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| <b>(54) Title:</b> HOLOGRAPHY, PARTICULARLY, EDGE ILLUMINATED HOLOGRAPHY<br><br><b>(57) Abstract</b><br><br><p>A metal halide sensitised medium recording a phase modulated image wherein voids in the medium modulate the image and the medium is substantially free of the metal of the metal halide and metal halide itself and a method of recording a phase modulated image.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |

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TECHNICAL FIELD**HOLOGRAPHY, PARTICULARLY, EDGE ILLUMINATED HOLOGRAPHY**

This invention relates to metal halide phase modulated recording media; a process for developing such recording media; and regenerative and hardening bleaches therefore. Thus, it relates to the recording of holograms.

This invention relates to edge illuminated holograms. More particularly it relates to such holograms utilizing a single pass, grazing incidence, reference beam in the edge illuminated substrate without the use of special index matching fluids or the like between the substrate and the holographic recording medium. The invention also relates to photopolymers containing photopolymerizable monomers having a higher index for use as a recording medium.

This invention relates to holograms and light panels, more particularly it relates to edge-lit and steep reference angle holograms and displays; holograms which are light panels used to illuminate other holograms, displays, and electronically switched pixelated screens, such as those used in computer and television displays (e.g. liquid crystal displays); and to methods of making such holograms and holographic light panels.

BACKGROUND ART

Although silver bromide films can produce finer grain images than that of dichromated gelatin, it has not been possible to produce holograms in silver halide sensitive gelatin of the phase modulated variety that are as good as those that may be made in a dichromated gelatin medium. Unfortunately, the dichromated gelatin does not provide the fine grain images of a silver halide gelatin system recording amplitude modulated images.

Grazing incidence single pass edge illuminated holograms have not been achieved in the prior art without the use of special index matching fluids or layers between the holographic medium and the substrate and the use of such does not lead to great precision in the holograms provided thereby.

Although invented in the late 1940's by Dennis Gabor (who later received a Nobel Prize for his invention), holography has been slow to gain widespread public acceptance. The invention of the laser in the early 1960's touched off an explosion of holographic research throughout the decade. Display holography was made possible by the invention of the laser-viewable, off-axis transmission hologram by Leith and Upatnieks, and the development simultaneously of the white light viewable reflection hologram by Denisyuk in the Soviet Union. Many companies spent millions of dollars researching holography in the 1960's, but significant improvements did not come fast enough to enable widespread public marketing.

Conductron/McDonnell Douglas set up the first mass production facility. Holograms were included with the World Book Encyclopedia, holograms were given as premiums in cereal boxes, but still the technology was lacking. White light viewable reflection holograms were dark and difficult to see, or one needed a laser to view transmission holograms, which obviously was not found in the common household. This prompted most of the large companies to scale back or cut off their research efforts.

Since then progress in Display Holography has been reasonably steady, with various incremental improvements occurring over the years in optical components, special photosensitive emulsions and their processing chemistries, vibration stability and a growing mastery of techniques by practitioners. With these developments came the breakup of holography into many subcategories. In 1968 Benton developed a technique to restrict the 3D information in the vertical direction, known as vertical parallax, creating a transmission hologram which could be replayed using white light. This was the birth of the "rainbow" hologram. These techniques were then quickly applied to reflection holograms as well.

Since the development of embossing techniques in the early 1970's to mass produce holograms into various plastic substrates, in combination with Benton's rainbow techniques, we have seen a proliferation of low cost, high volume display holograms as security devices on credit cards, as novelty stickers, in books and magazines, and so forth. The widespread attention to this field in the mid 1980's was due in no small part to a cover story on holography in National Geographic written by ImEdge's John Caulfield and read by 25 million people.

Other advances since then such as live portraiture, natural color holograms, holographic stereograms made from movies and computer graphics, computer generated holograms and many other techniques have finally begun to permeate our everyday lives and make the public much more aware of this technology.

There are other media in which holograms are made. The most common is silver halide emulsions made by Kodak, Agfa and Ilford. Kodak was very active in developing new emulsions until the early 1970's when it scaled back research and just kept a few of its emulsions on the market. Agfa has since dominated the field. Ilford very recently made a decision not to make holographic emulsions anymore. Another common medium, most familiarly seen in holographic jewelry, pendants, and the like is dichromated gelatin (DCG). DCG holograms are very bright, and noise-free, but very humidity sensitive. Some processing techniques for silver halide and DCG can be toxic, and require special safety equipment and precautions. DuPont has a new photopolymer which holds great promise for the field. Polaroid also has a proprietary photopolymer, known as DMP-128, and has recently set up a mass production facility to address the display market with DMP-128 holograms.

#### Problems with Public Acceptance

Regardless of the material, serious impediments to mass market acceptance have still remained. There are many reasons for this. These include:

1. **Color** - Display holograms have mostly been monochromatic, and frequently in unattractive or unrealistic colors. More recently pseudocolor techniques have vastly improved, yielding multicolor images. But few full, real color holograms exist in the marketplace.
2. **Appearance** - Many hologram images are grainy in appearance.
3. **Brightness** - Often hologram images are too dark, or too dim to see well.
4. **Contrast** - Holographic media scatter and diffract unwanted light causing background noise which diminishes image contrast.
5. **Cut-off** - Many holographic images, particularly deep ones can only be seen within a small angular range, and beyond that disappears, or "cuts-off".
6. **Lack of Vertical Parallax/Rainbow Effects** - Many people find rainbow holograms, the result of elimination of vertical parallax information disturbing or unattractive and still not color-realistic enough over a wide enough angular viewing range.
7. **Obstruction** - If one wants to view a reflection hologram carefully up close, the viewer's head gets in the way of the reconstruction beam.
8. **Inconvenience of Display** - A special light must be hung and aimed from the ceiling or across the room. Room lights can cause annoying secondary images.

These problems are all being addressed by numerous researchers, and great strides are being made to eliminate these problems. Some are severely constrained by the laws of physics, and require very clever schemes, or technical band-aids to overcome. It will turn out that solving these problems creates new, unanticipated uses for holography. This is a major item of technical leverage we will

explore below. For the moment, however, let us concentrate on improving display holography.

The Primary Problem : Illumination is the Key

Although the above problems are significant, the primary problem leading to lack of mass market acceptance of display holograms has been the difficulty in illuminating them to achieve a suitable attractive image. Holograms require an external light source, and not just any light source, but a point source light, of adequate intensity, in order to properly view the image. These are typically strong incoherent sources with small filaments, lasers, or the sun. In addition, the light source must be located at just the right distance and angle. Holographic images are not viewable at all or look very poor in standard diffuse room light. But, we live in a world with mostly diffuse artificial light sources. This has been a very severe restriction. On the other hand, point-like room lights produce weak but annoying secondary images.

Thus the point-of-purchase and sign markets, for example, have been reticent to embrace holography, since the set-up of appropriate lighting involves special space, viewing and light source location requirements which necessitate more cost and effort than these industries are interested in expending. The same holds true for the home wall picture market, and many others.

Definition of Transmission and Reflection Holograms

As noted above, traditionally Display Holograms have been divided into two major categories: Transmission and Reflection. Display Holograms are made by splitting the beam from a laser, (usually an Argon, Krypton, Helium-Neon or Helium-Cadmium laser) into two beams, using one, the "object beam" to illuminate an object and the other, the "reference beam" travelling directly to the photosensitive medium. Light reflected from the object reaches the photosensitive medium and interferes with the reference beam, to form (depending on the medium) an amplitude and/or phase modulated region within the medium. After appropriate photochemical processing, the image of the object in the finished hologram can be viewed by illuminating it with a reasonable duplicate of the reference beam (called the reconstruction beam).

Without getting into details of the many subcategories of holograms that exist now, in simple terms, a transmission hologram is one where the object beam and the reference beam strike the photosensitive medium from the same side of the medium (Figure 1). When viewing the image, the reconstruction beam is on the opposite side of the hologram from the viewer, thus transmitting the light through the hologram to the viewer. (Figure 2). A reflection hologram is made with the object beam and the reference beam on opposite sides of the photosensitive medium. (Figure 3). The image is viewed with the reconstruction beam on the same side of the hologram as the viewer, thus the light reflects off the hologram to the viewer. (Figure 4).

Over the years, the physics of reflection and transmission holograms have been studied and described in great detail in numerous publications. Many beautiful and exciting transmission and reflection holograms have been made and displayed. Viewers ooh and aah and marvel at the magic of viewing depth from a planar hologram. But people haven't bought them. The market has been disappointingly slow to get off the ground.

#### Edge Illumination

In the late 1960's and early 1970's researchers realized that another possibility existed for creating and reconstructing holograms - rather than having the reference beam enter the hologram from one side or the other, the reference beam can enter from the edge. Nassenstein<sup>1,2</sup>, Bryngdahl<sup>3</sup>, Stetson<sup>4</sup>, Lin<sup>5</sup> and others started exploring this concept. But the display holographers either didn't know about this work, didn't understand it or didn't appreciate it's significance. Standard transmission and reflection holograms are easier to make, and the market was in the early stages of being explored.

As the fiber optic and integrated circuit industries grew in the 1970's, and researchers gained better knowledge of guided waves, edge-lit, or waveguide holograms were proposed for integrated optics systems for holographic memories and other optical data processing and communications purposes (e.g. see Suhara<sup>6</sup> and Miler<sup>7</sup>).

Several years ago Upatnieks<sup>8,9,11</sup> proposed the use of an edge-illuminated hologram to create a compact holographic sight. He coupled a thick cover plate to a photographic plate with index matching fluid. The reference beam was introduced through a polished edge of the cover plate. However, this method was intended for narrow bandwidth or laser illumination, since the wavelength selectivity of this type of hologram is not great enough to permit white light viewing.

Moss<sup>10,11</sup>, working on the problem of holographic head-up displays for automobiles realized that the edge illumination concept provided a compact efficient solution. He sends the reference beam directly into the holographic layer. Reconstruction, as with Upatnieks' system is done with light of the same wavelength as the reference beam. As the wavelength bandwidth of the reconstruction beam increases, the resolution of the image decreases.

The evolution of the developments described above, coupled with the unsuccessful marketing experience for many years of standard reflection and transmission holograms, has led to a great resurgence of interest in edge-illuminated holograms for display purposes. As will be proposed here, we propose not only to investigate making better displays, but also the new concept of holographic illuminators, which will have a major impact on a wide range of industries as a new and better type of light source.

Current Edge Illumination Work, Waveguide Holograms:  
CAULFIELD, PHILLIPS, BENTON

In this section we will present current work being done on edge-illuminated display holograms, and the problems associated with various schemes.

Recently, Prof. H. John Caulfield, Prof. Nicholas Phillips, Prof. Stephen Benton, and others have started exploring various previously described concepts, and have developed new techniques to create holograms that can be illuminated from the edge. It is also known that researchers in the Soviet Union, Japan and other countries are working on edge-lit holographic techniques. Much of the significant ground-laying work in the field has been done by members of the ImEdge Technology, Inc. team. This work along with associated problems and solutions will be described in detail below.

Benton's Work

Prof. Benton<sup>12,13</sup> of MIT Media Labs, has applied an edge-lit technique, similar to that of Upatnieks, with a thick cover plate, to his well known rainbow holographic stereograms. Later experiments used a thinner, plastic cover plate, and a specially made index matching exposure tank, allowing white light to successfully be used for reconstruction.

The Waveguide Hologram

Prof. H. John Caulfield, and his graduate student, Qiang Huang<sup>14</sup>, have applied waveguide techniques to the creation of edge-lit display holograms and holographic illuminators. A waveguide hologram (WGH) consists of three important parts: the input coupler, the waveguide and the holographic emulsion, as shown in Figure 5. Light is conducted from the source into the waveguide by the input coupler, which can be a prism, a grating, or other edge-lighting mechanism. The waveguide used is typically a sheet of transparent material, such as glass or plastic, with two surfaces that are locally parallel and optically polished. In order to achieve waveguiding, or total internal reflection, the index of refraction of the waveguide must be higher than the index of the environment it is immersed in. Light propagates in a zigzag path through the waveguide, confined by total internal reflection from the parallel waveguide surfaces. The holographic photosensitive material placed parallel to the waveguide, in optical contact via index matching fluid. A guided wave similar to the one used for a reference beam is used to reconstruct the holographic image.

Waveguide holograms have many unique properties compared to conventional holography. Several of these include increased image-to-background contrast, multiple and thus more efficient use of the illumination beam, the twin image effect, and the multimode image blurring effect. It has also been shown that employing the WGH method, diffraction efficiency of a hologram can be increased dramatically.

With respect to image contrast, consider the image reconstruction process of a conventional hologram as shown in Figure 6a. When the illuminating beam enters from one side of the emulsion, only a small amount of light energy is diffracted to create an image if the diffraction efficiency of the hologram is not high. The major portion of the incident light may not be diffracted at all. Consequently, the undiffracted light may increase the brightness of the background. As viewers usually judge the brightness of the image of a hologram by contrasting it with the background, many holograms are not impressive because they lack image-to-background brightness contrast. As shown in Figure 6b, the WGH employs an illumination beam which is confined inside the waveguide by total internal reflection. Thus the undiffracted light makes no contribution to the background brightness. Therefore, a bright image with an inefficient hologram can be obtained by simply increasing the power of the illumination beam.

During the image reconstruction process of a conventional hologram or an edge illuminated hologram which does not utilize controlled multiple bounces, the illumination wave is utilized only once. Multiple utilization of the illumination wave can be achieved by the WGH technique. Consider the WGH illumination process shown in Figure 7. Assume the guided illumination beam is collimated. When it reaches the area where a hologram is placed, the beam encounters region 1 of the hologram first. Part of the light is diffracted as the reconstruction of the image, and the rest of the light is reflected. After the total internal reflection at the other waveguide surface, the residual light illuminates region 2 on the hologram and undergoes the second reconstruction. This process repeats until the illumination beam passes the hologram area. Because of this multiple utilization of the illumination beam, WGHs can reconstruct a holographic image more efficiently.

WGH's have a unique property, which we call the twin image effect, which can be a blessing or a curse depending on the particular product one is designing. In a WGH, two images can be reconstructed simultaneously, one on each side of the holographic recording medium. This effect is caused by the total internal reflection occurring at the hologram surface. Consider a WGH recorded as shown in Figure 8a. The object beam is simply a plane wave which is vertically incident on the holographic emulsion. The reference beam is a guided wave incident obliquely at angle  $\theta$ . The recording of the interference of the two beams yields a WGH grating. Thereafter, as illustrated in Figure 8b, this WGH is illuminated with a guided wave which is identical to the previous reference beam. Because of diffraction, a portion of the light is coupled out of the hologram in the direction of the original object beam and becomes the first reconstructed image beam. The rest of the illuminating wave travels in the original direction until it reaches the emulsion boundary. Because the emulsion has a larger refractive index than the environment, the undiffracted illumination wave suffers total internal reflection and creates a reflected beam. This situation is equivalent to having another illumination beam incident on the

hologram with an angle of  $\pi - \theta$ . Accordingly, a portion of this beam is diffracted and propagates in the opposite direction from the original object wave. This wave is the second reconstructed image beam. If the original object beam is not vertically incident but makes an angle  $\phi$  with respect to the normal of the hologram, the reconstructed twin beams will propagate along the angular directions of  $\phi$  and  $\pi - \phi$ . Usually, the output beam which propagates in the same direction as the original object beam (the first image) is stronger than the other one. The ratio of the intensity of these beams is related to the local diffraction efficiency of the recording material.

During the image reconstruction process of a WGH, there is an effect called multimode blurring, which causes many images to be reconstructed simultaneously, and overlapped to one another. The multimode blurring effect is caused by the angular divergence of the guide illumination beam. As shown in Figure 9, a diverging illumination beam with a circular cross section is coupled into the waveguide. It propagates and illuminates an elliptical area on one of the waveguide surfaces when it encounters the first total internal reflection. The reflected beam then travels toward the outer surface of the waveguide and undergoes its second total internal reflection. After that, the beam illuminates the previous surface again, but with a larger elliptical area. This process continues and distributes a series of illuminated elliptical areas with growing sizes along the propagating direction of the light beam. In the portion of the waveguide surface shown as the shaded area of Figure 9, these illuminated ellipses overlap one another. If a hologram is placed at these overlapping illuminated areas, multiple images are observed because they are reconstructed simultaneously by two or more illumination waves which have slightly different incident angles. These images are spatially overlapped, so the resultant image is degraded. Illumination by a group of light waves with different incident angles is called multimode illumination. Therefore we refer to this process as multimode blurring. It has been shown that multimode blurring can be eliminated by the combination of a proper input coupler and a slit to limit the divergence in one direction and control the extent of the reference beam in the other.

Experimental results have so far proven that the WGH technique is practical for generating 2-D and 3-D images for display, but work is still necessary to improve and optimize the quality of the images. Wavelength selectivity using the above WGH technique has so far not been satisfactory enough to allow for white light illumination of 3-D images, but 2-D images are on the hologram plane, and do not require that the illumination light have high spatial coherence. Therefore good results were obtained for 2-D images (whose uses are noted elsewhere in this document) with white light illumination, such as directly from a light bulb or with a fiber-optic ribbon conducting light from a remote source.

WGH-Practical, But Needs Work

Additional experiments<sup>15</sup> have demonstrated that by utilizing a thick holographic recording layer and a multimode waveguide, or simply the substrate that the recording layer is on, a single, white light reconstructible image can be obtained from a waveguide hologram. However, if the substrate is a multimode waveguide, the spatial coherence is limited, requiring that images be in or close to the hologram plane.

The WGH system, then, has the following advantages:

1. It is compact. The usual alignment necessary for conventional holographic recording and playback systems is not necessary.
2. The optical fiber, laser or incoherent source can be remotely located.
3. The reconstruction beam cannot be blocked, leaving the image obstruction-free.
4. No undiffracted light can enter the viewer's eye to cause either danger (from laser reconstruction) or contrast loss. Use of laser light for reconstruction of products for which monochromatic images are acceptable would allow the public to benefit from crisper, deeper images than are typically obtained with multicolor holograms or even monochromatic holograms made to be reconstructed with white light. The safety factor has prevented laser illuminated holograms from public display in the past.
5. The image can be very bright because of high image-to-background contrast and multiple utilization of the illumination beam.
6. The image can only be reconstructed by the light inside the waveguide. Other light sources cannot affect the quality of the WGH image.
7. The WGH system need not be planar. For example, it can be cylindrically shaped.

Mr. Huang and Prof. Caulfield<sup>16</sup> have also investigated another recording scheme to produce white light illuminated, edge-lit rainbow reflection holograms. Using a two step process, a standard transmission master (H1) hologram is generated using a collimated reference beam. A second hologram (H2) using the edge-lit concept is then recorded, where the object beam is the projected pseudoscopic real image from H1, which is illuminated with the optical phase conjugate beam of the original reference beam. Following Benton's rainbow hologram concepts, a slit aperture is placed in front of the H1 hologram to eliminate the information contained in the vertical parallax. A three-dimensional white light edge-lit reconstructed image was produced with this method.

Prof. Phillips - Another Approach

Prof. Nicholas Phillips<sup>17</sup> has investigated another way of feeding light into the edge-lit or waveguide hologram instead of the input coupling prism described by Prof. Caulfield. Prof. Phillips fed a laser beam through a single mode fiber, used as a spatial filter, then split the beam into object and reference beams. The reference

beam was fed into cylindrical expansion and collimating lenses. The cylindrically collimated laser beam was then introduced into the polished edge of a substrate onto which photosensitive material was coated. (Figure 10). Care was taken to avoid non-uniformity and unwanted divergence of the reference beam so that the reference beam created a collimated sheet of light passing through the substrate. The object beam was sent in normal to the recording medium. Results were evaluated using Dupont photopolymer and Ilford silver halide material. An interesting and unexpected result was achieved with the DuPont material. By careful alignment, the system could be set up so that the fluorescence in the recording layer became extremely uniform. In this case, it is proposed, that the reference beam was not bounced around inside the recording layer substrate structure, but rather continuously fed the recording layer from a travelling wave "diffractive feed" system. This concept may form the basis for eliminating the problem of lack of illumination uniformity (known as illumination depletion) present in the WGH scheme where the illumination beam is progressively more depleted as it bounces through the waveguide, resulting in a gradient in the brightness of the reconstructed image.

