on the left resembles a traditional picture frame. The one on the right is more stylized.
The edge-lit display can also be designed to stand freely on a tabletop. This opens up a new market for novelty holograms: people can keep edge-lit stereogram portraits of their loved ones on their desks!

The display can be reconfigured to fit in front of a CRT, for a holographic screen overlay.

The edge-lit display ushers in a more serious application for holography: holographic signs. Certain signs, floor plans, or maps contain information in depth or in layers that could be well communicated by a hologram. An edge-lit display is compact and sturdy enough to be used in public places. A holographic sign would also offer the advantage of attracting more attention than an ordinary sign.

Edge-lit holograms add to art holographers' expressive vocabulary. The art holographer Deiter Jung was quite struck by the edge-lit hologram. He pointed out that the image seems to fill the volume of the glass support; the image plane is no longer clearly defined. He remarked that this gave the medium a completely new feel.

The last virtue of the edge-lit hologram is relevant to holographers in particular: a holographer need only two pieces of new equipment in order to make edge-lit holograms, a thick transparent block and a block holder.

6.2.3 Unanswered questions

At this time, only one edge-lit hologram has been produced, a rainbow hologram, though the Spatial Imaging Group plans to record an achromatic edge-lit hologram in early 1989. This will be a first step in determining the expressive range of edge-lit holograms. Chapter 2 explained that an edge-lit hologram's wavelength and angular selectivity can vary. It remains to be seen how this will affect edge-lit holography.
Chapter 7: Making an edge-lit rainbow hologram and display unit

This section offers practical information regarding the specifics of making an edge-lit white light transmission hologram and display unit¹.

7.1 RECORDING AN EDGE-LIT RAINBOW HOLOGRAM

7.1.1 The two-step standard rainbow hologram recording process

Benton's two-step rainbow process [BENT69, 77] has become the standard means of producing white light transmission holograms. A first laser transmission master hologram (H1) is exposed and processed. The H1 is then masked off with only a thin (several mm) horizontal slit left uncovered. The slit is offered conjugate illumination, and projects a pseudoscopic real image. This image is recorded on a second piece of film, called a transfer hologram or H2. In conjugate monochromatic illumination, the H2 plays back an image of the slit. In conjugate white light, the hologram diffracts the slit out into a single broad spectrum that spreads in the direction normal to the slit (vertically, in the case of a horizontal slit). The result is a bright, spectrally colored image that is undistorted if looked at from within the intended view zone. The horizontal slit limits vertical parallax to one angle, but maintains full horizontal parallax. As our eyes are horizontally set, we aren't so very sensitive to the loss of vertical parallax.

7.1.2 The three-step edge-lit rainbow hologram recording process

A three-step recording process was used to produce the edge-lit rainbow hologram. The relationship between the reference beam and the illumination beam mandates this three-step process². The reason for this becomes clear if we follow the recording process backwards, beginning with the display of the edge-lit hologram.

The edge-lit hologram will be illuminated by a diverging point source placed near the edge of the hologram. We want to reconstruct an orthoscopic image with this diverging illumination source. Our reference beam could a priori be either a diverging beam mimicking the illumination beam, or be its conjugate, a converging beam. In practice, a converging beam is hard to obtain; we therefore use a diverging reference beam to record the edge-lit hologram.

¹The term "direct illumination" is used to denote illumination coming from the same angle and distance as a hologram's reference beam.
²See [BENT78] for another instance of a three-step recording process being used to accommodate a diverging illumination beam.
As both the reference and reconstruction beams will be diverging, the illumination source will offer direct playback. Direct playback forms an orthoscopic image of the object recorded. Because we are making a white-light viewable rainbow transmission hologram, our "object" will be a real image projected by a master hologram. However, a first generation master produces a pseudoscopic real image. As we require an orthoscopic real image, we resort to a three-step process in which we produce a second generation master that projects an orthoscopic real image (see Fig. 7.1).

First, we make a master hologram (H1) of our object. We replay this master with conjugate illumination; it projects out a pseudoscopic real image. In the second step, we record that real image on another master (H2). Finally, H2 is given conjugate illumination; the orthoscopic real image that H2 projects is recorded on a third plate (H3), using the glass block recording geometry. When the processed H3 is index-matched onto a thick slab of glass and edge-illuminated with a point source, an orthoscopic image appears!
STEP 1: record a slit master of the object

STEP 2: Record a full aperture master of the pseudoscopic real image projected by H1

STEP 3: Using the glass block recording geometry, record a steep reference angle hologram of the orthoscopic real image projected by H2.