One important problem common to silver halide holographic recording materials is that they shrink after processing. Tanning developers can prevent that, but add an absorptive stain which reduces efficiency, particularly with transmission holograms. The shrinkage changes the slant of the fringes inside the hologram which then changes the acceptable input angle for the reconstruction beam. This angle can put the hologram out of the edge-lit regime. This phenomenon must be well understood and controlled in order to successfully use silver halide materials for edge-lit products.

Since edge-lit holograms rely on a fringe slant which is different from conventional reflection and transmission holograms, the dispersion of the image on reconstruction is not subject to familiar rules. Optimization of edge-lit images may require some bandwidth reduction of the reconstructing light or a concept such as the use of single parallax master images.

This work on the various edge-lit recording methods means that holograms can now be displayed in a compact, self-contained format, where the illuminating light source can be hidden within a frame or otherwise mounted to the hologram. Combining the new edge-lit concept with new advances being made, both in the West and the Soviet Union, in holographic materials and processing techniques, as well as improved methods of achieving realistic, full color images, provides a major new impetus toward the mass marketing of display holograms...

### 1. Commercial Images and Displays

The world is poised to experience an explosion in the use of holograms for both industrial and consumer products. As holograms become more common, as they have on the credit cards that millions of Americans carry in their pockets, as well as magazine and comic book covers, baseball cards and cereal boxes, the public expects to see technological marvels such as the holographic projection of Princess Lea's message we all loved in "Star Wars" become available. This dream may yet be a little too far from current reality, but as holographic images become more widespread much residual resistance to the current state of the art will diminish. This resistance, to a large degree, can be traced to burdensome illumination requirements. The necessity of a hard (point) source of light kept at a specific angle and distance from the image is a formidable obstacle to holography achieving the pervasive or even dominant role it should achieve in display images. In spite of the proliferation of embossed holograms which can be viewed in "room" light, the real "quality" images with true depth and sharp detail still cannot be viewed without special lighting. The edge lit principle of being able to illuminate one of these holograms with an incorporated light source overcomes this major obstacle.

The first half of this discussion of edge-illumination, then, centers on the economic benefits of holography as a display medium. The thesis is that holography will become a pervasive display medium when reconstruction illumination is simplified.

#### Magical Medium

The special nature of a hologram that differentiates it from other imaging media is that the image is "reconstructed" rather than simply illuminated. The very nature of edge illumination truly adds another dimension to the benefits of holography. By reconstructing an image of an externally illuminated hologram with any light source, we also must necessarily illuminate whatever is in the

vicinity as well. Likewise, holograms whose images are meant to be reconstructed by using external light sources have an image which will be adversely affected by "stray" light from other sources which happens to fall on this hologram. In contrast, an edge illuminated hologram can have the unique and wonderful characteristic that it will not be affected by any light source other than the edge illumination. Its image is virtually non-existent unless and until the reconstruction illuminator at its edge is turned on. The nearest analogy may be the nature of backlit display transparencies, which, when properly set up, can compete favorably with extraneous light. They can be also made to appear black when their illumination is turned off. Although this can be an effective display technique, it pales in comparison to the fact that when an edge lit hologram's reconstruction illumination is turned off, you can see through it as if it were clear glass. This "magical" quality can do more than make it the most impressive display medium. It can make these holograms useful in totally new and unusual ways.

This new technology we have invented will allow us to bring the world of holography into its next stage. The expected growth of the U.S. technology and knowledge base should be exponential. Entire industries will need to adopt this technology in ways that we can only begin to predict or imagine. Much as photography has become the dominant medium in the print segment of our visual society which needs to capture the visual realities of our world, so holography is the logical next step. It is the only viable three-dimensional method which can be viewed, anywhere, without the aid of special glasses or other encumbering paraphernalia or computer hookups.

Actually entering the various commercial markets required that we perfect techniques and inventions with respect to:

1. Determining the optimum edge-lit scheme to produce marketable 2D and 3D holograms. This involves understanding the theory, and achieving experimental success with a given scheme.
2. Size of the holograms. Size is an essential ingredient of most displays. If we can make 2 foot by 2 foot high quality holograms, this will open up the point of sales market (probably the largest market area we have identified). Billboards and other outdoor signs are usually larger, but we can use arrays of these "small" holograms for them. For prior holograms, size offers no fundamental problems. For our holograms, large size lead to nonuniformity through illumination depletion.

We

compensate for this nonuniformity.

3. Uniformity of the image. (see 2)
4. Efficiency of the image.
5. Image quality.
6. Reconstruction beam type and quality. (see 1)
7. Scatter from the hologram. Scatter is a source of unwanted noise. It is worst in the blue/ultraviolet region of the spectrum. We develop low scatter holography.
8. Illumination means and mechanisms (which may vary with the application). Illumination methods impact many aspects of these waveguide/edge-lit holograms. Some of the key issues are:

- a. Compactness
  - b. Ruggedness
  - c. Image or Beam Quality
  - d. Color or White Light imaging or illumination
  - e. Coupling efficiency
  - f. Cost
  - g. Safety for laser illumination.
9. Determine the optimum recording material.

### HOLOGRAPHIC LIGHT PANELS

Holographic light panels are a new development originally conceived by Professor Caulfield. These panels constitute a new kind of light source, where light enters through or near the edge of the light panel and is then re-emitted in a controlled pattern from the face. These low cost, thin, flat light panels can produce uniform, directed beams of light, which can be white light or laser light, depending on whether the light entering the panel edge is white or laser generated. Furthermore, the panels can be designed to produce a beam or multiple beams which can be narrow, highly directed or wide angle or even fully diffused. Such light sources have numerous applications including: converting standard holograms to edge-lit ones, image projection, flat panel television displays, security and biotechnology applications. They allow significant reduction in the physical volume necessary for illumination of LCD's, transparencies, holograms, and various other objects.

### DISPLAY HOLOGRAPHY

In the past, the striking three dimensional images produced by traditional display holograms could only be seen when the holograms were illuminated either by a distant, precisely positioned, narrow width, bright spot light or by a laser. This constraint has severely limited the markets available for traditional holographic displays. Home and office decorators, point-of-purchase advertisers, and others involved in display industries have consistently shown fascination with the potential of three dimensional holographic displays. However, the inability to view the images under standard room lighting conditions, without setting up special permanent external spot lighting directed to the hologram has prevented the acceptance of holography for these applications.

### Steep Reference Angle Display Holograms

Steep reference angle display holograms have many (though not all) of the applications of edge illumination without the engineering necessary to commercially achieve with the edge-lit approach. Steep reference angle display holograms may be used in movie theater lobbies.

### Edge-Lit Holograms

Advances in edge illumination technology are being pursued at various universities and government sponsored facilities.

Nevertheless, even if this or some of the other industrial or academic technology is made available for commercial exploitation, we are confident that we have the advantage of a broader perspective coupled with superior independent technology. As one typical example, we do not know of any other group which has appreciated the potential power of edge-lit technology as the basis for the holographic light panel.

One of the major applications of an edge-lit holographic light panel is back-lighting of liquid crystal displays (LCDs), particularly for notebook computers.

The requirements are most stringent for back-lighting the LCDs used in notebook computers. These requirements affect the size, weight and battery life of the notebook computer and in turn its competitive position in the marketplace. The requirements for a competitive LCD back-lighting system are:

1. Produce even illumination fully covering the user's entire comfortable field of view with no reduction in display clarity caused by the illuminator and its optics.

2. Have minimum bulk and weight to make the notebook computer as thin and light as possible.

3. Produce the required display brightness with minimum battery power in order to increase battery life. Short battery life is one of the greatest complaints from users of notebook computers.

There are several non-holographic competitors for LCD back-lighting that attempt to meet all these requirements.

Many manufacturers of LCDs and notebook computers which use LCDs have expended engineering efforts to meet the requirements listed above. Notable among these is COMPAQ Computer Corporation, with two issued back-lighting optics patents assigned to it. These optics use a series of horizontal steps to achieve the required illumination coverage. However, these horizontal steps interact with the line structure of the LCD producing an undesirable moire effect in the display.

3M has developed plastic sheeting that is designed as a general purpose optical element to produce a sheet of illumination similar to that of the COMPAQ Computer Corporation patented optics. The 3M product comes in two forms: a reflective form named RAF (right angle film) and a transmissive form named TRAF (transmissive right angle film). Both of these are made with very fine grooves which, like the step structure patented by COMPAQ, interact with the line structure of the LCD producing the same sort of undesirable moire effect.

In both of these products, the undesirable effect of moire pattern in the display is reduced by adding a diffusing element to the optics. This increases the bulk and weight of the package and reduces the display brightness through the reduction in optical efficiency.

One of the many advantages of our holographic light panel is that, unlike the above products, it has no inherent structure to produce moire effects in the LCD display.

Thus, it does not require the added weight and bulk of a diffuser.

A basic inherent advantage of the holographic technology is that the physics of holograms causes the light to be redirected in a highly efficient manner, in contrast with competitive systems which inefficiently direct light by means of scattering it and/or diffusing it.

OBJECTS OF THE INVENTION

Among the objects of the invention are:

to provide true one pass edge illuminated holograms;

to provide improved steep reference angle holograms;

to provide holographic illuminators;

to provide such illuminators that direct the light emanating therefrom as desired;

to provide such illuminators that are true one pass edge illuminated and steep angle illuminated;

to provide such illuminators that provide pixelated illumination in mono chrome and in three primary colors;

to provide a holographically illuminated liquid crystal display; and

to provide apparatus and methods of making and achieving the foregoing.

. Other objects of the invention will in part be obvious and will in part appear hereinafter. The invention accordingly comprises the features of construction, elements, arrangements of parts; articles of manufacture comprising features and properties and relations of elements; and methods comprising the several steps and the relation of one or more of said stages with respect to each of the others - all of which will be exemplified in the construction, articles, and methods herein described.

The scope of the invention will be indicated in the claims.

## FURTHER APPLICATIONS OF THE HOLOGRAPHIC LIGHT PANEL

Beyond providing back-lighting for LCD's, other applications of the holographic light panel include medical, diagnostic and laboratory tools, all of which would be improved by this unique ability to pump light into areas that are extremely close to the source of the light without having any interference in viewing or photographing the area. The holographic light panel also can easily be configured to place the heat generating source of the input light remotely, resulting in a completely "cold" illumination source.

Photo studio and dark room procedures could be revolutionized by the holographic light panel:

The simplest applications here are for displaying photographic transparencies. Every user of and worker in photography, from the photographer himself to the advertising agency, to the printer, to the ultimate client use light boxes. These boxes are big and bulky, and command a significant price along with their significant claim to work-top real estate. A compact light box that is only one quarter inch thick should take-by-storm the photographic industry which prizes sleek high-tech appearance and light weight compactness. In fact, photographers and their sales representatives have long sought a truly portable unit which can accommodate large format transparencies (8 X 10 in.) and still be stored in their sleek custom tailored portfolios. Similar reductions in size, weight and power can be obtained for all types of projectors: slide, movie and overhead.

Holographic light panels can also be used to provide similar advantages in darkroom light sources particularly for photographic enlargers by reducing the enlarger bulk and the heat that is generated by current light sources. They will also simplify the enlarger by allowing a change from a condenser enlarger to a diffusion source with modular switching between holographic heads.

One of the bulkiest pieces of a "location" photographer's travel baggage contains the light "heads" and reflectors. The reflectors, by their nature must be large parabolas requiring bulky shipping cases. A holographic light panel can accomplish the same task with a small fraction of the depth necessary. The holographic light panel can generate light in almost any desired shape. With the holographic light panel, it is possible to view or even shoot through the light source. It is important to remember that the holographic light panel will be transparent from the "back". When looking through or photographing through it, the holographic light panel acts as if the light is coming right from the viewer's eye.

Another photographic advantage: one of the most flattering ways to light a model's face is to surround it with even lighting from all directions. This eliminates shadows that accentuate wrinkles or folds in the skin and "washes out" pores, blemishes and other imperfections. At present, the methods used are not only very awkward and time consuming to set up but they either create some shadow from the photographer or make it difficult for him/her to move about. The perfect solution is a large holographic light panel

which eliminates all shadows, yet give the photographer freedom of movement. It would also reduce the heat generated in the photo studio, which creates a major problem today in keeping models from profusely perspiring or melting. In the photographing of food displays or any other product that is heat sensitive, the advantages of reduced heat from the illuminator are self evident.

We have found ready interest from manufacturers of light boxes and lighting equipment to license this technology for next generation illuminators.

Photography is not the only non-computer application that can use efficient illuminators to project light along the line of sight without obstructing it. Other possibilities include:

- \* Microscope Illuminators - allowing for precise lighting to be applied from close proximity
- \* Law Enforcement - Finger illumination for optical fingerprint reading. Equipment can easily be carried in a patrol car. (We are already in negotiation to develop this.)
- \* Doctor/Dental/Surgery lights - a precise lighting instrument with line-of-sight projection for small orifices and cavities
- \* Display case lighting without the source being visible (for jewelry, stores, museums, etc.)
- \* Illuminating protective glass covering for works of art in a museum or gallery.
- \* Compact biosensing and immunochemistry instruments. In this application, the light is reflected (or scattered, fluoresced, etc.) from the object being examined, passes through the hologram with no distortion or loss of information to a detector viewing the object through the panel illuminator.

DISCLOSURE OF THE INVENTION

Method and Apparatus for Recording Holograms  
and Light Panels Using Effervescent Wave  
Caused Index Matching

I have discovered that by utilizing a photopolymer comprising a photopolymerizable monomer having a higher index of refraction than the polymer component as the recording medium on a substrate having an index of refraction slightly greater than that of the recording medium, such grazing incidence, one pass, reference beam edge illuminated holograms may be produced since the evanescent wave formed in the recording medium during the recording process will polymerize the photopolymerizable monomer in the evanescent layer and then cause the migration of additional monomer to the evanescent layer which causes that layer to increase in index of refraction by as much as .01 to .07.

During the recording process, you can see that the evanescent layer glow due to the fluorescence of the material and after a certain length of exposure time, the hologram will bloom as the index at the interface in the photopolymer rises to match that of the substrate.

I use exposure times of a few tens of seconds, usually about half a minute or so. The photopolymer obtained from DuPont's Optical Element Venture Group has a bulk index of approximately 1.5 and I have used substrates of silica, acrylic, BK7 and BK10 glasses successfully. The index change achievable in the photopolymer can be made to range from about .01 to about .07. Thus the difference in index of refraction of the recording medium and the substrate can vary by this amount.

BEST MODE FOR CARRYING OUT THE INVENTION

Method and Apparatus for Recording Holograms  
and Light Panels Using Effervescent Wave  
Caused Index Matching

Holograms in the edge-illuminated geometry - new materials developments

## ABSTRACT

Some rigorous statements are made about the recording of holograms in the true edge-illuminated geometry. An essential asymmetry is outlined between the role of the substrate refractive index and that of the recording medium. Laboratory observations indicate that unique possibilities exist for recording in this regime using the photopolymers of Du Pont. Unlike any other regime of holography, numerous optical criteria have to be met simultaneously. We believe that self-induced index matching between the recording polymer layer and the substrate on which it is mounted is the key to a workable recording system.

## 1. INTRODUCTION

In recording holograms in the edge-illuminated geometry, the assumption that the usual constraints apply is misleading. In fact the geometry is very restrictive as we shall see below. An edge illuminated hologram is perforce one in which compactness is the prime target of the exercise but although this is very laudable it is the cause of major restrictions on the properties of the recording materials used. A recent paper by Upmicks<sup>1</sup> gives a concise and educated view of the problem.

We shall enlarge on the remarks of that paper in what follows and examine the materials requirements that are demanded by the regime. The relationship between the refractive indices of the recording material and its substrate is the most important aspect of the work. This is outlined in the discussion. In practice, the matching requirements of these indices is normally very tight and either impractical or impossible to achieve in a simple non-fussy manner.

In this paper, we report laboratory observations that indicate novel regimes of recording that are enabled by the unusual properties of the new range of Du Pont imaging polymers.

We first examine the geometry and consider the case in which the indices of the recording material and its substrate are in the relationships  $n_m/n_s > 1$  and  $n_m/n_s < 1$  where  $n_m$  is the index of the recording medium and  $n_s$  is the index of the substrate. These two cases are importantly and subtly different; neither looks favourable to the recording process at first sight. We begin the paper by a detailed consideration of geometry and then report some interesting observations in the laboratory.

## 2. CONSIDERATIONS OF GEOMETRY

Since the overriding importance in the recording apparatus relates to the substrate geometry, we show a view of the substrate and its input reference in Figure 1.

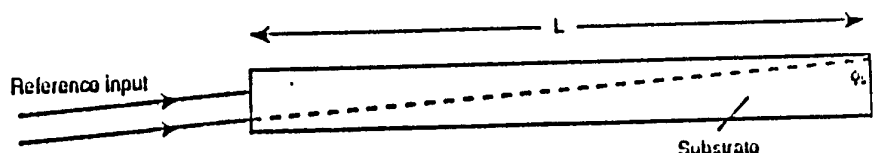


Figure 1 — Showing the substrate geometry and the minimal angle of attack of a reference beam launched from the edge of the hologram into the substrate, given by  $\tan \phi_s = L/t$

The apparatus that we have used is shown in Figure 2. Beam shapes and cleanliness are adhered to with maximum rigour.

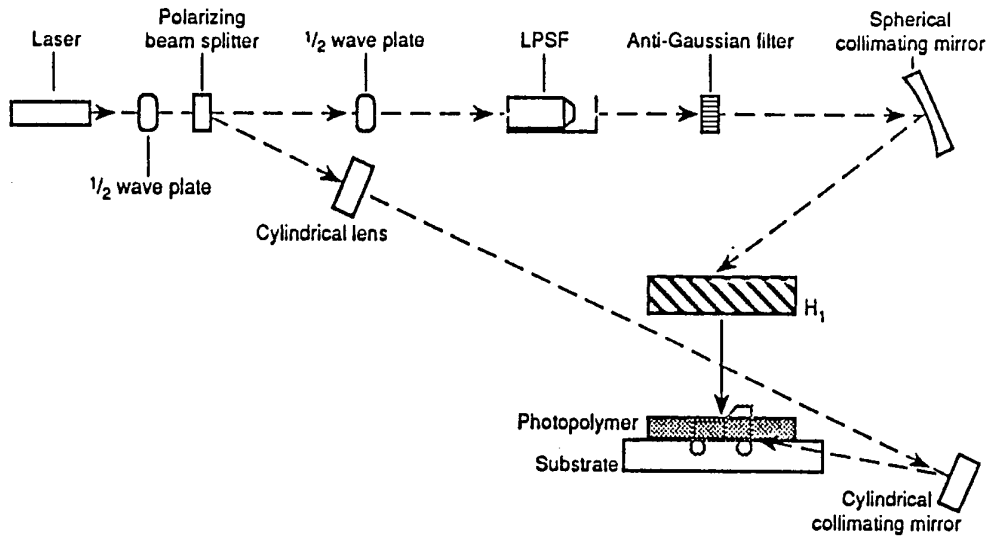


Figure 2 — The recording set-up for the edge-lit hologram. The object beam is used to illuminate  $H_1$ , with the half wave plate used to match the signal polarization with the final reference beam. The reference beam is expanded vertically through a cylindrical lens and is coupled into the photopolymer at a typical angle of  $88^\circ$

It is obvious that considerable restriction is imposed on the angle of attack of the incoming reference on the interface between the substrate and the recording material. We see that the angle  $\phi_s$  is of the order of that given by the relationship

$$\tan \phi_s = \frac{L}{t} \quad (2.1)$$

where  $L$  is the length of the substrate and  $t$  its thickness.

The amplitude of light transmitted at the interface between the substrate and overcoated recording layer is given by the relationship

$$\frac{A_t}{A_i} = \frac{2 \sin \phi_m \cos \phi_s}{\sin(\phi_m + \phi_s)} \quad (2.2)$$

where  $\phi_s$  and  $\phi_m$  are the angles with respect to the normal to the interface in the substrate and medium respectively. To this equation, we add Snell's Law.

$$n_m \sin \phi_m = n_s \sin \phi_s \quad (2.3)$$

where  $n_m$  and  $n_s$  are defined above.

First, we consider the case  $n_m > n_s$  so that the ray diagram looks like that in Figure 3.

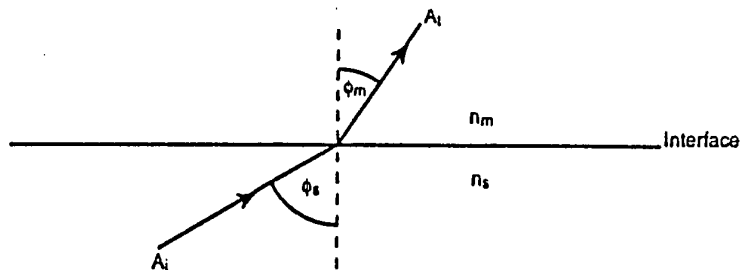


Figure 3 — Interfacial refraction geometry for the case  $n_m > n_s$

Returning to equation (2.2), it can be expressed in the form

$$\frac{A_t}{A_i} = \frac{\left(\frac{2n_s}{n_m}\right)}{\sqrt{1 + \frac{2\Delta n}{n_s} \tan^2 \phi_s + \frac{n_s}{n_m}}} \quad (2.4)$$

Where we have written  $n_m = n_s + \Delta n$  and  $\Delta n$  is regarded as small enough. This expression reveals that unless the criterion

$$2 \frac{\Delta n}{n_s} \tan^2 \phi_s \ll 1$$

holds then as  $\phi_s$  approaches  $\pi/2$  then the transmittance drops to zero. Since we have restricted the values of  $\tan \phi_s$  by the relationship  $\tan \phi_s = L/t$ , we can write the above criterion in the form

$$\Delta n \ll \frac{n_s}{2} \left(\frac{t}{L}\right)^2$$

This sets a stringent demand on index matching in the recording process. Figure 4 shows a set of plots of intensity transmittance against  $n$  for a set of values of  $\phi_s$ .

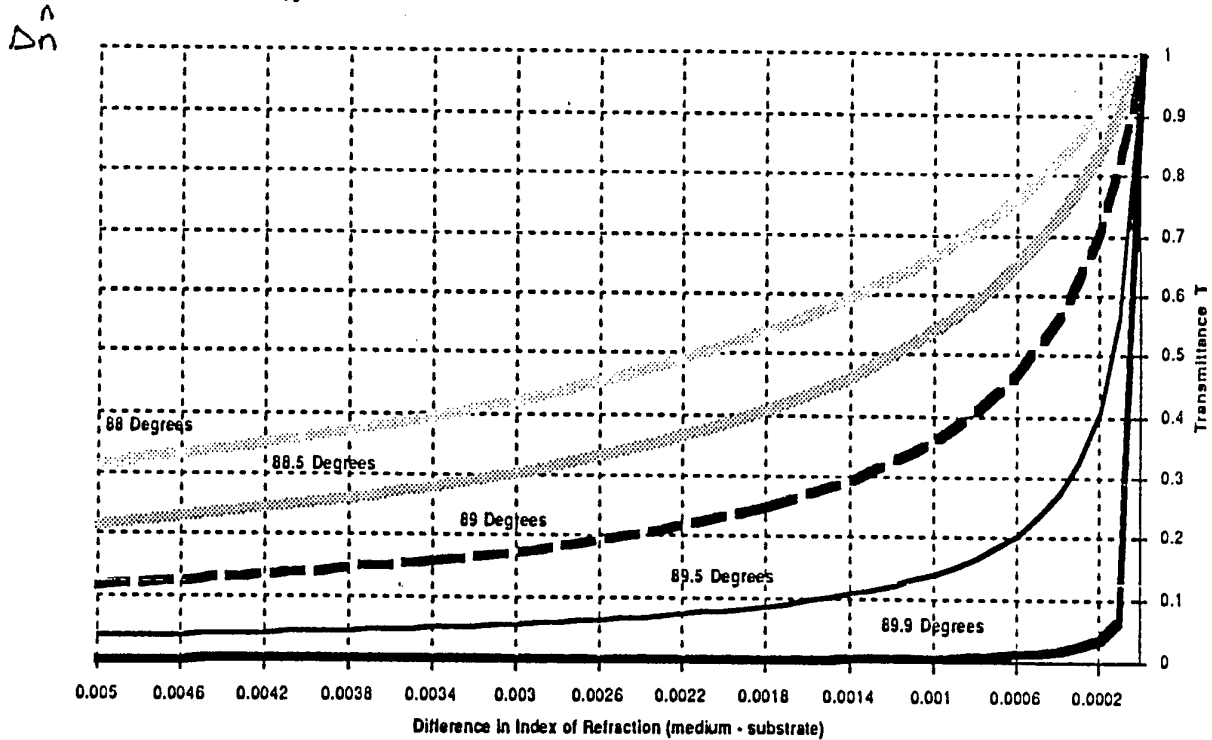


Figure 4 — Transmitted intensity versus refractive index difference for angles approaching grazing incidence

Using Fresnel's relations and Snell's law we can derive the intensity transmittance in the form

$$T = \frac{4 \sin^2 \phi_m \cos^2 \phi_s}{\sin^2(\phi_m + \phi_s)}$$

Figure 4 shows data with  $n_s$  starting at 1.49 and approaching 1.495 with  $n_m = 1.495$  for  $\phi_s$  approaching grazing. Figure 4 illustrates a solution to the problem of coupling a reference beam into the hologram at a steep angle. By choosing the index of the substrate to

be just below that of the recording material, we are able to couple light reasonably efficiently into the film at angles approaching grazing incidence

When the relationship between the indices is such that  $n_m < n_s$ , then the situation is much more subtle. Once the angle of attack  $\phi_s$  exceeds the critical angle ~~geometry~~ given by the relation

$$\sin \phi_s = \frac{n_m}{n_s}, \quad (2.5)$$

then total internal reflection occurs and the light fails to enter conventionally the second medium. Moreover, an evanescent layer is created, Figure 5, just inside the interface in the recording medium. This effect is well known and is the result of a detailed study in the excellent article by Bryngdahl<sup>2</sup>. The penetration depth of the evanescent field depends on the angle of attack  $\phi_s$  and in essence decreases as  $\phi_s$  increases.

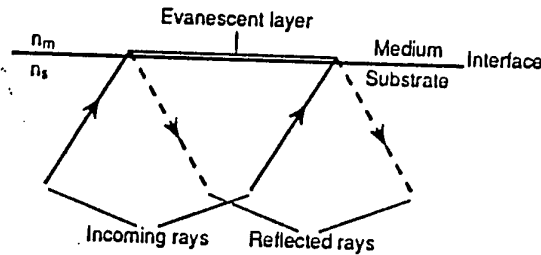


Figure 5 — The creation of an evanescent layer by reflection of light which is incident from the denser medium ( $n_s > n_m$ ). The reflected light is subject to a spatial shift — the GOOS Hänchen shift (see Bryngdahl<sup>2</sup>)

Detailed calculation shows that

$$\lambda_p = \frac{\lambda_a}{(n_s^2 \sin^2 \phi_s - n_m^2)^{\frac{1}{2}}} \quad (2.6)$$

where the evanescent wave amplitude falls off as

$$\exp\left(-\frac{2\pi z}{\lambda_p}\right)$$

$\lambda_p$  is thus a penetration parameter,  $\lambda_a$  is the air wavelength and  $z$  is a coordinate normal to the interface.

Given the considerations above, we can write expression (2.6) in the approximate form

$$\lambda_p = \frac{\lambda_a}{\left\{ (n_m^2 + 2n_m \Delta n) \left[ \frac{L^2}{L^2 + t^2} \right] - n_m^2 \right\}^{\frac{1}{2}}} \quad (2.7)$$

where  $\Delta n = n_s - n_m$

Equation (2.7) is finally written in the form ( $\Delta n \ll n$ )

$$\lambda_p = \frac{\lambda_a \sqrt{t^2 + L^2}}{\sqrt{2n_m \Delta n L^2 - n_m^2 t^2}} \quad (2.8)$$

$$\approx \frac{\lambda_a L}{\sqrt{2n_m \Delta n L^2 - n_m^2 t^2}} \quad (2.9)$$

Now suppose that we let  $\Delta n \rightarrow 0$  from above zero. We can see that penetration is perfect for

$$\Delta n = \frac{n_m t^2}{L^2} \quad (2.10)$$

These discussions above are fundamental to the process of transmission at the interface in the case  $n_s \geq n_m$ .

### 3. CONSIDERATION OF TRANSMISSION OF LIGHT THROUGH A DIELECTRIC LAYER

Here we use the conventional diagram as in Figure 6.

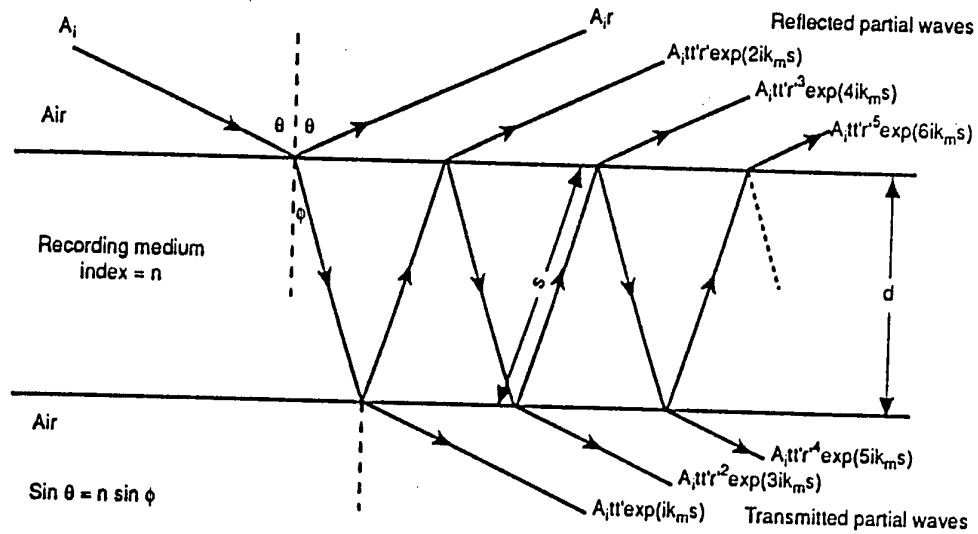


Figure 6—Basic geometry for light reflecting off and transmitting through a layer of dielectric material of thickness  $d$

We deduce the familiar results that the total transmitted amplitude through a layer is given by

$$A_t = \frac{A_i t' \exp(ik_m s)}{1 - r^2 \exp(2ik_m s)} \quad (3.1)$$

Thus yielding the transmitted intensity in the form

$$\frac{I_t}{I_i} = \frac{(1 - r^2)^2}{(1 - r^2)^2 + 4r^2 \sin^2(k_m s)} \quad (3.2)$$

The properties of this equation are well known but are subject to a new importance when the angle of attack  $\theta \rightarrow \pi/2$ . As the light approaches grazing incidence then the angular sensitivity of (3.2) diminishes. This is because

$$s = \frac{d}{\cos \phi} \quad (3.3)$$

$$= \frac{d}{\sqrt{1 - \frac{\sin^2 \theta}{n^2}}} \quad (3.4)$$

where  $n$  is the index of the layer. Evidently, coarse angling of the layer can 'tune' the transmission with relative ease and this effect is observed in the laboratory.

Here  $S \cos \phi = d$  and  $k_m = \frac{2\pi}{\lambda_m}$

where  $\lambda_m$  is the wavelength of light in the medium and as usual  $\lambda_m = \lambda_a/n$  where  $\lambda_a$  is the air wavelength. The transmittances  $t, t'$  and reflectances  $r, r'$  are given by the usual Fresnel relationships.

$$r = \frac{n-1}{n+1}, \quad r' = -r \quad \text{and} \quad tt' = 1 - r^2$$

Paradoxically, the introduction of the partial wave system encouraged by reflection off the second face of the layer in fact enables the transmittance of the layer and avoids the shortcomings of reflectance shown in the single interface calculation. This effect is of course endemic in any etalon situation where two highly reflective metal films can combine to transmit strongly under the right conditions of separation. However, in our edge lit hologram case, failure to suppress the partial reflections will lead to intolerable 'orange peel' cosmetics in the recording.

#### 4. POLARIZATION RESTRICTIONS IN THE RECORDING PROCESS

A major drawback of recording of edge lit holograms lies in the geometrical restrictions imposed on the polarization of the recording light. The problem is illustrated in Figure 7.

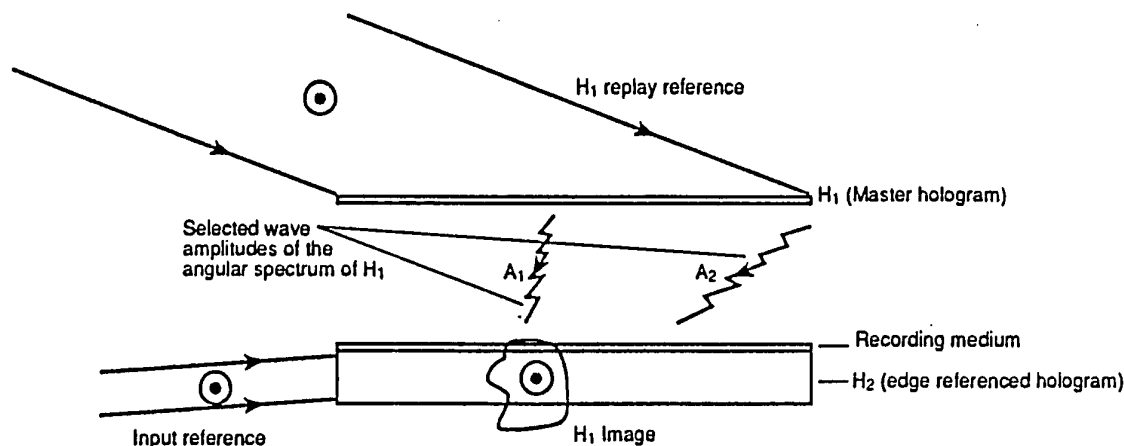


Figure 7 — Polarization is restricted to the s mode regime denoted by  $\odot$ : this can lead to serious orange-peel fringes in  $H_2$  and more importantly, bi-refrident base material for polymer recording will lead to variations of polarization of the angular spectrum of waves from  $H_1$  represented by  $A_1$  and  $A_2$ . This complex issue is difficult to resolve

The polarizations are directed by the symbol  $\odot$  implying an s polarized regime of recording. This is unavoidable since the p mode leads to a true negation of fringe contrast.

Another irritating problem arises if bi-refrident base material is used to back the recording layer eg a halide film on Mylar or Du Pont polymer on Mylar. Such bi-refridence then varies across the angular spectrum from the master thus leading to some strange fringe contrast performance in the  $H_2$  copy hologram.

#### 5. RECORDING MATERIAL DEVELOPMENTS - DU PONT'S PHOTOPOLYMER

This regime of recording is extremely intolerant of material performance. Shrinkage in the recording layer is not permitted without the risk of spurious replay via the large surface of the layer.

The refractive index of silver halide layers is not adjustable and in any case, that medium is at risk of shrinkage and generally poor performance. New methods currently under development by the authors may help to ease this situation however. (Phillips *et al*<sup>3</sup> 1993).

The prime candidate for recording in this regime is undoubtedly the Du Pont family of photopolymers. These are ideal materials due to their low scatter and useful modulation indices. They do however have a serious drawback. Their dissociation from their bi-refrident base Mylar

is difficult and special techniques are necessary to avoid problems from this area as outlined in section 4. They do shrink but the magnitude is unlikely to shift the replay reference geometry from edge to large surface. However, the major expansion of layers permitted by Du Pont's novel monomer transfer process is of course questionable since that ~~was only first~~ the slanting fringes of the regime out of their tolerable direction. Their main and extremely subtle contribution is self-induced index matching, which is discussed in the next section.

## 6. SELF INDUCED INDEX MATCHING — A NOVEL PHENOMENON ASSOCIATED WITH THE DU PONT POLYMERS

We first make the following observation:

The bulk index of the Du Pont materials (measured at the interface) used as an overcoated layer at an interface lit from the substrate side is only likely to increase. This is due to shrinkage after solvent evolution or by the action of light. This remark needs to be well qualified and can be understood with reference to Figure 8.

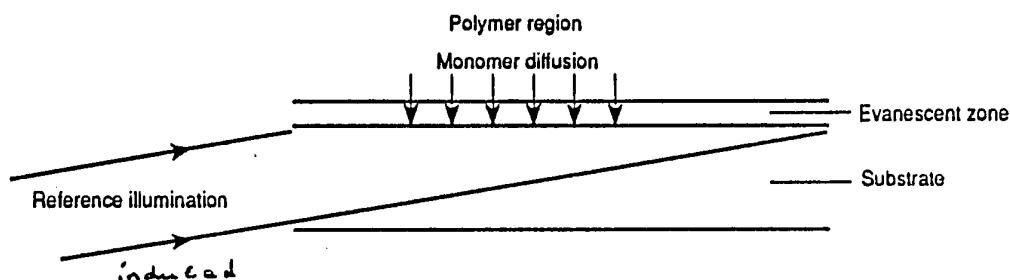


Figure 8— Showing the self index matching phenomenon in Du Pont's self imaging photopolymers. As the reference light generates the evanescent region, monomer is in effect drawn towards it thus enhancing the penetration of the reference beam. All successful simplistic recordings made by ourselves work according to this principle. The effect is observed by noting the increasing fluorescence in light from the sensitizing dye in the photopolymer

The evanescent layer can encourage monomer to diffuse towards it thus increasing the index in the polymer adjacent to the interface. This phenomenon has been observed by us in frequent cases. It is a novel and fascinating effect signified by the progressive increase of fluorescent light from the sensitising dye in the polymer layer. This effect permits a novel and effectively unique approach to local optimisation of light transmittance at the interface.

The observation of this phenomenon is, in our work, an important diagnostic feature and extremely helpful in developing a clear understanding of the overall method.

## 7. CONCLUSIONS

This restrictive geometry is still in the early stages of study. Generally, thin edge-lit holograms are needed and the restrictions are palpably severe. The discussion of optical geometry reveals that the coupling of the reference into the layer is a subtle process which can be helped by self-generated attributes of the photopolymer layers.

Surprisingly, the regime that looks ostensibly unpromising, ie that in which total reflection and evanescence is induced, looks the most interesting and in fact, promising.