STEP 4: H3 can be played back in direct illumination.

Figure 7.1: the edge-lit rainbow hologram three-step recording process.
7.1.3 The size of the masters

The viewer will effectively be looking at the object through three "windows": H1, H2, and H3 (see Fig. 7.1). The image will cut off from viewing positions where the three windows do not overlap. To ensure a substantial view zone, H1 and H2 are recorded on plates wider than H3. The edge-lit rainbow hologram produced for this thesis was 4"x5"(10cm x 12.5cm); its H1 was recorded on a 10"wide slit master, and its H2 was recorded on an 8"x10"(20cm x 24.5cm) plates.

7.1.4 Positioning the masters

The relative position of the masters must be carefully considered (see Fig 7.1 for correct positioning). Let us assume the general case, that in the final hologram the plane of the plate intersects the image of the object, and let us define the position of each of the three holograms.

H1 is positioned in a standard way with respect to the object. The object is roughly on-axis. The Benton math [BENT82] is used to determine the object-H1 distance, given the desired viewing distance. The H1 reference beam angle is inconsequential.

H2 is expected to project an orthoscopic real image that H3 can intersect. This can only happen if the distance between H2 and the focused real image from H1 is the same as the distance between H2 and H3. The H2-H3 distance should be minimized; this maintains a wide view zone by keeping the three holographic windows close together.

The H3 recording geometry places a constraint on the H2 reference angle. If this angle is too shallow, the zeroth order from the H2 conjugate illumination beam will shine on H3 (see Fig. 7.2). A suitable angle for the H2 reference beam can be obtained through simple trigonometric identities. If the H2-H3 distance will be 17cm, then the H2 reference beam should be at 115° (see Chapter 2, Section 2.2.1 for angle convention).
7.1.5 Masking off the slit

Like all rainbow holograms, the edge-lit rainbow hologram is made from a slit master. The question arises: which master bears the physical slit, H1 or H2? It must be H1. If H2 were the slit master, the real image projected towards H3 would be diverging from a slit, and it would not diverge quickly enough to cover H3 by the time it reaches a focus. Instead, H1 bears the slit, and H2 is a full aperture master of the reduced-parallax image projected by H1. The final H2 to H3 recording is a full aperture transfer. Because H2 will be illuminated with a fully diverged beam, it is important that it be an efficient master.

7.1.6 Positioning H3 on the block

The H3 plate's distance from the edge of the block depends on the illumination beam optics. The illumination beam should be as close as possible while still evenly covering the entire plate. The H3 made for this study was placed vertically in the center of the block, 4" (10cm) from either edge, as illustrated in Figure 7.3.
7.1.7 Forming the steep-angle reference beam

Chapter 4, Section 4.4 offers pointers on sending the reference beam through the edge of the glass block. For an edge-lit hologram, the diverging point source reference beam should be placed as close to the block as possible, provided that the playback illumination can be effectively positioned in the same manner. There are two constraints on the playback source distance: the source must diverge quickly enough to evenly cover H3, and heat generated by the source must not deform H3's support block (this is a concern when using a plexiglass support block). These constraints could be done away with. A negative lens index-matched to an edge of the support could help diverge the illumination beam, and a fiber optics cable could bring cool light to the support. The prototype did not have such enhancements; the H3-illumination source distance was 22cm (as measured from the edge of the plate).

If a lens is used to diverge the playback source, one might be necessary for the reference beam as well. A negative lens index-matched onto the block diverges the beam; however, it is difficult to cleanly apply the lens to the edge of the block. Bits of dust trapped in between the lens and the block edge frequently mar the reference beam. The alternative is to place a negative lens right after the spatial filter, to increase the divergence of the beam, though this wastes light.

7.1.8 Angle of the steep reference beam

I found that as the reference beam angle became steeper, the wood grain on the plate became coarser. I suspect that this problem is due to various refractive index mismatches within the system (refer to chapter 4, section 4.3 for more details). I obtained holograms nearly free of wood grain when I directed the beam from the center of the block through to the center of the plate. This provided a reference angle of approximately 64.3° (see Chapter 3, Section 3.1.3).

1"Wood grain" is the colloquial name given to the dark lines that can be seen on a process unbleached plate (see Chapter 4, Section 4.5.1).
The holographer must decide from which edge to bring the reference beam. The reference beam can be sent from either the left or the right of the block; if the direction is not chosen with due consideration to the display configuration and the image's orientation on the H2, the image might appear upside-down in the display.