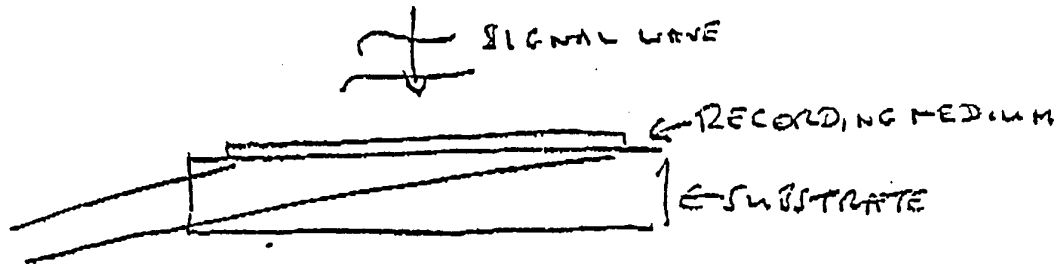
## 8. ACKNOWLEDGEMENTS

The authors especially wish to thank Michael Metz and Carl Flatow of Im Edge Technology Inc for their personal and financial support in part of this work and Mrs Kathy Phillips and colleague Peter Marsh for their efforts in preparation of the manuscript.

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It has been observed that in the formation of edge illuminated holograms, the action of the signal wave can increase the refraction index of the recording layer thus increasing the coupling of the reference wave into the hologram when it is incident at an angle close to grazing incidence.



NB The recording material is chosen to have a refractive index just below that of the substrate.

It is noted that where the signal beam arrives, the hologram is seen to be switched ON in regions of high signal strength thus indicating that the refractive index has increased in that locality thus enabling the penetration of the reference wave by index matching.

We note that enhancement of the refractive index at the interface can be achieved by either reference or signal wave activity. Such enhancement could be achieved by for example by exposing the recording layer to a diffuse page of signal wave on its own prior to exposure to the holographic pattern  $A_B$ .



The bulk index of the recorder layer is thus increased.

THE BULK INDEX INCREASES BECAUSE POLYMER OCCUPIES LESS VOLUME THAN MONOMER.

N.B. WE NOTE THAT SIGNAL WAVE <sup>GATED</sup> ~~HOLOGRAMS~~ HOLOGRAMS CAN HAVE ZERO NOISE BACKGROUND SINCE INTERFERENCE PATTERNS ARE ONLY PRESENT WHERE THE REFERENCE WAVE IS PERMITTED TO LEAK IN.

DISCLOSURE OF THE INVENTION  
Halide Phase Recording Medium, and  
Regenerative Bleach Therefore

I have found that the large values of index modulation observed in dichromated gelatin are probably caused by gelatin hydrolysis in the nodal parts of the image. When collapse of the recording layer is inhibited, void modulation occurs ranging between the refractive indices of gelatin and air. I found that the use of a persulphate is very effective in preventing the collapse of the voids in the gelatin, particularly, Potassium Persulphate and this is one aspect of my invention as this may be applied to both dichromated gelatin and silver halide-sensitized gelatin.

My novel systems for recording phase modulated images in silver halide-sensitized gelatin, involve exposing the film to the desire image; developing the film conventionally; removing the silver filaments formed at the image antinodes by bleaching and hardening the area around the voids by releasing Chromium 3 ions where the metal grains were; then in the first process uniformly exposing the film to sensitized all of the silver halide grains remaining in the film; developing them into silver filaments; and then again removing the silver filaments by a solvent bleach which forms a small void where the silver was and hardening the gelatin adjacent to the voids. The voids formed in the antinode regions of the image, in this second bleaching step, appear to be smaller than those formed in the nodal areas, due to the previous hardening of the gelatin during the first bleach and hardening step. I then amplify all voids using hot or graded propanol drying.

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In a second preferred process, after the first bleaching and hardening step, I merely fix the film using conventional hypo (sodium thiosulphate) or rapid fixer (ammonium thiocyanate) and then amplify the voids using hot or graded propanol drying.

I used Potassium Dichromate to supply the chromium ion through reaction with the silver, Potassium Persulphate for regeneration of the reduced silver oxide, Potassium or Sodium Hydrogen Sulphate, and Distilled Water in my bleaching hardening solutions.

The Ferric Nitrate (or Sulphate) mentioned below in formula SS1 cannot be used as it tends to soften rather than harden the gelatin around the voids in my process for recording phase modulated images in silver halide films. The formula SS2 is preferred in the Repeat (2 development) Method; SS3 in the one step preferred method. Other metals beside silver could be used, such as, platinum, gold, or the like in the metal halide.

Those skilled in the art will note that, ideally, in my repeat method for the formation of phase modulated gelatin which has been activated by silver bromide, the antinodes of the image should underexpose the film so that some silver bromide grains will be left at the exposed antinodes to form voids in the second bleaching step. Furthermore, those skilled in the art will realize that the illumination necessary in the second exposure is uniform in the sense that it activates all remaining silver bromide grains in the gelatin. Any form of illumination which accomplishes this result may be utilized.

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In the preferred one step process, the voids predominate in the antinodal regions and are few, smaller, or absent in the nodal regions. Holograms produced by this process are startlingly good.

In the one step process, I reverse the proportion of Dichromate and acid in the bleaching solution so that the gelatin will harden throughout. This apparently reduces or prevents the formation of voids at the nodal regions when the silver bromide is removed by the fixer.

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DETAILED DESCRIPTION

Halide Phase Recording Medium, and

Regenerative Bleach Therefore

Dichromated gelatin — some heretical comments

## ABSTRACT

This paper looks at some ideas old and new that relate to the formation of images in dichromated gelatin. The traditional view that the dichromated system hardens gelatin thus preventing solubilization of the material must be balanced against other observations such as that of the reduction of the bulk index of the gelatin layer and the appearance of gelatin in the processing solutions. We revisit the problem and take a look at some new chemical ideas that relate to the behaviour of gelatin during solvent bleaching of silver halides. A new method for the processing of silver halide-sensitized gelatin (S.H.G.) is proposed which we call the Repeat Method.

## 1. INTRODUCTION

The subject of dichromated gelatin as a recording medium for holograms has received enormous attention over the years due to the importance of the medium to the manufacture of heads-up displays for military and latterly civilian cockpit applications in aeroplanes and motor vehicles.

Dichromated gelatin (D.C.G.) is a complex structure involving care and consistency with the recording and processing technique in order to exploit its full potential. It is not possible to give a full bibliography of the subject since much important Soviet work has remained buried due to their needs of classification and just general lack of communication. In the West, the important contributions of Shankoff<sup>1</sup> and Chang<sup>2</sup> amongst numerous other workers cover key details of the process. Much interest has of late centred on hybrid techniques in which silver halide layers are converted to pure phase modulated gelatin revisited later on in Figure 4, using subtle process techniques. We should perhaps single out the work of the Spanish group under Fimia<sup>3</sup> in this area of activity which builds on early developments by Chang and co-workers<sup>4</sup>, Graver *et al*<sup>5</sup>, Angell<sup>6</sup> and others. Silver halide gelatin (S.H.G.) essentially combines the high signal to noise possibilities of D.C.G. with the high innate light sensitivity of the silver halide materials. There are however serious penalties to pay when one extracts salts of silver from a gelatin layer, the most important being the collapse of the Bragg structure and the need to find some finishing method of 'propping up' the voided material. Scatter may not indeed be as low as desirable due to the fact that silver halide when removed leaves voids in the gelatin which themselves act as scattering centres.

The purpose of this paper is to provide some food for thought in the background to the process for D.C.G. and S.H.G. We shall look at a number of key laboratory observations based upon the study of the silver halides that pose important and as yet only partially answered questions. We do not offer an entirely new route to the manufacture of D.C.G. at this stage but the way is left clear for a range of detailed studies that may ultimately enable us to replace D.C.G. as such with new chemical formalisms and processes.

What we propose in this paper is that the large values of index modulation observed in D.C.G. are plausibly caused by gelatin hydrolysis in the nodal parts of the image structure. If the collapse of the recording layer can then be reversed or inhibited, void modulation occurs, ranging between the refractive indices of gelatin pure and air.

We structure this paper by first spelling out what are seen as a set of key observations in the laboratory. These are then collated to provide guidance for a further understanding of the D.C.G. and S.H.G. processes.

Whilst there is no disputing the hardening of gelatin by dichromate, we must add to this the observation that dichromate bleaches used in their rehalogenating or solvent form on the silver images can cause layer softening and disruption of the images.

## 2. KEY LABORATORY OBSERVATIONS THAT RELATE TO THE IMAGE FORMING MECHANISM OF D.C.G.

(a) Major solvent bleach agents for silver are capable of disruption of gelatin layers.

Here, we observe that the removal of developed silver by a solvent bleach in order to provide modulation of a hologram can cause the disruption of the gelatin layer.

We specify such solvent bleaches as belonging to the class of constituents shown below; their ionic Redox potentials accompany them.

|                        |                                |
|------------------------|--------------------------------|
| Sodium Dichromate      |                                |
| Potassium Dichromate   | 1.33 Volts — low pH conditions |
| Ammonium Dichromate    |                                |
| Pyridinium Dichromate  |                                |
| Potassium Permanganate | 1.65 Volts — low pH conditions |

The dichromate family and permanganate all exhibit large redox potentials which enable their corrosive ability when attacking silver in a gelatin layer. By comparison, we have an odd man out of low potential:

|                 |            |
|-----------------|------------|
| Cupric Sulphate | 0.16 Volts |
|-----------------|------------|

To this family, we have recently added a new combination:

|                              |            |
|------------------------------|------------|
| Ferric Sulphate (or Nitrate) | 0.77 Volts |
| + Potassium Persulphate      | 2.00 Volts |

This strange combination relies on the intrinsic oxidising power of the Ferric compounds together with the regeneration of the reduced form of these compounds (as a result of attacking silver metal) back to their original Iron III form. Potassium Persulphate itself cannot attack silver strongly despite its large redox potential because of a charge barrier problem that prevents close proximity of the Persulphate ion to the silver site. However, Persulphate can be used to regenerate (or oxidise) other compounds in common solution. Bjelkhagen, Phillips, Wang<sup>7</sup>.

We have compounded a novel silver solvent bleach as follows:

|                              |         |
|------------------------------|---------|
| Ferric Nitrate (or Sulphate) | 30 gm   |
| Potassium Persulphate        | 20 gm   |
| Potassium Hydrogen Sulphate  | 50 gm   |
| Distilled Water              | 1 Litre |

This solution will remove silver from a developed layer. The pH is low due to the acidity of the Potassium (or Sodium) Hydrogen Sulphate. Rates of silver solution can be controlled much more sensibly than with the usually over-rapid dichromates. To obtain a similar rate of silver solution with a typical dichromate and the same acid buffer, we might use just one quarter of a gram of the dichromate. This is not a happy concentration for a properly buffered solution. In fact, the Ferric compounds can be replaced by dichromates in the above list if it be desired to do so. The weights will have to be judged in terms of bleach rate of course.

We have also examined the role of the Kodak etch bleach EB2 compounded as follows:

|                        |        |
|------------------------|--------|
| Part A Copper Sulphate | 120 gm |
| Potassium Bromide      | 7.5 gm |
| Citric Acid            | 150 gm |
| Distilled Water        | 500 ml |

**Part B 3% Hydrogen Peroxide solution**

|                 |        |
|-----------------|--------|
| Distilled Water | 500 ml |
|-----------------|--------|

N.B. The addition of Potassium Bromide effectively enables the Cupric Ion with its low Redox potential of 0.16 volts to attack the silver. Without the Bromide, the action will not proceed.

Equal parts are mixed just prior to use. The rôle of this bleach is traditionally to provide etched bars of gelatin in large scale (e.g. > a few  $\mu\text{m}$  in scale) lithographic images. Typically, such a bleach will destroy layers of high spatial frequency gratings and cause the developed zone to peel off into the processing solution.

It is notable that the Ferric Nitrate-Persulphate bleach mentioned previously tends to exhibit a similar performance to the EB2 in terms of gelatin disruption when Peroxide is added, though it can still be disruptive in the absence of Peroxide.

(b) Acidified dichromate solution tends to increase the granular scatter of bleached silver halide layers.

An often used technique to reduce printout in bleached silver-halide layers is to immerse the bleached layer in acidified dichromate solution. The reduction of printout sensitivity is dubious but a notable effect is an observed increase of grain in the bleached layer. Such ripening implies a detachment of silver halide from its protective colloid (the gelatin) which then permits a form of Ostwald growth.

(c) If a Lippmann layer recorded in silver halide using a solvent bleach, is dried conventionally, it shrinks — moving its reflectance from the red of the HeNe for example, to a green colour. If it is dried in hot or graded Propanol, it emerges a red colour after drying.

This effect is most striking and illustrates the power of Shankoff's method (Smith<sup>8</sup>) by which the bulk of the dried layer is recovered in the drying process. Obviously, such voiding as is generated by the removal of the silver is manifestly demonstrated when rapid drying in hot propanol is invoked. A case history is outlined in Figure 1.

Figure 1 — A possible two cell history of the solvent bleaching of a silver halide layer

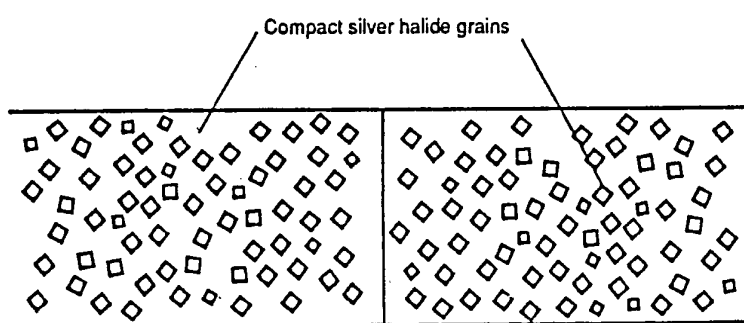


Figure 1.1 — Unexposed material

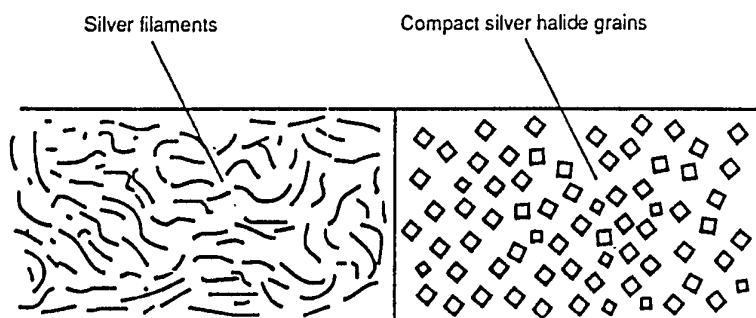


Figure 1.2 — Conditions after the development of the layer

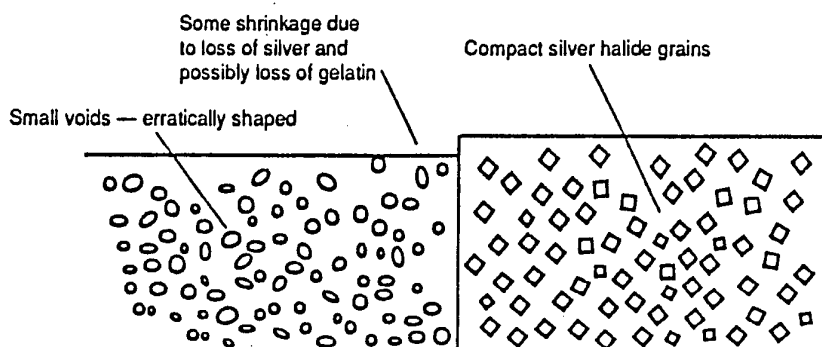


Figure 1.3 — Conditions after the removal of the silver filaments

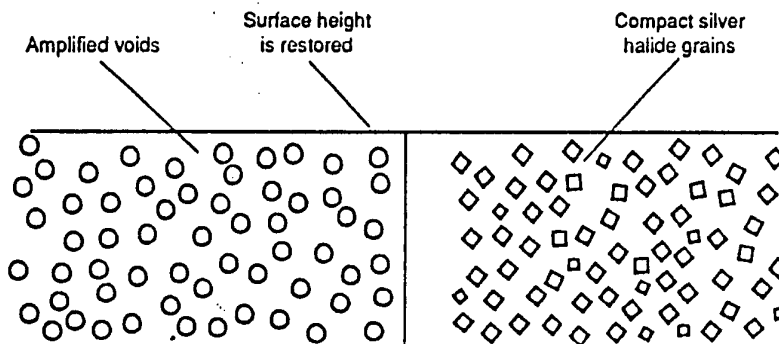


Figure 1.4 — Conditions after hot or graded propanol drying of the solvent bleached layer. Modulation is then determined by air voids and silver halide grains. Scatter can be high because the voids are shaped from the original developed silver filaments

(d) When D.C.G. layers are processed, then a gradual build-up of deposited gelatin is observed in the processing dishes or vessels.

This observation has been confirmed by one of us (RR) over many years of work in the field of D.C.G. processing. One has to ask why does this situation arise — is it relevant to the underlying mechanism in the formation of the D.C.G. image?

(e) The bulk index of processed D.C.G. is in general less than in its preprocessed state.

This observation again confirmed by one of us (RR) but is the subject of much argument between various working groups. It seems extremely unlikely that the mean index of a D.C.G. layer can be in excess of its original unprocessed values. Perhaps we could be more precise and say that the integrated optical path measured orthogonally to a gelatin layer is unlikely to increase as a result of D.C.G. recording and processing. Our firm belief is that it always decreases.

(f) If solvent bleaching of silver halide layers is conducted with ultrasonic agitation then the disruption of the gelatin layer

is considerably greater than when the solvent action takes place without such agitation.

Ultrasonic agitation has been found by us to be an effect way of clearing away the debris of gelatin hydrolysis which occurs when the bleach EB2 or our synthetic bleach Ferric Nitrate (Sulphate) + Potassium Persulphate is used. In traditional crude etch bleaching, the gelatin surface is wiped over to remove the debris with, however, the risk of damage to the layer. Evidently, the loosening of gelatin present when etch bleaches are applied can be effected by either the deliberate addition of Hydrogen Peroxide to the bleach or the exploitation of some other aspect of the chemical formulation to achieve the same end result.

### 3. A COLLATION OF IDEAS BASED ON THE OBSERVATIONS OF SECTION 2

In Section 2, we have observed a set of key phenomena which we believe give some clues as to the true fundamentals of the D.C.G. process. Let us consider a plausible train of events as depicted in Figure 2.