7.1.9 Baffling the block

The importance of index-matched baffles to avoid wood grain from back reflections was stressed in Chapter 4. The baffles on the H3 must cover as much of the glass block as possible while still leaving H3 a full view of H2. Figure 7.4 illustrates proper baffling.

![Diagram of baffling](image)

*Figure 7.4: A properly baffled block leaves just enough of the block uncovered so that H3 can receive light from the entire H2.*

7.2 THE EDGE-LIT DISPLAY UNIT

The edge-lit display prototype built for this study is but one possible design for the display unit. This section describes the prototype display unit and includes general design considerations.

7.2.1 Display dimensions

The dimensions of the display depend on the size of the hologram and on the distance of the light source to the edge of the hologram. In most cases, the display will probably be expected to be as compact as possible. The plexiglass support must be at least as large as the size of the hologram. The prototype was 17.5cm wide by 34.5cm tall (including the hologram) by 11cm deep.

7.2.2 Light source

The hologram illumination source should be a point source, so that it mimics the reference beam; it should be small, to keep the unit compact; it should be bright, to reconstruct a bright image. I found that quartz halogen miniature lamps fulfilled these requirements. They cost around $8 each and usually require a transformer. They also produce a lot of heat; the bulb envelope wall temperature is between 250° and 400°. This is a problem if plexiglass is used to support the hologram; the
plexiglass will crack\(^1\) if is not insulated from the heat of the bulb. A future design might include noiseless thermo-electric cooling, insulation, or light-trapped air holes to control the heat. The bulb used in the prototype was an Osram 64-440 12V 60 Watt bulb with an output of 850 lumens.

A clear 150 Watt bulb with a vertical filament can also serve as an illumination source. Its advantages over the quartz halogen bulb are that it is cheaper, cooler, and it runs on household voltage. Unfortunately, it takes up a lot of room, because it is a full-size bulb; also as it is not a well defined point source, it reconstructs a slightly blurred image.

An experimental xenon arc fiber optic lamp was successfully used to illuminate the prototype edge-lit hologram. Fiber optics can provide a relatively heatless light source.

### 7.2.3 Holding the light

In the design stage of the prototype, it was decided that the light's position should be adjustable, to be able to compensate for variation in the reference beam angle. There are two relevant position parameters: the bulb's height relative to the hologram, and the bulb's distance from the center of the plexiglass' edge. In the interests a simple design, the bulb's height was kept fixed, and the height of the plexiglass support was made adjustable (see Section 7.2.6). The bulb's socket (a number H912 Gilway socket) screws onto a small aluminum base. The base is mounted onto a threaded rod (see Fig. 7.5). One end of the rod protrudes from the front of the unit's base, and the other end is cradled in a niche in the opposite face of the unit. When the knob is turned, the bulb translates along the threaded rod. This lead screw mechanism provides a simple way to adjust the illumination angle.

![Figure 7.5: Lead screw mechanism for translating the illumination point source.](image)

\(^{4}\) This cracking due to repeated heating and cooling of the plexiglass is known as crazing.
7.2.4 Material

The display box should be made of a material that is opaque, sturdy, and heat resistant. The prototype was machined from 3/4" (1.8 cm) thick aluminum; this thickness was arbitrary, and in hindsight it is clear that the box could have been made out of thinner metal, say, only $\frac{1}{4}$" (.6 cm) thick.

7.2.5 Possible configurations

The display design can be tailored for specific applications (see Section 6.3 for descriptions of these applications). If light is concealed under a frame, and the glass is covered by a mat, the hologram looks like a self-luminous painting. The display can be designed to stand on a desktop, to be mounted on a wall, or to be integrated into a pre-existing environment, such as an edge-lit CRT overlay, an edge-lit display for a holographic hardcopy peripheral, a decorative edge-lit window, or an edge-lit sign.

7.2.6 The transparent support

The transparent support used in the prototype was 1 1/4" (6.7 cm) thick. This was the minimum thickness that would allow the beam to fan out to cover the entire 4"x5" plate. I suspect a thinner block could be afforded by index-matching a diverging lens to the edge of the support. The lens would spread light so that it would evenly cover the plate. I also suspect that the block could be thinner if the edge through which the light enters were chamfered. The bevel of the chamfer would afford a larger surface through which light could enter the block. This would result in a larger surface of the support being illuminated in each bounce of internally reflected light. As no experiments in this direction have as yet been undertaken, it is not clear to what extent refraction might hinder the effect of the bevel. Figure 7.6 offers an comparison of the surface a beam can cover if it enters a block through a normal edge and through a chamfered edge. A beam of light is sent through an edge of each of two blocks. The blocks share the same thickness, but the block on the right has a chamfered bottom edge. In this block, the light is able to uniformly cover a larger surface than in the block with the perpendicular edge.

The hologram in the prototype is supported by a 1 1/4" x 4" x 9" (4.2 cm x 10 cm x 22 cm) piece of plexiglass. Plexiglass was used rather than glass, because the plexiglass was cheaper and more readily available. Glass 1 1/4" thick is not a stock item, it has to be ordered from the factory, with a minimum cost of $80. A piece of plexiglass of the same dimensions cost $33. Unfortunately, plexiglass scratches easily and cracks under moderately high temperatures (such as the temperature of the improperly insulated prototype display box).

As mentioned above in section 7.2.3, the height of the plexiglass -and therefore of the hologram- is adjustable. The plexiglass is held by a simple collar (see Fig. 6.2) that can be tightened at any height. When the plexiglass is inserted into the slot in the display unit, the collar comes to rest against the top of the unit, limiting the height of the hologram.
7.2.7 Blackening the inside of the display unit

The natural metallic silver color of the aluminum reflects light from the bulb. This slightly diffuses the illumination light, so that it becomes less of a point source. To remedy this, the inside of the display unit was anodized black. The outside of the unit was blackened as well, for aesthetic reasons, though at the same time this is expected to increase the unit's heat radiation. Black spray paint, though not as smooth or durable, is a more economical alternative to anodizing.

7.2.8 Laminating the hologram to the transparent support

The hologram must be index-matched to the glass support. The prototype hologram was laminated to the support using a UV-curing epoxy, Norland Optical Adhesive #68 (refractive index 1.54). The adhesive is particularly suited to laminating onto plexiglass: extra laminate can be cleaned off with methanol and a soft cloth without damage to the plexiglass.

The edge-lit hologram is recorded with its emulsion facing away from the glass block, as explained in Chapter 4, Section 4.5. When the finished hologram is laminated to its plexiglass support, the emulsion faces the support, to protect it from dirt and moisture. This means that the hologram is flipped top-to-bottom with respect to the reference and playback beams (see Fig. 7.6).
At first glance, it does not appear possible to offer the flipped hologram proper reference illumination. However, total internal reflection works in our favor and allows such a configuration. If the light source is placed in front of the hologram (as though the hologram were being illuminated in reflection) the image appears. The read-out light travels through the block, through the plate, through the emulsion without initially producing an image. At the air-glass interface, the light is totally...
internally reflected and heads back through the emulsion. This light now mimics the reference beam, and an image is reconstructed. Curiously, the transmission hologram appears to be lit in reflection\(^1\).

The edge-lit display of the future should have some sort of reusable index-matching system. Holograms would not have to be permanently attached to their glass support and so could be lit more compactly.

7.2.9 Cost of the display unit

The estimated cost of the display unit is broken down in table 7.1.

<table>
<thead>
<tr>
<th>ESTIMATED COST OF EDGE-LIT HOLOGRAM DISPLAY UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>plexiglass block, 4&quot;x1(1/4)&quot;x9&quot; (10cm x 3cm x 22cm)</td>
</tr>
<tr>
<td>8 lbs aluminum</td>
</tr>
<tr>
<td>Osram bulb #64-440</td>
</tr>
<tr>
<td>Gilway socket #H129</td>
</tr>
<tr>
<td>4 amp transformer</td>
</tr>
<tr>
<td>misc. small parts (screws, cord, etc)</td>
</tr>
<tr>
<td><strong>SUBTOTAL</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ADDITIONAL COSTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norland Epoxy #68 (approx 1 oz. needed)</td>
</tr>
<tr>
<td>Black Anodizing</td>
</tr>
<tr>
<td>Black Spray Paint</td>
</tr>
</tbody>
</table>

Table 7.1: Estimated cost of the display unit.