Figure 2 — A plausible two-cell history of dichromated gelatin

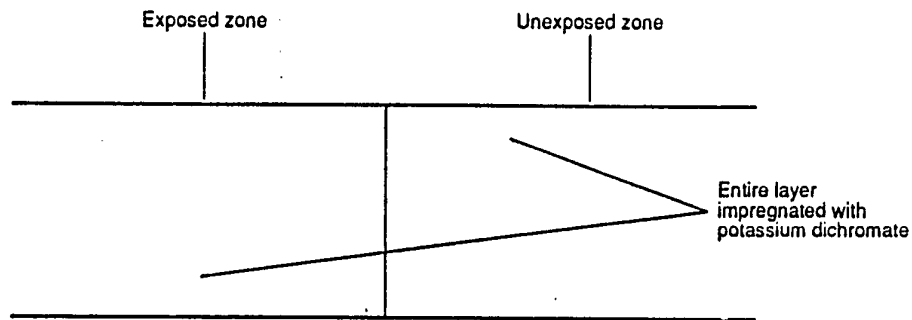


Figure 2.1 — Dichromated gelatin — initial conditions

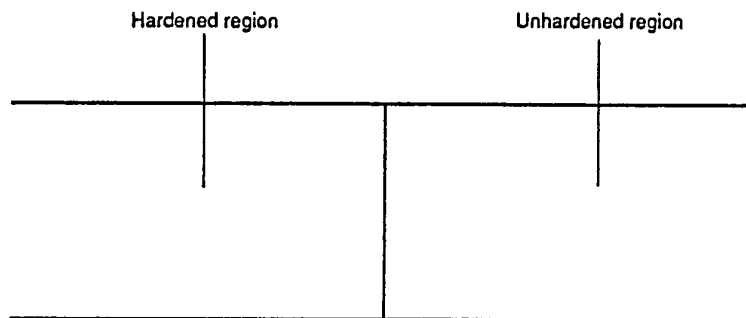


Figure 2.2 — Conditions after exposure to actinic light

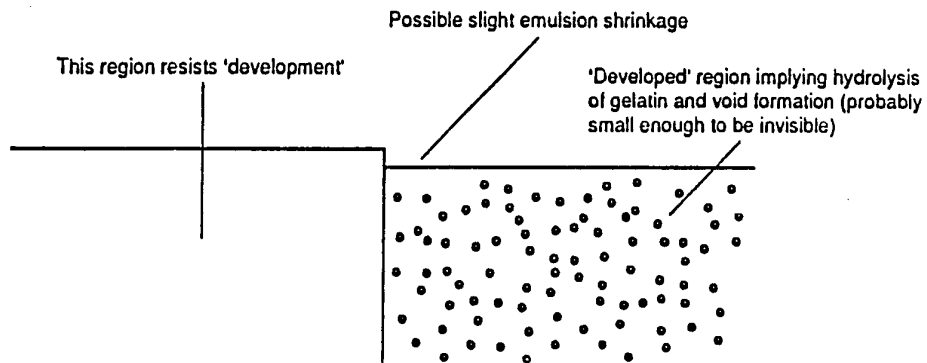


Figure 2.3 Conditions after 'development' — the hardening photographic fixer used increases bulk hardness of the unexposed zone and at the same time removes loosened gelatin. Modulation is amplified by void enlargement. Hardening fixers contain Chrome Alum hardener and a gelatin solvent — Acetic Acid.

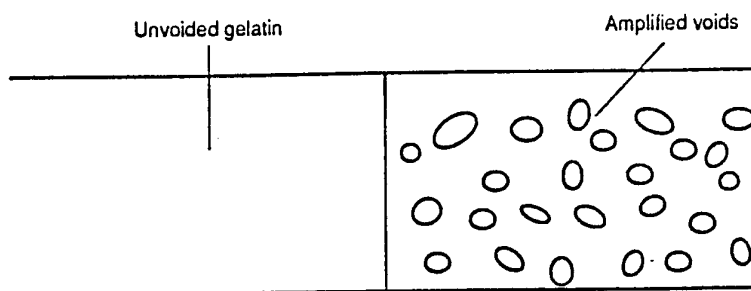


Figure 2.4 — Conditions after hot or graded iso-propanol drying in voids are now amplified, emulsion swells and layer thickness returns

- (i) The dichromated layer is exposed to the holographic light pattern.
- (ii) In the antinodal regions, a photo-induced hardening reaction takes place. We shall clearly not argue against this long accepted and well proven idea. We might, however, take issue with the assumption that photo-reduced dichromate is only responsible for the hardening process for reasons which will become apparent later in this paper.
- (iii) In the nodal regions some softening takes place together with a degree of gelatin hydrolysis which is controlled by 'development' in a hardening fixer. Here 'development' describes a process involving some hardening of the layer and we should remember that some hydrolysis may be encouraged by certain constituents of the fixer.
- (iv) Shankoff's rapid or graded drying process allows the regions of partially hydrolysed gelatin to expand so as to contain amplified air voids.

In sub-section (iii) we see an essential and simplistic ingredient in which the unusually large levels of index modulation are easily explained.

Clearly, the photo hardening reaction is very important in providing resistance to hydrolysis. The hydrolysis itself and its origins will be discussed in detail in the next section.

#### 4. REASONS FOR THE HYDROLYSIS OF GELATIN

If we consider the action of the bleach EB2 then we can see that hydrogen peroxide is added to provoke hydrolysis of the gelatin. It does this by acting on the loose ends of gelatin created when the silver removal breaks the protective colloidal structure of gelatin thus liberating free ends of the protein structures. These loose ended structures are made hydrophylic by the attachment of functional groups which originate from the peroxide in solution. Many other gelatin solvents exist, the most pertinent being Acetic Acid commonly used in fixer buffers.

When gelatin is photo-hardened then neighbouring zones will have loose ends available as can be seen from a binary two zone model shown in Figure 3.

Figure 3 A — comparison of the two chosen models showing the basic difference between D.C.G. and the solventbleached silver halide

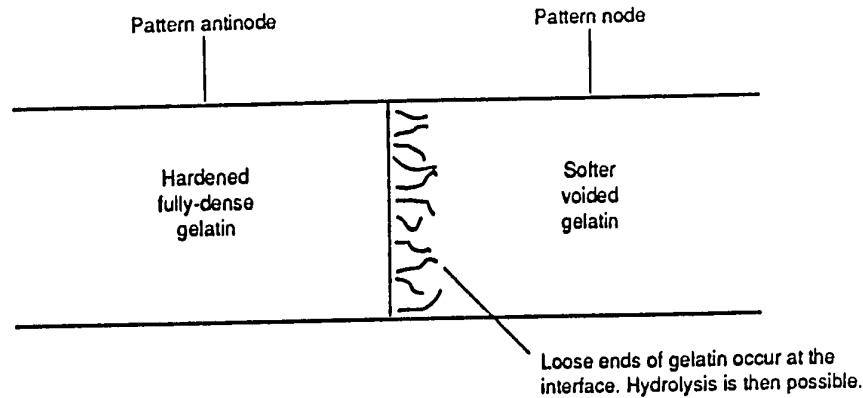


Figure 3.1 — A simplistic view of the final D.C.G. image.  
Note that the higher index material is located at the antinode of the pattern

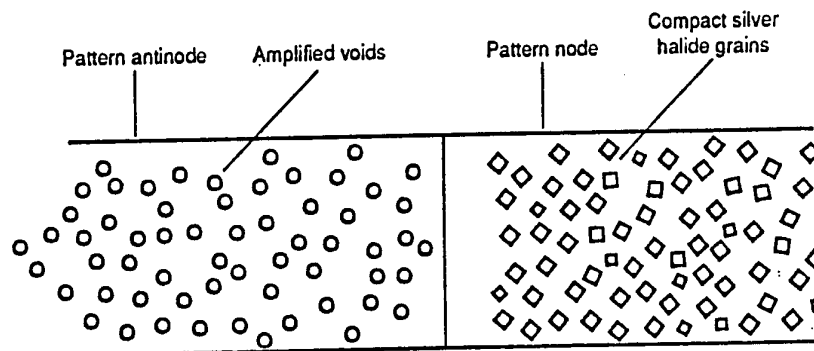


Figure 3.2 — The final result for a solvent bleach silver halide layer dried in hot or graded Iso-propanol.  
The highest bulk index coincides with the pattern node

On the right hand side of the interface then loose ends from strands of gelatin in region 2 cannot be tied up in the hardening reaction present in region 1. Under such conditions, the ends at the boundary of region 2 can be caused to have an affinity to water (hydrolysis by the action of  $H_2O_2$ ). The problem is a little like the Van der Waals forces at the surface of a gas or liquid — an essential anisotropy is introduced.

We note that the observed granulation of silver halide layers mentioned in Section 2(b) is explainable by a degree of hydrolysis caused by an interaction between the gelatin and the bleach solution. It seems likely that any solution containing agents of high enough redox potential is capable of a similar effect. We might expect the hydrolysis of gelatin (as the attached protective colloid of the silver halide layer) to be triggered off by the presence of any suitable agent such as  $H_2O_2$  which can create hydrophylic conditions for loose gelatin strands. In the case of the silver halides, the necessary loosening is created by the solvation of silver grains.

We now interject a completely new chemical process for the phase modulation of gelatin.

This method was invented in the belief that previous studies were somewhat restrictive and to an extent flawed since they failed to provide adequate spatial frequency response of the recording. The inherent advance of this new method lies with avoidance of the use of fixer or excessively rapid solvent bleaches which attack the oxidation products of either developer or bleach. Such questionable solvent bleaches include Permanganate and Ammonium dichromate. The essence of the method is to be extremely gentle with the effects of tanning of the layer thus preserving the structure of voids in the gelatin.

Figure 4 — A case history of the formation of voided or phase modulated gelatin (S.H.G.)  
— a new chemical approach; the Repeat Method

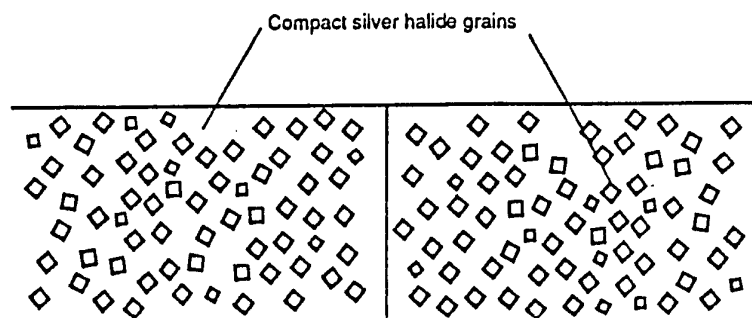


Figure 4.1 — Initial state of two cell layer

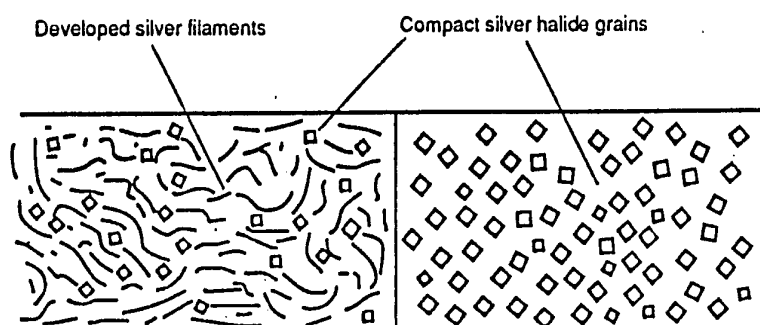


Figure 4.2 — Showing partial development of the left hand cell and consequent creation of silver filaments

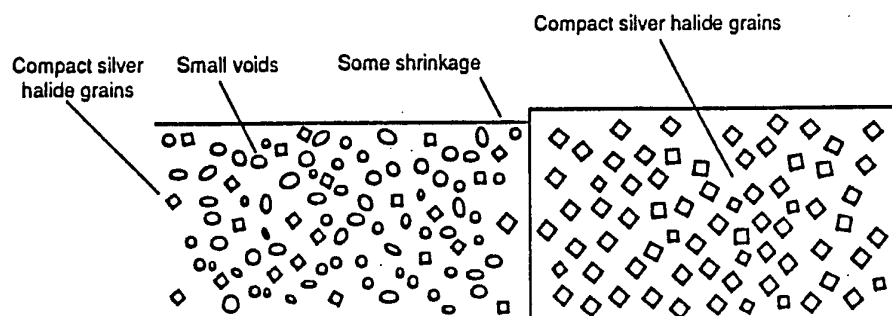


Figure 4.3 — The left hand cell has now lost its silver by the action of a solvent bleach

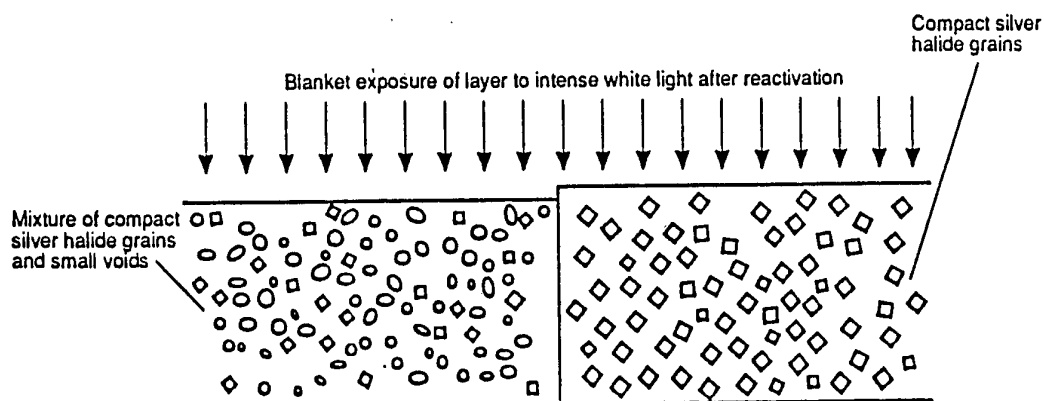


Figure 4.4 — Intense white blanket exposure is used to make all the reactivated grains developable

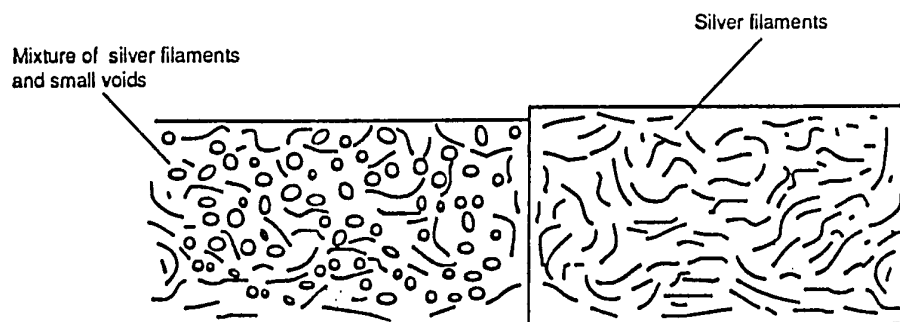


Figure 4.5 — The structure now contains only silver filaments and voids (in the left hand cell) after second development

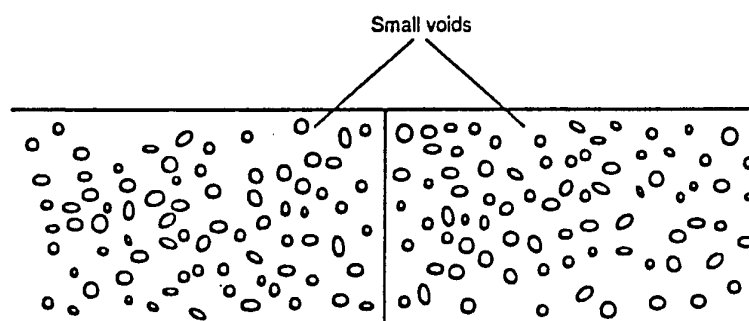


Figure 4.6 — Further application of the solvent bleach leaves small voids in both cells

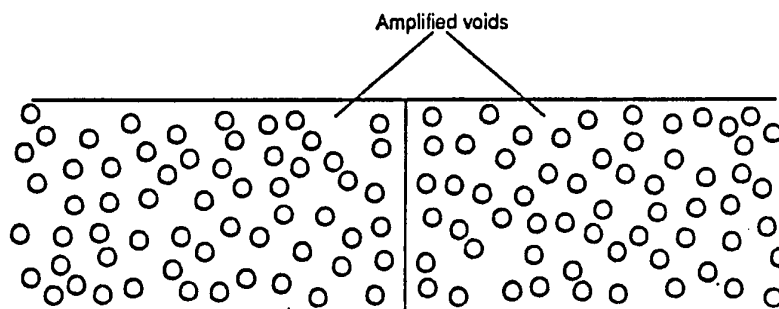


Figure 4.7 — Voids are now amplified using hot or graded Propanol drying

## DISCUSSION

Dichromated gelatin offers a uniquely interesting set of attributes both in its capabilities for high index modulation and in the simplicity of processing. Possibly, the substitution of the dichromate family by other chemical compounds is inhibited by the need for those other compounds to have a similarly potent photo-hardening reaction. For example, the ferric compounds (Nitrate or Sulphate) being brown certainly have a reasonable ability to absorb actinic light or even mid-spectrum green. The general wisdom however is that their photo-hardening ability, though significant, is not the same as that of the dichromate family.

The reader is referred to the book by Kosar<sup>9</sup> (page 39) for a discussion of the role of Ferric and Ferrous compounds on the cross-linking of gelatin. Evidently, the Ferric ion can assist gelation of a gelatin solution though the ion is converted to Ferrous by the action of actinic light. Ferrous ion causes gelatin to soften making it prone to hydrolysis.

This situation allows some fascinating processes such as the True-to-Scale Process in which Ferricyanide from a blue print transfers by contact into a moist gel containing Ferrous ion. The oxidation of the Ferrous ion to Ferric by the ferricyanide then insolubilises the gelatin in that region of contact. Interestingly, the Ferric bleach mentioned by us in this paper contains a regeneration mechanism for the Ferric ion. As the Ferric ion is reduced by oxidation of local silver then the Potassium Persulphate can

regenerate the original Ferric population from the Ferrous population. It is our belief that further studies of the relative proportions of Ferric (Nitrate/Sulphate) and Potassium Persulphate will reveal new methods of manipulation for the silver halide layers discussed earlier. A word of caution is needed however since the Persulphate may itself promote the hydrolysis of gelatin via its reaction with water.

The softening of gelatin by Ferrous ion reveals some interesting properties of the solvent bleach process discussed in this paper. As the silver is removed thus leaving voids in the layer then the gelatin is simultaneously softened by the generation of Ferrous ions.

The overall integrity of the gelatin thus suffers and indeed, the recorded region of silver halide may just peel off the substrate after bleaching especially if ultrasonic agitation is invoked.

Now we can reconsider an alternative solvent bleach namely acidified dichromate solution. Does such a silver solvent bleach tan the gelatin layer or does it soften it? Here the evidence is sparse, but the action of reduced dichromate ion present after oxidation of the silver must be questioned. It seems likely that softening takes place as evidenced by the removal of the recorded region by acidified dichromate under ultrasonic agitation (i.e. in the case of a small patch of recorded grating say, then this patch will detach from the substrate).

The work related in this paper is of course derived in the main from studies of silver halide layers in which development is followed by removal of silver. To simulate the photo-hardening reaction in the antinodal regions offered by the dichromate process we have used developers that tan the layer in the locality of the developed silver (notably those containing catechol as in CWC2 for example). However, such powerful tanning developers can promote layer distortion and persistent inhomogeneous stain images.

We found that non-tanning developers such as Ascorbic Acid left the layers prone to attack by hydrolysis and hence risked detachment of the gelatin layer during solvent bleaching. Since the tanning developers such as Catechol create oxidation products that tan, it is assumed that the nodal regions are tanned by diffusion of these products from the antinodal region.

The interesting difference of integrity of layers which were ultrasonically agitated during bleaching and those that were free from agitation provided strong insights into the presence of gelatin hydrolysis in the weakening of the recorded layer.

Some of the reporting of bulk index changes in D.C.G. layers have a degree of unreliability. Obviously, the bulk or average index of a gelatin layer can only decrease bearing in mind the effect of hydrolysis and could only increase if serious physical compression was invoked.

The observation 2(c) of recovery of layer thickness during hot isopropanol drying is most interesting because it implies a sort of 'memory' built in to the gelatin layer that pre-disposes it to return, when forced, back to its original thickness before recording. Of course such an observation is not precise and is probably capable of serious modification if required but its simplistic description provides a working start point.

## 6. CONCLUSIONS

This paper makes a comment on the technology of D.C.G. and S.H.G. The complex and often tortuous discussions of where the modulation levels come from are easily focussed if gelatin hydrolysis is invoked. The set of observations presented here provide a talking point for new investigations and offer a degree of the 'heresy' suggested by the title namely that dichromate can both tan (or cross-link) gelatin and at the same time effect its hydrolysis.