\(^1\)As mentioned in Chapter 4, Section 4.6.1, if the hologram was made without the benefit of index-matched baffling at the air-emulsion interface, total internal reflection contributed a second unintentional reflection image. This image can be seen when the transmission-mode H3 is played back "in reflection". The unintentional reflection image can be eliminated from playback by index-matching it away onto black glass.
Chapter 8 - Conclusion: personal reflections and directions for further research

This thesis has presented an exploration of a new hologram recording method, the glass block recording geometry. The research was conducted over a period of 7 months. During those 7 months, I was able to familiarize myself with the glass block recording geometry and build up an intuition for its potential. I now offer some of this intuition by suggesting directions for further research. I also share some personal thoughts regarding the research I conducted.

8.1 DISPERSION COMPENSATION

I feel that there is still quantitative and analytical work remaining to be done on the dispersion compensation system. A more mathematically sophisticated model of the system's behavior could be developed. Perhaps one day the dispersion compensation system could be used to produce full color holograms. I imagine that three gratings could be made such that each would place a full-sized red, green, or blue image on-axis. The superposition of these three images would produce a full-color image. The Benton math could be used to determine the set-up for the gratings. I think that this would be straightforward, though tedious, as precise color control can be a quirky beast.

8.2 EDGE-LIT DISPLAY HOLOGRAMS

I am very enthusiastic about the edge-lit display's potential to change the field of display holography. This thesis leaves in its wake a number of research projects. The plexiglass block should be made thinner, either through faster beam-spreading optics or by cutting the plexiglass' edge at an angle, so that more light can get through it. The system should be scaled up, so that larger edge-lit holograms can be produced (currently only 4"x5" edge-lit holograms have been recorded). The scaling up is again a question of reference and illumination beam optics; the problem lies in being able to spread the beam quickly while still having it evenly cover the whole plate. Total internal reflection within the emulsion should be controlled, either through meticulous index matched baffling, or by coating the emulsion onto a substrate that has a refractive index closer to that of the emulsion.

I am closer to the art holography community than to industrial holographers; as I worked on the edge-lit display, I was particularly committed to making a system that would be feasible for independent art holographers to implement. If display holographers begin to produce edge-lit holograms, I will consider my research time well spent! Unlike certain recent holographic advances, such as stereograms, the edge-lit hologram requires only two new pieces of equipment (a glass block and a
glass block holder). This makes it financially accessible to any holographer. There is the issue of the cost of the display unit; some holographers may balk at the added expense, both in terms of raw material and time. I hope that the cost of the display box will be outweighed by its advantages: the hologram is self contained, and guaranteed to "work" (i.e., no more "but when I got home, the image was gone").

When I think about the future of holography, I think about a conversation I had with a friend of mine. We were talking about making holograms, and I was telling her about setting up the optics and exposing the plate, when she confidently interrupted me and said "and then you send it out to be processed, right?" Well, I look forward to the day when "One Hour Holo" opens on the corner in Harvard Square, and I can talk of the old days when holography was not automated, and we made holograms by hand, from start to finish!

But more seriously, I'm waiting for the day when holographers do not have to expose themselves (and the environment) to toxic chemicals in order to work their art. In the interest of promoting good contamination prevention habits, I have included as an appendix a paper [CREN85] describing the health hazards of chemicals most often used in holography processing.
Art holographer Melissa Crenshaw has kindly allowed the following paper to be included as an appendix to this thesis. I hope that holographers will take the time to familiarize themselves with this important information her paper presents.
Hazards of the processing materials used for holography

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Abstract

Commonly used chemicals for processing holograms pose specific health hazards when contamination occurs. It is advisable that holographers educate themselves, employees, and students regarding ways to avoid contamination, and as to the dangerous properties inherent in these processing materials.

Introduction

Educating oneself and informing other practitioners is the first step in providing a healthy, safe atmosphere to work in. A few simple guidelines are recommended to help ensure the safety of those who work directly with processing chemistry. Included is a list of commonly used holography processing chemicals, their potential hazards, as well as precautions for their use. This information should be posted in or near each processing darkroom.

Protection

A combination of good housekeeping, personal hygiene, physical barriers, and proper ventilation will provide adequate protection for most chemicals used in holography.

Personal hygiene and good housekeeping

At the minimum hands should be washed well with soap and hot water before leaving the processing area. Contamination is often re-contamination. Clean work clothes are essential as dust is easily carried from one location to another on clothing. Lab coats are helpful if processing area work clothes can not be left at the lab. Facilities should be swept with an industrial strength cleaner on a regular basis. All work surfaces should be wet wiped frequently. Scales and other measuring devices should be cleaned after each use.

Physical barriers

Chemical supply companies can direct you to a respirator supply company in your area. After reviewing the various types of problems; dust, vapors, fumes, and splashes a suitable respirator will have a full face shield that fits snug to the face, will cover the nose and mouth, and contains dual chemical-mechanical filters. These dual filter types will cost between $150-200 (US).

Ventilation

Exhaust systems. Air flows from one location to another when there is a difference in air pressure between the two points. An exhaust system provides this pressure difference. The path that the fresh air follows as it flows from the entrance point out through the exit point is an important consideration. A basic rule is that the air should enter over or around the chemicals, and then exit out and away from the processing area.

Fume Hoods. These vary in depth and shape according to your needs and the types of materials used. A fume hood is basically a barrier that has a self contained ventilation system, affords freedom of movement and an unobstructed view.

Miscellaneous

All labs with flammable materials should provide a fire extinguisher and fire alarm system. Consult proper local authorities for information regarding the storage of flammable materials.

Eye wash stations should be provided for each processing darkroom. Even a simple extension hose that will reach the face will provide backup protection in case of a splash up to the eyes.
Processing chemicals

The following chemicals are among those found in some of the most popular processing formulas used for processing holograms. In addition there is information regarding index matching fluids and alcohols which are often used for drying developed holograms. The chemicals are listed alphabetically.

AMMONIUM BICHROMATE (DICHROMATE) (NH₄)₂Cr₂O₇. SYMPTOMS: Chrome ulcers and sores of the skin are common as well as perforation of the nasal septum. May lead to kidney damage. PROTECTION: Rubber apron, rubber gloves, respirator, ventilation.

BROMINE Br₂. SYMPTOMS: Irritating to mucous membranes of the eye and upper respiratory tract. May result in pulmonary edema (fluid in the lungs). Chronic exposure lead to symptoms of depression, psychosis and mental deterioration. PROTECTION: Rubber gloves, rubber apron, full face shield respirator, ventilation. WARNING: Highly dangerous when heated. Emits highly toxic fumes and will react with water to produce toxic fumes.

FERRIC NITRATE Fe(NO₃)₃. SYMPTOMS: Moderate irritation upon skin contact. PROTECTION: Rubber gloves, rubber apron, ventilation.

HYDROQUINONE (C₅H₆O₂). SYMPTOMS: Dermatitis can result from direct skin contact. Normal solution use does not present serious hazard. Has been demonstrated to cause death after ingestion of 5 grams. PROTECTION: Rubber gloves, rubber apron, ventilation.

ISOPROPANOL 99%. SYMPTOMS: Eye irritation and blurred vision. Excessive inhalation of vapors can cause nasal and respiratory irritation, dizziness, possible unconsciousness and asphyxiation. Overexposure has been suggested as a cause of kidney damage. PROTECTION: Rubber gloves, rubber apron, full face shield respirator, ventilation. WARNING: Flamable liquid, store in flamable liquids room or cabinet.

MERCURIC CHLORIDE HgCl₂. SYMPTOMS: In slow poisoning dryness of the throat and mouth. Tremors and psychic disturbances are common. Psychic disturbances include memory loss, insomnia, lack of confidence, irritability, and depression. Severe psychosis may occur in severe cases. PROTECTION: Rubber gloves, rubber apron, lab coat, full face shield respirator, ventilation. WARNING: Mercury is a proto-plasmic poison. After absorption it circulates in the blood and is stored in the organs and bones. Non-lysing bleaches which contain mercury will in essence contaminate a plate or film. Such plates should never be given the "lip test" to determine the emulsion side.

METHYL ALCOHOL CH₃OH. SYMPTOMS: Toxic effects are to the nervous system and the optic nerves and retinae. Visual difficulties may clear temporarily only to reoccur later and possibly progress to blindness. Once absorbed it is very slowly eliminated. It is regarded as a cumulative poison. Daily exposure to fumes may result in the accumulation of enough in the body to cause illness. PROTECTION: Rubber gloves, rubber apron, full face shield respirator, ventilation.

NAPHTA (Kerosene) - an index matching fluid. SYMPTOMS: Irritating to the skin. Inhalation of high concentrations can cause headache, drowsiness, and possibly coma. PROTECTION: Rubber apron, rubber gloves, respirator, ventilation. WARNING: Store in a flamable liquids room or cabinet.