An entirely new process for the creation of S.H.G. has been presented. At a first look, it seems to be free of the uncertainty of previous methods though much is still to be done to optimise and even explain the procedure. It is clear from our studies that bleaches that contain rapid acting dichromate or those that contain Ammoniacal compounds with their concomitant silver halide solution action do not properly relate to this process. Ferric Nitrate and Persulphate form a uniquely controlled and regenerative bleach system apparently ideal for this new process. Our finding is that fixer can result in uncertain behaviour of such solvent processes and is best left alone. We did in fact obtain a competent result by fixing the layer and then solvent bleaching out the developed silver. In truth however, the results were not at all competitive with the Repeat Method.

It is probably true to say that the S.H.G. process relies on the integrity of complex oxidation product deposits in the gelatin — liberated at both the develop and bleach stages. The Ferric-Persulphate bleach went through two clear phases — (i) removal of silver leaving a dark brown stain residue and (ii) a gradual clearance of that stain until the layer was notionally colourless. Ammonium dichromate as a bleach oxidising agent attacked the stain with extreme rapidity and the overall process failed to work efficiently.

From extensive tests of what we might call complementary methods using fixation, we concluded that fixer can damage the integrity of oxidation product deposits.

## 7. ACKNOWLEDGMENTS

The authors wish to thank Mrs Kathy Phillips and colleague Peter Marsh for their sterling efforts in the preparation of the structure of this paper.

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## CHEMICAL FORMULARY

## Silver solvent bleaches

|                                       |         |                                       |        |
|---------------------------------------|---------|---------------------------------------|--------|
| SS1. Ferric Nitrate (Sulphate)        | 30 gms  | SS3. Potassium Dichromate             | 10 gms |
| Potassium Persulphate                 | 20 gms  | Potassium Persulphate                 | 20 gms |
| Potassium or Sodium Hydrogen Sulphate | 50 gms  | Potassium or Sodium Hydrogen Sulphate | 2 gms  |
| Distilled water to 1 Litre            |         | Distilled water to 1 Litre            |        |
| SS2. Potassium Dichromate             | 0.5 gms |                                       |        |
| Potassium Persulphate                 | 20 gms  |                                       |        |
| Potassium or Sodium Hydrogen Sulphate | 50 gms  |                                       |        |
| Distilled water to 1 Litre            |         |                                       |        |

*N.B. In these bleaches novel regeneration of the reduced silver oxidant is effected by the Persulphate which itself cannot effectively attack silver because of a double layer problem. This helps the confinement of the reduced oxidant to sites close to the silver site that is under attack. We specifically do not recommend the use of Ammonium dichromate.*

## 3. Eastman Kodak's etch bleach EB2

*This bleach produces major gelatin hydrolysis. It is often preceded by hardening fixation or a chrome alum bath to avoid major disruption.*

## Part A Cupric Sulphate 120 gms

|                           |         |
|---------------------------|---------|
| Potassium Bromide         | 7.5 gms |
| Citric Acid               | 150 gms |
| Distilled water to 500 ml |         |

## Part B Hydrogen Peroxide 3% 500 ml

*Mix equal parts just before use.*

*N.B. Bleach SS1 will etch in just the same way as EB2 by the addition of Hydrogen Peroxide.*

## Developer for phase modulated gelatin (S.H.G.)

*The Eastman-Kodak concentrated developer HC 110 is an ideal simplistic developer for the Repeat Method. Dilution can be 1 + 30 to 1 + 60. Based on concentrated Quinol, we believe this developer to endow just the right level of tanning action.*

## Reactivator solution RA

|                             |        |
|-----------------------------|--------|
| Sodium Sulphite (Anhydrous) | 50 gms |
| Sodium Hexametophosphate    | 1 gm   |
| Distilled water to 1 Litre  |        |

## The Repeat Method for the formation of phase modulated gelatin

Before proceeding, read Fimia *et al.*<sup>10</sup> for instructions on presoftening of Agfa gelatin.

## 1. Develop in HC 110 developer diluted to 1 + 30 to 1 + 60 at 20°C.

Typically to density of 2.5 for Agfa's 8E56 HD or 8E75 HD.

*N.B. Eastman Kodak's maximum resolution plate type 1 performs exceptionally well probably due to its softer gelatin compared to the Agfa product.*

2. Wash 5 minutes.
3. Solvent bleach in SS2: ~~do not agitate~~. Allow time for all developer stain to clear.
4. Wash 5 minutes.
5. Reactivate in solution RA — 2 minutes. Remember that this contains a silver halide solvent (Sodium Sulphite) so do not allow too much protraction of this step.
6. Wash 2 minutes.
7. Expose to an intense white light.
8. Develop to completion in HC 110.
9. Wash 5 minutes.
10. Solvent bleach in SS1. Wait until all stain is cleared. Do not agitate.
11. Wash scrupulously and use hot or graded Propanol dehydration.

The one step Method for the formation of  
phase modulated gelatin.

Before proceeding, read Fimia et al.<sup>10</sup> for instructions on presoftening of Agfa gelatin.

1. Develop in HC 110 developer diluted to 1 + 30 to 1 + 60 at 20°C. Typically to density of 2.5 for Agfa's 8E56 HD or 8E75 HD.

N.B. Eastman Kodak's maximum resolution plate type 1 performs exceptionally well probably due to its softer gelation compared to the Agfa product.

2. Wash 5 minutes.
3. Solvent bleach in SS3. Allow time for all developer stain to clear.
4. Wash 5 minutes.
5. Thoroughly fix using sodium thiosulphate or ammonium thiocyanate.

### Novel developing agent for Holography and Lithography

This invention describes a novel developing agent based on the developing activity of Ascorbic Acid in combination with ~~peroxide~~<sup>phenidone</sup> and other specified compounds. The oxidation products of Ascorbic Acid have a strong solvency effect on silver halides and thus provide partial fixing action of a silver halide layer which is undergoing development. Such effects have a deterrent effect on the dynamic range and achieved density of holograms developed in Ascorbic Acid.

Ⓢ  
Phenidone

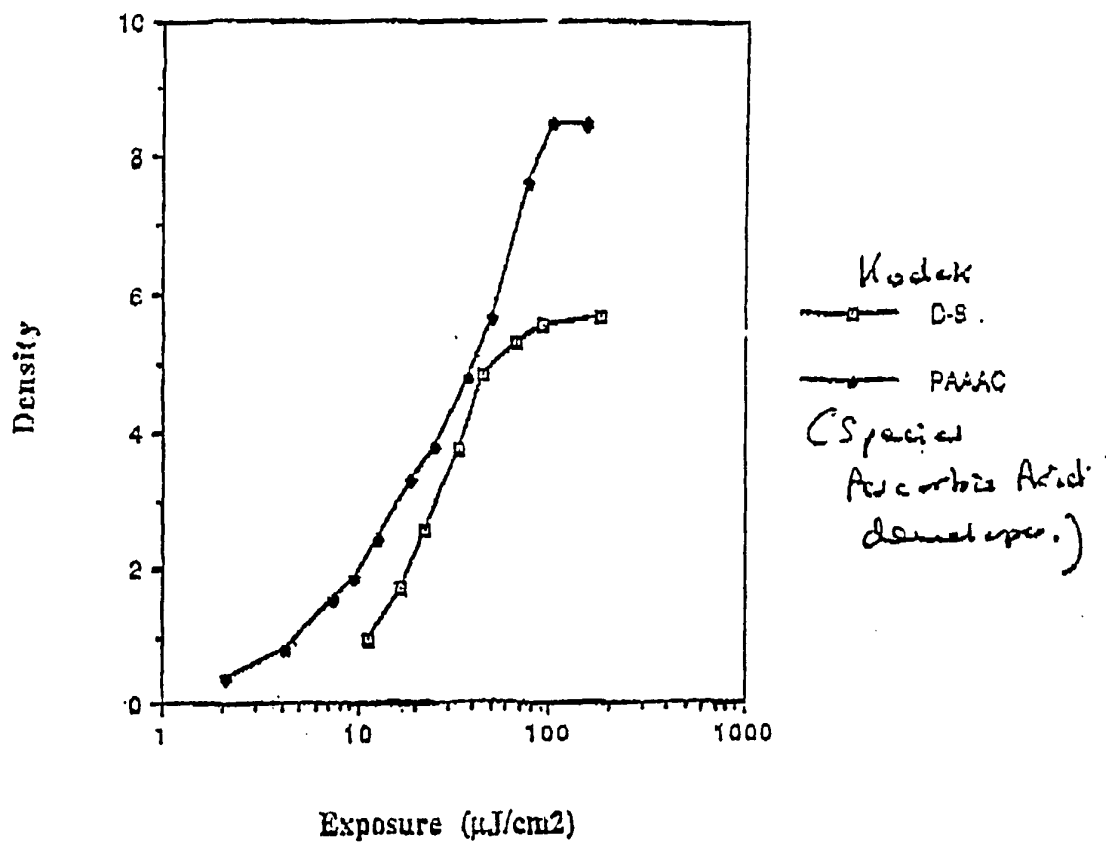
A novel combination of agents provides for unusual developer energy, enhanced dynamic range and elimination of the silver halide solution problem.

<sup>normal</sup> Whereas ~~under~~ developing agents applied to for example an Agfa-G<sup>Ⓢ</sup>paert 8E95HD layer will create an optical density of at most 6. We have observed densities approaching 9. Thus illustrating a greatly increased dynamic range. In a subsequent bleached hologram, a great improvement of signal to noise ratio is observed.

- The second embodiment of the process of index matching by light induced effects may set throughout the layers as distinct from localised index matching induced by the evanescent field of the reference wave near the interface between recording medium and substrate.

In either method, the effects are to be employed just prior to the recording of the holographic pattern.

SUCH HIGH DENSITIES (e.g. 9) ARE OF COURSE  
REMARKABLY IMPORTANT IN MASS MANUFACTURE WHERE  
ZERO TRANSMISSION IS REQUIRED.

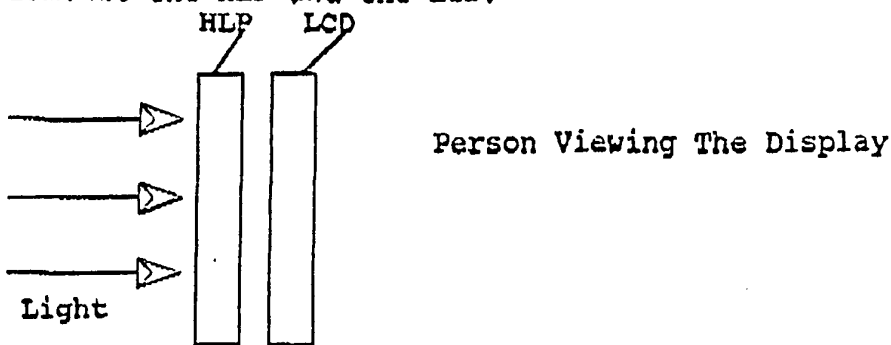


Agfa-Gevaert 8E75 plate material.  
used for recording.

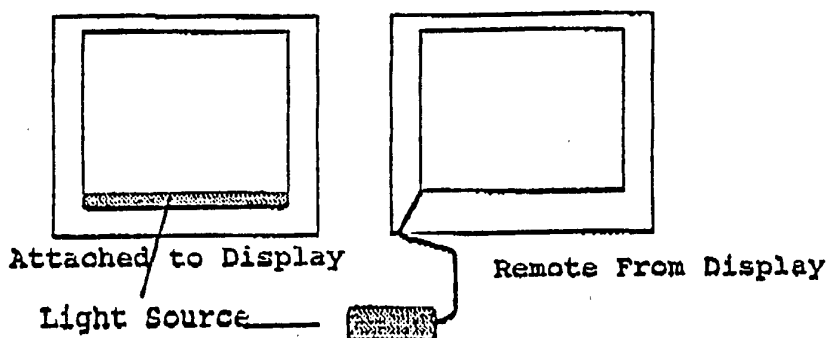
DISCLOSURE OF THE INVENTION AND BEST MODE  
FOR CARRYING OUT THE INVENTION

COLOR DISPLAYS

The holographic light panel is a two dimensional application of a hologram. The HLP can replace many existing illuminators and light sources which require bulky and expensive optics with a much thinner, lighter, less expensive "sheet illumination". The concept would be to combine the HLP and the LCD.



The HLP would be edge-lit. This would allow the light source for the hologram to be at the base of the hologram or at a location remote from the display. The light would then be routed to the display via fiber optics and distributed by the hologram for uniform illumination across the LCD.



One advantage of the HLP is that the light can be shaped so that light from the display can be sent out in small solid angles or large solid angles.

#### Color Displays from Mono-LCDs.

A colored (red, blue, green) illuminator would be used. No color filters would be employed. The LCD would be a monochromatic device. The illuminator would provide the color to the LCD display. A brightness advantage over current color LCDs of 10x or more is expected by taking advantage of the efficiency of light transfer via the HLP and by shaping the light to match the specific requirements of each display. Additional brightness is expected because this process will generate color pictures without filtering. This process would allow the use of large remote light sources. There would be no Red, Blue, Green (RGB) point failures because the color would be coming from the HLP and not from the LCD. Point failures within the LCD would be possible, but the probability would be reduced by using a monochromatic LCD.

99.99% of all holograms are copies of original holograms. The copy process is simple, exact, and inexpensive. Once a "perfect" HLP has been produced for the mono or color application, large numbers of low-cost copies can be produced that will have the same properties as the master.

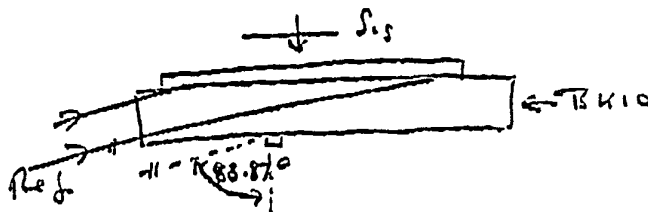
#### Depixelator:

An additional HLP would be used in front of the LCD display. The depixelator would expand the light from each pixel so that no black mask would be required between the pixels. This would result in a 10% to 30% increase in brightness of the display as well as increased image fidelity.

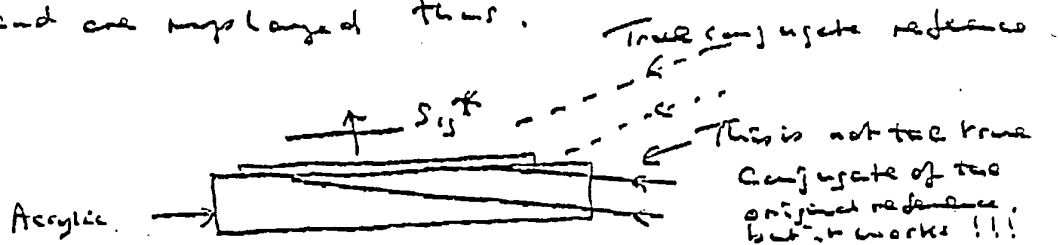
MANUFACTURE OF TRUE EDGE-LIT MONOCHROME HOLOGRAMS

We are sending 4 samples of true edge-illuminated results direct to Alabama A&M University. They go out tomorrow but with guaranteed next day delivery.

They are recorded @  $514.5 \text{ nm}$



and are imaged thus.

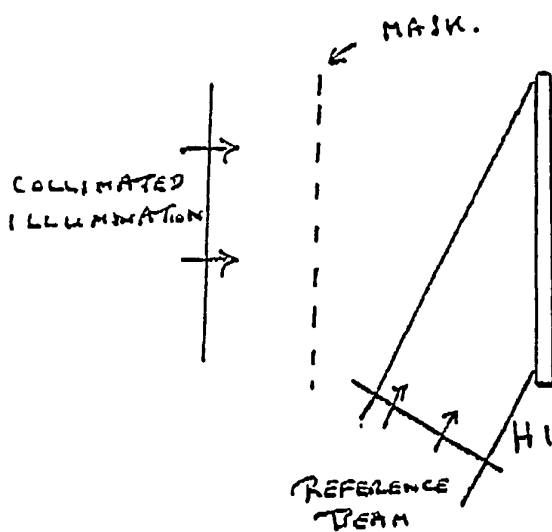


You will see that the index shift  $\text{BK10} \rightarrow \text{Acrylic}$  has turned almost exactly to a slightly incorrect conjugate for replay. This bit of luck is crucially important, but the results clearly work well.

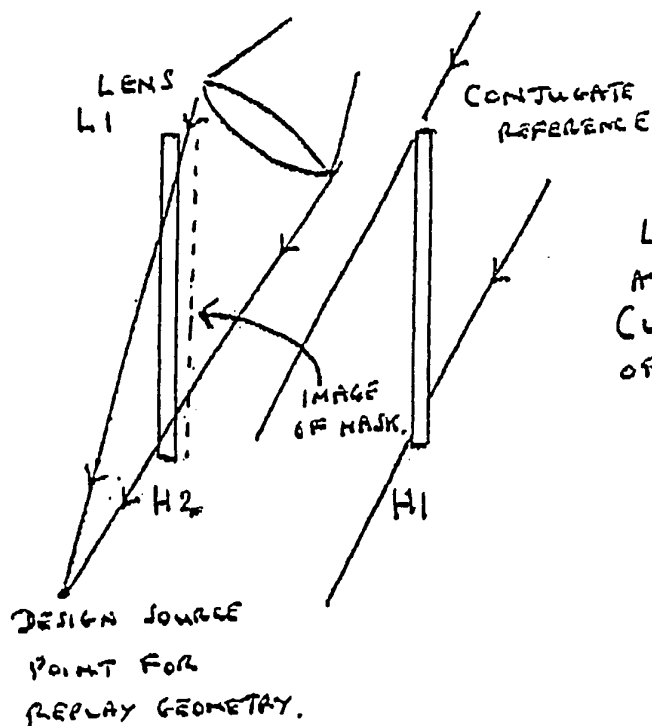
## TWO MAJOR TECHNIQUES FOR MAKING ILLUMINATORS.

### 1. HOLOGRAPHIC ILLUMINATORS FOR WHITE SPOT GENERATION.

STAGE (i) - THE MAKING OF HOLOGRAM H<sub>1</sub>.



STAGE (ii) REPLAY OF H<sub>1</sub> INTO THE COPY H<sub>2</sub>

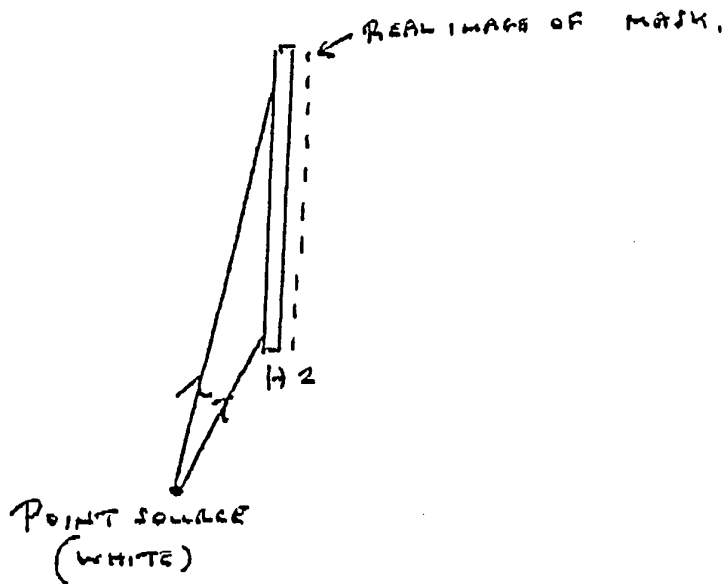


L<sub>1</sub> MAY NEED TO BE AT LEAST BEST FORM (LEAST SPHERICAL ABERRATION) OR EVEN ASPHERIC.