P-BENZOQUINONE (QUINONE) PBQ OC₆H₄O. SYMPTOMS: By contact in solid state, solution, or vapors, it may cause severe damage to the skin, possibly causes necrosis (cell death). When eyes come in contact dangerous disturbances of vision (irritation, conjunctivitis, photophobia - abnormal sensitivity to light) result. Can cause damage to all the layers of the cornea resulting in an appreciable loss of vision. PROTECTION: Rubber gloves, rubber apron, full face shield respirator, ventilation, lab coat. WARNING: Damage is so severe from such minimal contact that the standard for regulating workroom concentrations allowable in the air has been as judged by the comfort of personnel involved. If it is noticable, it is dangerous.

POTASSIUM BROMIDE KBr. SYMPTOMS: Irritating to eyes, skin, and mucous membranes and respiratory tract. Highly toxic by inhalation and ingestion. PROTECTION: Rubber gloves, rubber apron, full face shield respirator, ventilation. WARNING: Avoid high temperatures and store in a cool dry place away from combustible, organic, or oxidizable materials.
PYROCAKEHOL (PHENOL) C₆H₅OH. SYMPTOMS: Dermatitis is common. Prolonged exposure to low concentrations of the vapors may result in digestive disturbances, vomiting, difficulty in swallowing, excessive salivation, and nervous disorders (headaches, dizziness, mental disturbances). PROTECTION: Rubber gloves, rubber apron, respirator, ventilation. WARNING: Death has been demonstrated after absorption through the skin. When heated may emit highly toxic fumes.

PYROGALLOL (PYROGALLIC ACID) C₆H₃(OH)₃ SYMPTOMS: Ingestion may cause severe gastrointestinal irritation, renal and hepatic damage, hemolysis (destruction of red blood cells), methemoglobinemia (circulatory collapse). PROTECTION: Rubber gloves, rubber apron, respirator, ventilation. WARNING: Death has been demonstrated to occur from absorption through the skin. When heated may emit toxic fumes.

SODIUM CARBONATE Na₂CO₃ SYMPTOMS: Chronic systemic difficulties unknown. PROTECTION: Rubber gloves, rubber apron, respirator, ventilation.

SODIUM HYDROXIDE NaOH SYMPTOMS: Upper respiratory tract and lung tissue damage may result from inhalation of the dust. Has a corrosive effect on tissues causing deep ulceration. PROTECTION: Rubber gloves, rubber apron, respirator, ventilation.

SODIUM SULFITE Na₂SO₃ SYMPTOMS: In solution under normal conditions may cause irritation to the eyes, nose and throat. PROTECTION: Rubber gloves, rubber apron, respirator, ventilation. WARNING: Has been demonstrated to cause respiratory paralysis when swallowed. Emits toxic fumes.

SULFURIC ACID H₂SO₄ SYMPTOMS: Severe burns and rapid destruction of tissue. Repeated or prolonged inhalation of the mist can cause inflammation of the upper respiratory tract leading to chronic bronchitis. PROTECTION: Rubber gloves, rubber apron, full face shield respirator, ventilation, additional protection from splashes provided by a lab coat. WARNING: Dangerous when heated. Will react with water to produce heat. Never pour water into sulfuric acid, gradually add small amounts of sulfuric acid to your solutions.

TRIETHANOLAMINE (CH₂OHCH₂)₃N SYMPTOMS: Has been demonstrated to produce liver and kidney damage in animals after chronic exposure. PROTECTION: Rubber gloves, rubber apron, ventilation.

XYLENES C₆H₄(CH₃)₂ SYMPTOMS: Irritating to the skin and upper respiratory tract. Vapors in high concentrations are an anesthetic. PROTECTION: Rubber gloves, rubber apron, respirator, ventilation. WARNING: Store in a flammable liquids room or cabinet.

Recommendation

In recent years we have enjoyed an improvement in the diffraction efficiency of holograms. A fair amount of this success is due to improvements in processing chemistry and new formulas. As responsible professionals publishing articles in an emerging field, it is advisable to list warnings for the individual chemicals we are promoting.

Reference sources

Blakiston's Gould Medical Dictionary; Third Edition


U.S. Department of Labor (OSHA) Materials Safety Data Sheets Form #44-R1387

For further information: Consult the following governmental hygiene agencies (USA). Other countries contact the Ministry of Labor and Health Departments

U.S. Public Health Services, Department of H.E.W., Washington, 25 D.C.
BIBLIOGRAPHY


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