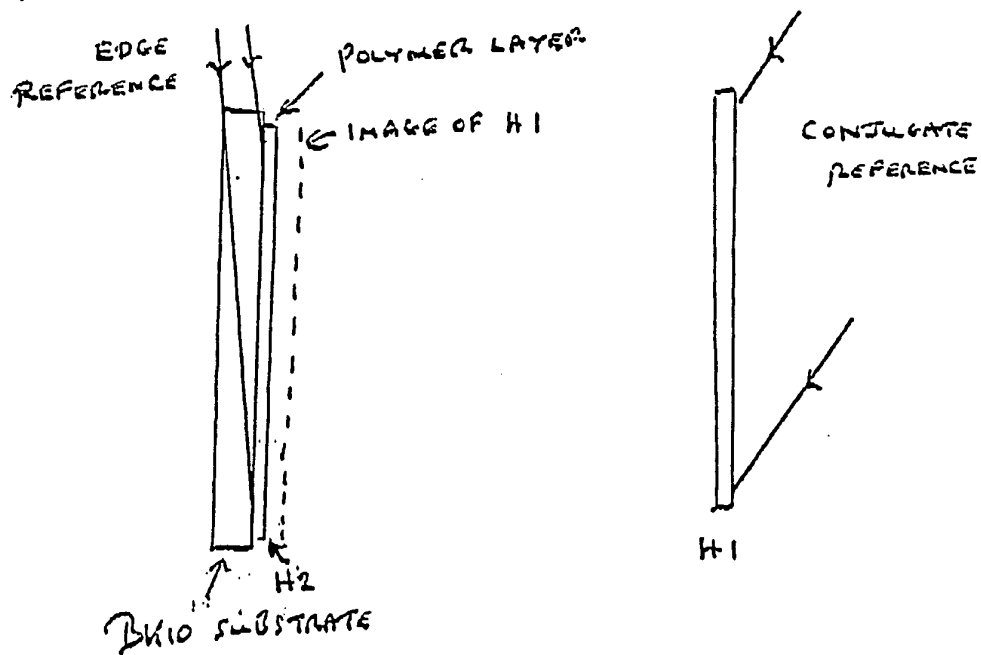
53

2.

STAGE (iii) REPLAY OF H2.



2. HOLOGRAPHIC ILLUMINATION FOR COLOURED SPOT  
ARRAYS - IN THE FIRST INSTANCE GREEN.



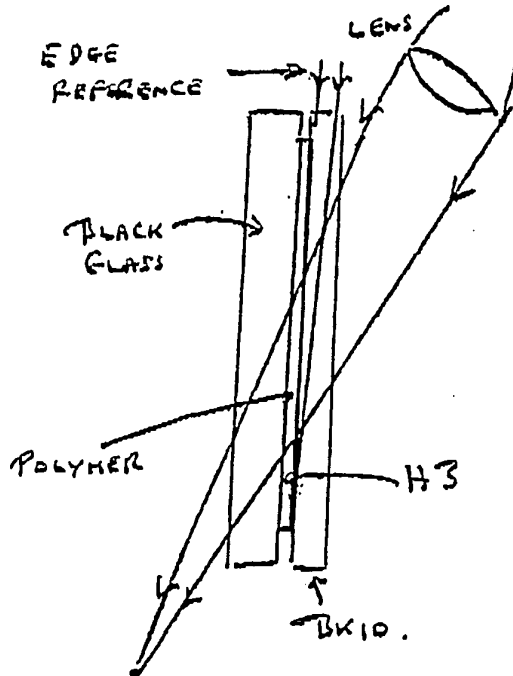
STAGE (i) FORMING AN EDGE REFERENCE HOLOGRAM OF THE  
SPOT ARRAY IMAGE OF H1.

WE DO NOT PROPOSE TO REPLAY H2 DIRECTLY WITH  
WHITE LIGHT.

54

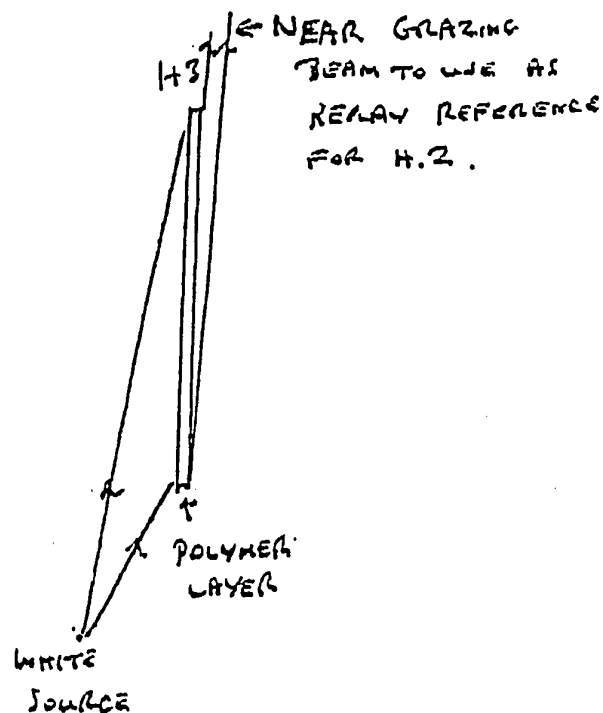
3.

STAGE (ii) FABRICATION OF CONVERTOR HOLOGRAM H3 TO RELAY H2.



IN THIS STAGE, WE ARE MAKING AN EDGE REFERENCE GENERATOR HOLOGRAM.

THE FINAL USE OF H3 IS AS FOLLOWS:

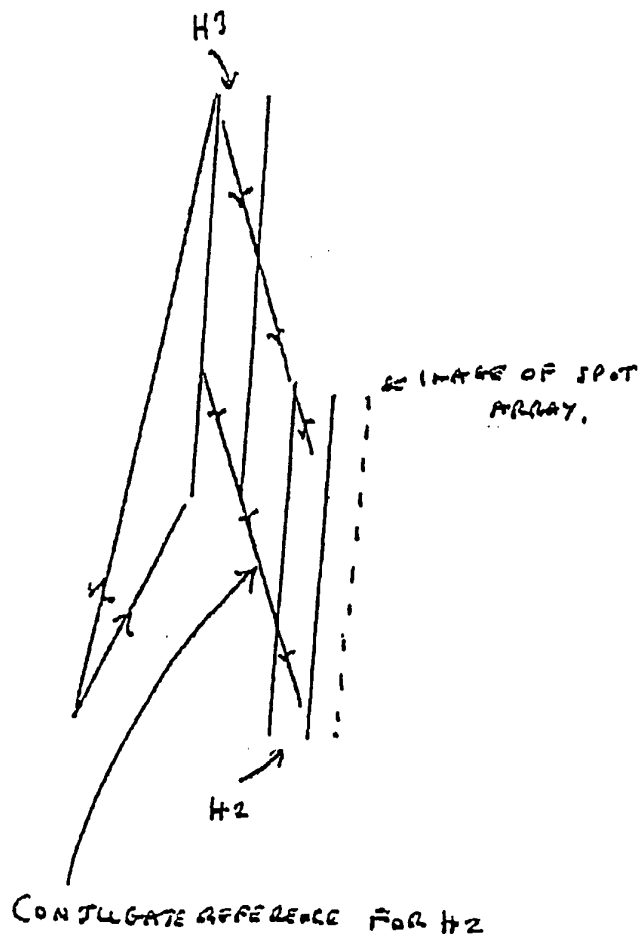


55

4.

NOW WE LAMINATE H3 TO H2 THUS RECREATING THE  
CONJUGATE REFERENCE FOR H2 USING H3. NOTE THAT H3  
IS ILLUMINATED OVER ITS LARGE AREA.

THE COMPLETE REPLAY ASSEMBLY IS AS FOLLOWS:



H3 IS LAMINATED  
TO H2 FOR  
REPLAY. NOTE  
THAT NO REPLAY  
SUBSTRATE IS  
INVOLVED.

N.B. BECAUSE OF THE LARGE REPLAY ANGLES INVOLVED  
THE REGENERATED EDGE REFERENCE FROM H3 IS MONOCHROME  
BUT MATCHES THE MONOCHROME EDGE REFERENCE REQUIREMENT  
ON CONJUGATE REPLAY OF H2, THUS H2 REPLAYS IN  
MONOCHROME.

E.

## ESTIMATES ON

1. SIZE

DEPENDS ON LASER POWER - BUT SUGGEST UP TO 10" X 8" IN THE FIRST INSTANCE.

2. HOW LONG TO BUILD EACH OPTICAL RESULT SETUP?

WITH SKILL DESIGN AND SENSIBLE COMPONENTS - A FEW DAYS TO SET UP BASIC RIG AND DEBUG - A FEW MINUTES TO CHANGE FROM STRATEGY 1 TO STRATEGY 2. (- WHITE SPOTS - COLOURED SPOTS.), SO MUCH DEPENDS ON RUGGED AND ERGONOMIC DESIGN.

3. WHAT THROUGHPUT?

DEPENDS ON ENGINEERING RIGIDITY AND TIME OF LOADING AND UNLOADING THE RECORDING.

eg. FIRST SETUP LINEAR FACILITY SO THAT LAMINATING IS NEXT TO RECORDING SETUP.  
 LAMINATION TO TAKE 3 min IN A CRUDE LAYOUT  
 LOADING SUBSTRATE ON TO RECORDING RIG 2 min  
 EXPOSURE 2 min OR LESS. UNLOADING OF RESULT  
2 min. REMOUNTING OF RESULT ON ACRYLIC  
2 min.  $\approx 10-11 \text{ min} / \text{result}$ .

THIS WOULD BE GREATLY REDUCED BY HIGH SPEED CONTACT COPYING FOR EXAMPLE.

4 MATERIALS IN THE MAIN ARE

(a) PHOTOPOLYMER - (DuPont)

(b) LAMINATING MATERIALS (VIRTUALLY NEGLIGIBLE COMPARED TO DuPont).

(c) ACRYLIC REPLAY SUBSTRATES

6.  
5. THROUGHPUT IN FWT SYSTEMS.

WE MIGHT CONSIDER THAT ILLUMINATION AND DISPLAYS  
FIGURE HERE.

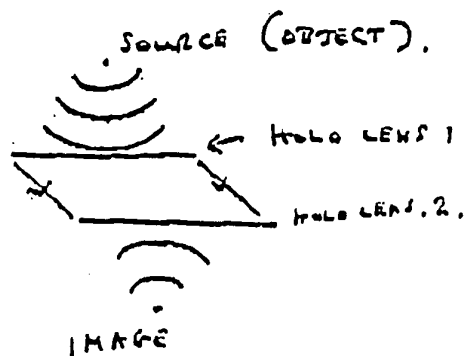
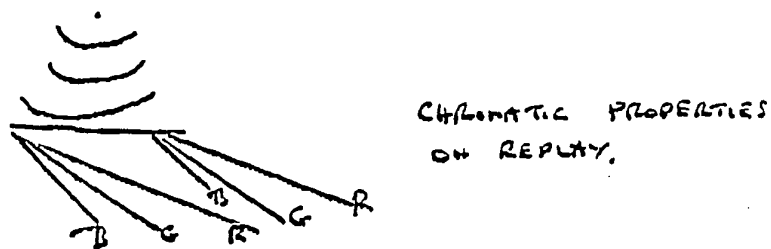
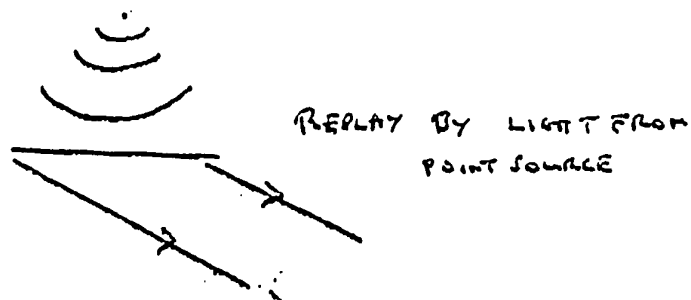
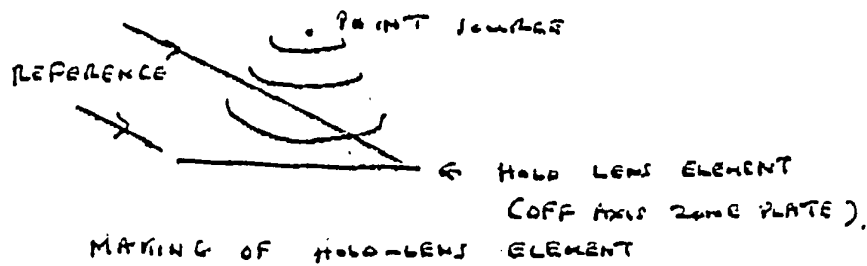
WITHOUT MASS PRODUCTION, ONE RELOADING RIL  
MIGHT YIELD 6 RESULTS / HOUR. BUT IF  
WE RAN LAMINATION, DE-LAMINATION — LOADING ON  
TO BK10 SUBSTRATES IN PARALLEL WE MIGHT MULTIPLY  
BY UP TO 5X. — 30 RESULTS / HOUR

CLEARLY WE NEED TO ADDRESS MASS-REPLICATION  
EARLY ON IN THE PROGRAM.

BASIC CONCEPTS

1.

A BASIC DIAGRAM OF A TWO COMPONENT  
HOLO-LENS ASSEMBLY WITH FREEDOM FROM  
TRANVERSE CHROMATIC ABERRATION



WHEN LENS 2  
IS REPLAYED BY  
LENS 1

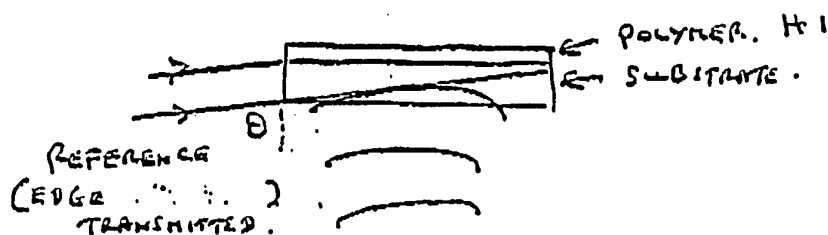
WAVELENGTH AND  
ANGLE ADJUST TO  
GIVE LATERAL  
ACHROMATISM.

2.

IN THESE PRECEDING DIAGRAMS, THE REFERENCE ANGLE  $\theta$  IS KEPT SMALL ENOUGH SO THAT THE HOLES ARE NOT ESPECIALLY WAVELENGTH SELECTIVE



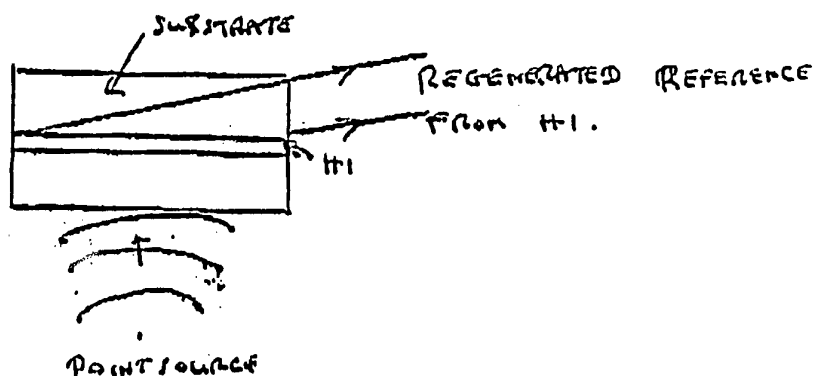
WE NOW RECONSIDER THE REDUNDANT GEOMETRY SO  
THAT THE REFERENCE DOES NOT ENTER FROM AHEAD !



• POINT SOURCE

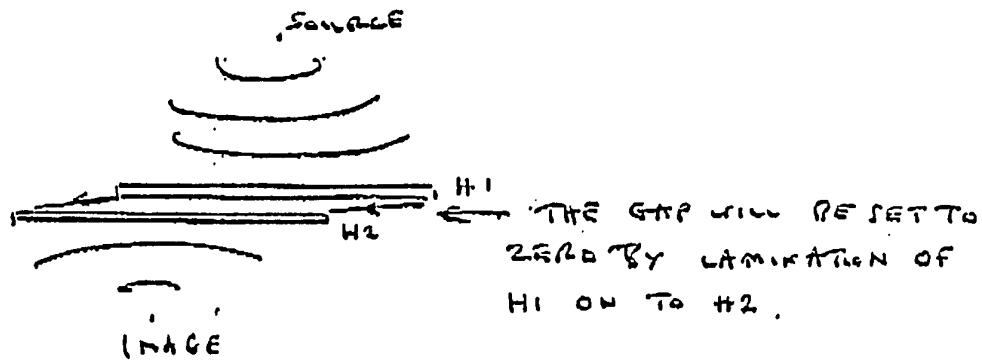
NOW, THE ANGLE OF ATTACK  $\theta$  IS BEYOND THAT ATTAINABLE BY ALLOWING THE REFERENCE TO ENTER THE RECORDING LAYER FROM AIR.

THEORETICALLY, REPLAY OF H1 SHOULD BE  
AS FOLLOWS:



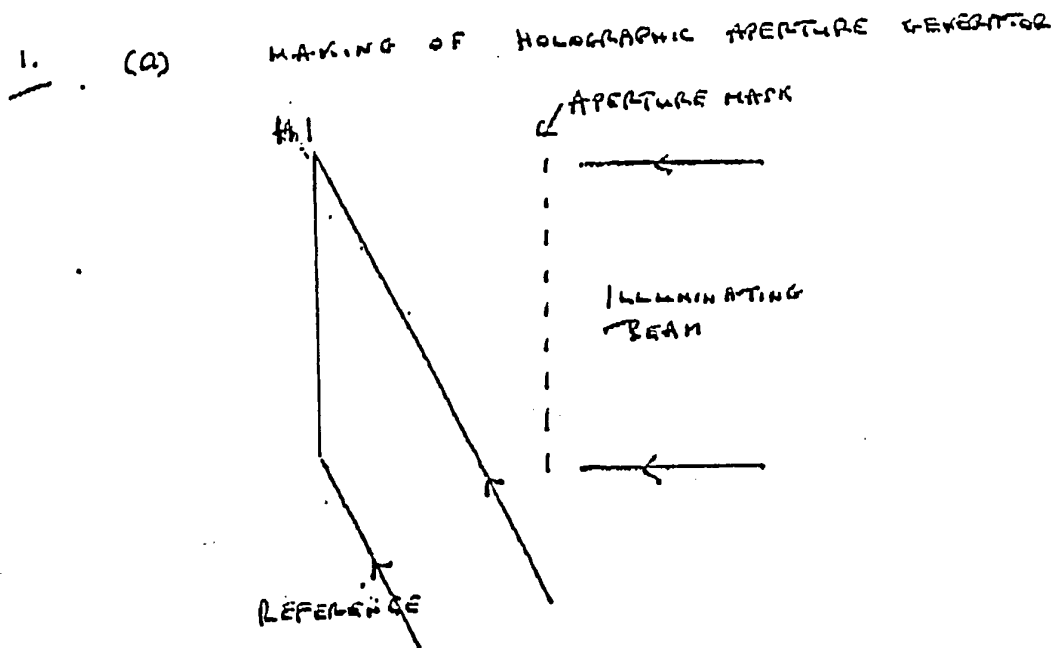
3.

HOWEVER, IF THE REPLAYED REFERENCE IS COUPLED DIRECTLY INTO AN H2 AS BEFORE, THE EXTREME REFERENCE ANGLE CAN BE INVOKED THUS

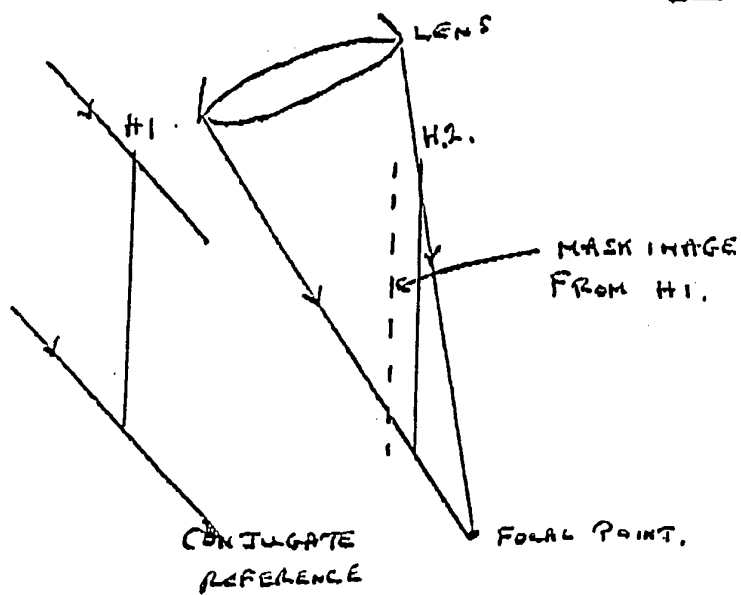
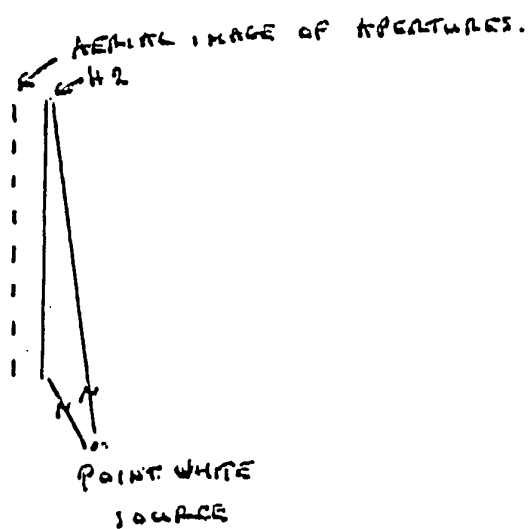


IN SUCH AN EXAMPLE, CHROMATIC SELECTIVITY IS NOW HIGH.

### E.C.D. ILLUMINATORS - MAKING STRATEGIES



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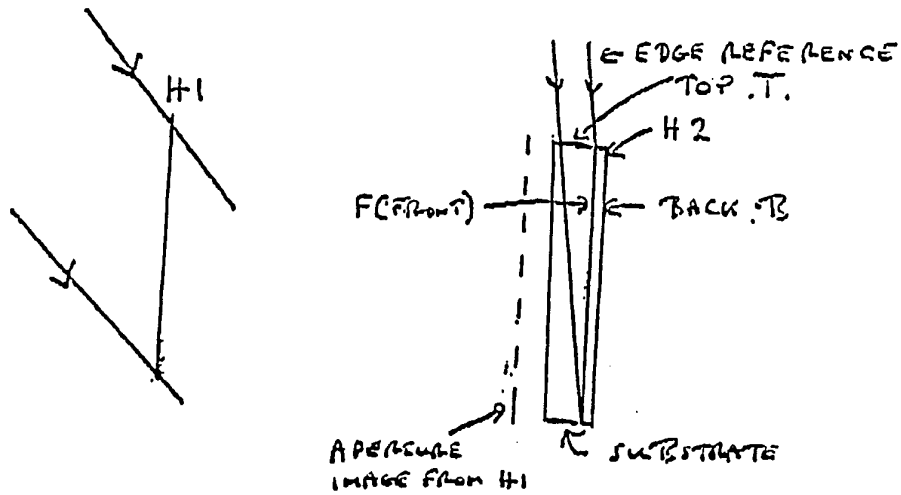
4.  
—(b). COPYING OF  $H_1$  INTO AN  $H_2$  BROAD BAND ILLUMINATOR(c) REPLAY OF  $H_2$  — BROAD BAND

NOTICE THAT A SINGLE HOLOGRAM ( $H_2$ ) IS USED  
IN THIS CASE

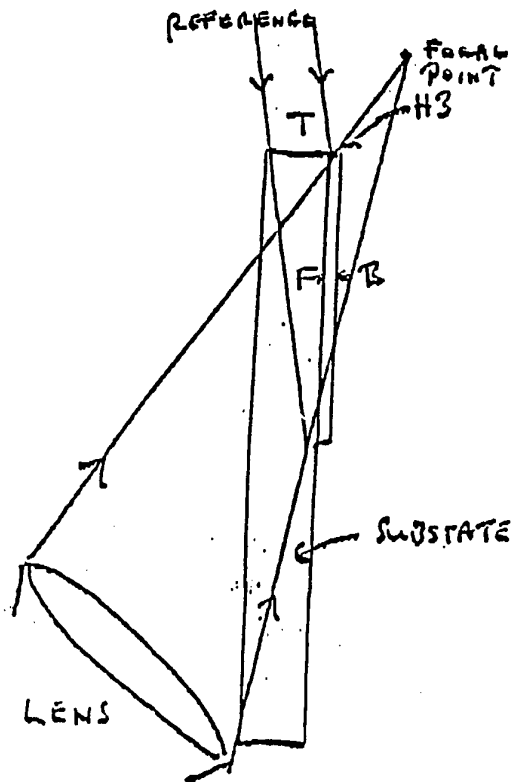
62

5.

(c). RECORDING OF A HOLOGRAPHICALLY REPLAYABLE MONOCHROME ARRAY



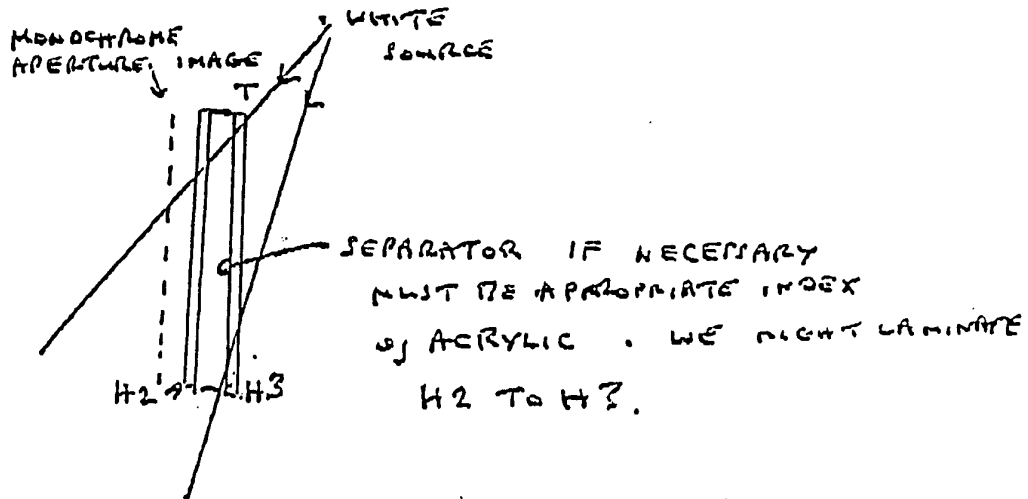
(d) RECORDING OF EXTREME EXTERNAL REFERENCE HOLOGRAM  
FOIL REGENERATION OF CONTRAST REFERENCE OF H2.



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6.

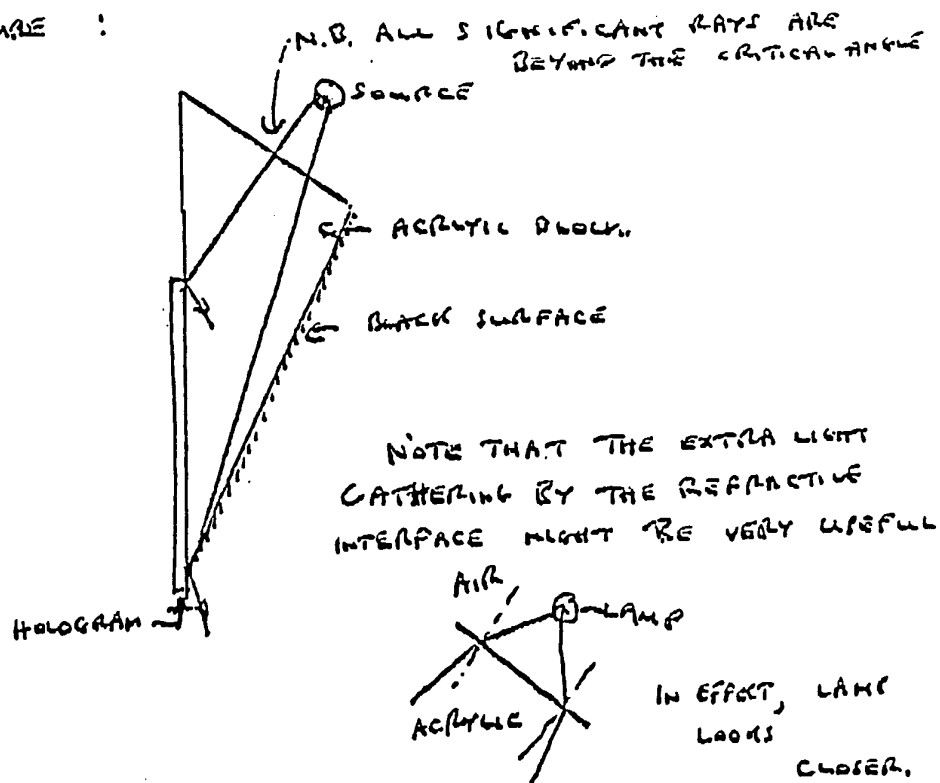
REPLAY OF H2 BY H3.



CONJUGATE REGENERATED REFERENCE FROM H3 REPLAY H2

WE MIGHT NEED TO USE SOME TRICKS TO PREVENT  
 'ZERO ORDER' LIGHT FROM LAMP LEAKING THROUGH.

FOR EXAMPLE :



64

7.

TO SUMMARISE, WE NEED TO MAKE HOLOGRAMS AND SUPPORTS OR SPACERS IN THE FOLLOWING CATEGORIES;

1. SINGLE HOLOGRAM H2 CONFIGURED FOR EXTREME EXTERNAL CONVERGENT REFERENCE AS ON PAGE 6.

2. DUAL HOLOGRAM MONOCHROME CONVERTER SYSTEM AGAIN USING CONVERGENT REFERENCE IN MANUFACTURE

3. BASIC H1 ARRAY HOLOGRAMS - THESE COULD PROTECT ANY SHAPE OF ELEMENTAL APERTURE - ROUND OR RECTANGULAR

4. GENERAL DISPLAYS

WHAT ABOUT COLOUR?

AT THE MOMENT ONLY GREEN IS UNDERSTOOD.

THE H2 REPLAYED BY H3 SCENARIO OPENS THE DOOR TO OVERLAYED MASTER APERTURE ARRAY!

SAY WE USE 3 H1'S FOR THE TRAINING AND RECORD H3. WITH SIMULTANEOUS R.G.B.

MUCH OF THIS IS UNKNOWN TERRITORY AS YET !!

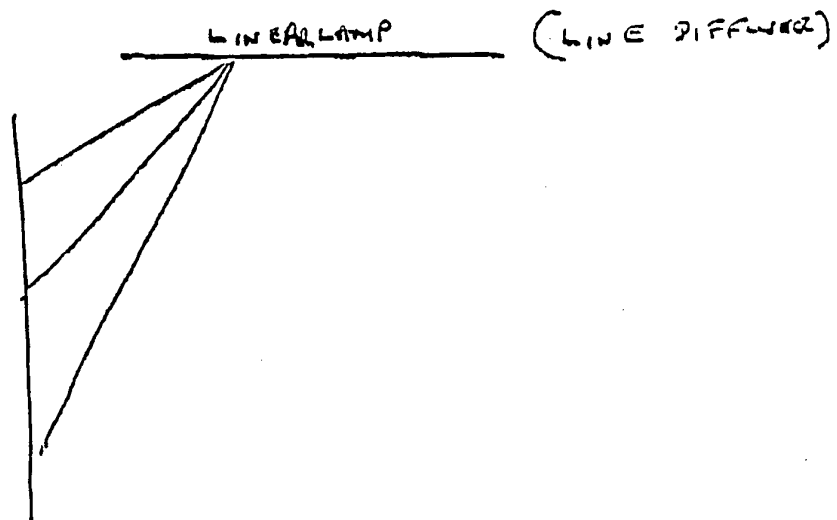
EXTREME REFERENCE ANGLE HOLOGRAMS (REFLECTION MODE) MAY BE POSSIBLE; THOUGH WE REMEMBER THAT ~~EXTREME~~ EDGE ILLUMINATED HOLOGRAMS CAN BE REPLAYED IN TRANSMISSION THOUGH RECORDED IN REFLECTION MODE (OIL GREEN OILS FOR EXAMPLE)

8.

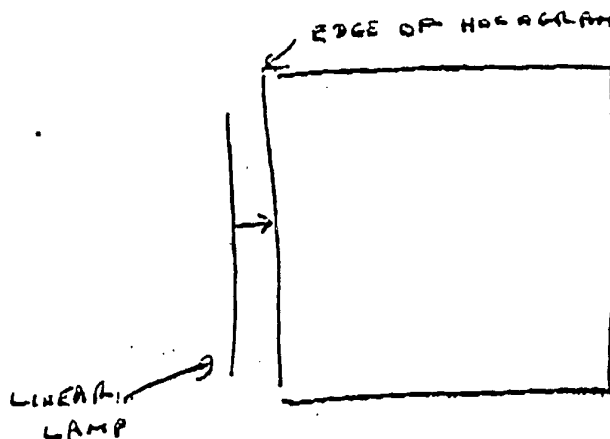
LIGHT SOURCES

NOTE THAT COLLECTION OF LIGHT FROM THE SOURCE IS THE ALL IMPORTANT ASPECT

A LINEAR LAMP WILL REPLAY A RAINBOW HOLOGRAM AS FOLLOWS



IT WILL NOT REPLAY A DUAL PARALLAX HOLOGRAM BECAUSE OF THE RAY DIRECTIONS FROM THE SOURCE



ONLY RAYS ENTERED INTO THE LAYER AT RIGHT ANGLES TO THE EDGE ARE REPLAYED.

SUMMARY

This is a review of some of the overall concepts regarding holographic light panels. So far we are making two kinds of "edge-lit" holograms: True Edge Lit (ELH) and Steep Reference Angle (SRA). The third, Waveguide Hologram (WGH) has yet to be explored.

Our light panels will be characterized by whether they are ELH, SRA or WGH, and what their output is. There are several possible outputs that we foresee right now:

- **Narrow beam (NB)**  
This is where we want there to be a beam out with a narrow field of view, i.e. a collimated beam (over a distance of several mm to several feet, depending on the application) comes out of the face of the hologram. This is good for sensors (like for fingerprints).
- **Lambertian beam (LB)**  
The object was a diffuser, and the light out of the face of the light panel travels in all directions. This is good for transparency illumination.
- **Pixellated beam (PB)**  
This is good for LCD displays: flat panel television, computer monitors, etc. Computer monitors, for example would require a narrow beam output;

For visual applications, a pure white or pure monochromatic beam is required. Uniformity will be required in most cases. For detection applications, uniformity and/or chromatism may not be an issue. For example, with a fingerprint sensor, high transmissivity is important since we want the light to come in the edge, go out the face, illuminate the finger, pass through the hologram to a detector. Uniformity may not be an issue, since that can be compensated for in software.

1. EXPLANATORY POINTS

- (a) True Edge Lit (ELH) will be defined as single pass. Steep Reference Angle (SRA) by its very nature is external reconstruction, and therefore single pass. Waveguide Holograms (WGH) are covered by Caulfield, and are multi-pass.
- (b) What will come out of the hologram is not Lambertian, and maybe not semi-Lambertian. we will need a separate microdiffuser if color blending, consistency or whiteness is important. We can make a hologram create a diffuse patch in air, but it will pick up chromatic aberration as the light travels. The diffuser will smear the colors to create white or whitish. We may want to call it "widely diffused light" or some other such thing.  
We can control the NA of the exiting beam from being narrow to wide.
- (c) The sensor (finger or bio or whatever) detector can be considered to be "in the rear" (the opposite side of the light panel from the finger).
- (e) The diagrams for making all of the combinations we suggest are .
- DISCLOSED ~
- "BASIC CONCEPTS", SUPRA.
- (f) The "holy grail" for a pixellated light panel is separate RGB dots. This can be done with a carefully masked multiple exposure process, or three separate carefully aligned, holograms. VERY IMPORTANT NOTE: The true edge lit (ELH) creates POLARIZED output, which would eliminate the need for separate polarizers with the LCD panel (the cases of using them or not should both be covered in the claims). Since the colors, if they were in a single hologram, will not travel well over a long range (they'll aberrate, or change with viewing perspective) we will pick up the light as it begins to disperse and send

it through a microdiffuser before it hits the window in the LCD. We can also make crude white dots, instead of RGB, but they will also aberrate and would probably need to be augmented with a diffuser.

*A PRIOR METZ U.S. PATENT*

2. One key point is that the monochromatic true edge lit hologram is a TRANSMISSION NOTCH FILTER. Holographic notch filters, like the one in *patent*, are REFLECTION holograms. We are not aware of anyone who has ever made a TRANSMISSION HOLOGRAPHIC NOTCH FILTER. As with the reflection notch filters, though, the thicker the hologram, the more wavelength selective it will get; the thinner the hologram, the more broadband the output.
3. With the true edge lit, the reference beam appears to be generated WITHIN THE SUBSTRATE, therefore the effects of Snell's Law are quite different than with the SRA, where the reference beam is external from air, as with standard holograms.
4. With the ELH, we have used BK10 glass to make it work during creation of the hologram. The BK10, or any equivalent substrate whose index is tightly matched to that of the monomer, or slightly higher (when using DuPont photopolymer) is essential to making high quality ELH's. Even with the SRA, using BK10 helps to minimize microfringing, which causes unpleasant cosmetic problems. After the hologram is formed, it is delaminated from the BK10 substrate, and then relaminated onto Acrylic or some other less expensive substrate, which works acceptably for replay of the hologram.
5. Just a note for future reference: another method that may be considered for the multicolor or 3 dot process is to use rainbow holograms...simultaneous rainbow masters whose images are overlapped properly. ~~We~~ think, however, that this would severely limit the usable viewing angle in the vertical direction.
6. One advantage of using the light panel is that it can direct the light beam from the hologram into the clear apertures of the LCD without the light going to the TFT area, thus utilizing the light more efficiently. You make the master H1 which replays an array of spots, use the aerial image of the dots a little remote from the H2 (not exactly in the plane of the H2) so that the light can converge into the LCD's windows. (H1 and H2 refer to first and second generation holograms in the recording process.)
7. Let us define an SRA to have a reconstruction beam greater than 80 degrees to the normal to the plane of the hologram.
8. Note that the chromatic aberration is minimal the closer the image from H1 is to the plane of H2, and increases as the image from H1 is displaced from the plane of H2.
9. The use of the large lens, as depicted in the diagrams requires very careful attention to the conjugate relationship of the feeding beam to that lens. You need a very circular patch of light coming from a carefully collimated system (or whatever

conjugate the lens was designed for). Otherwise the hologram will suffer from spherical and chromatic aberrations. Note that Benton's edge lit patent makes use of such a large lens.

10. To change the uniformity of the output light across the light panel, we can manipulate the recording process with an amplitude masking filter  
or (for a pixellated beam) make the apertures change in size from one end of the hologram to the other. This latter solution may not be practical for LCD applications, but may be ok for other types of applications.
11. The light out of the ELH is strongly polarized. This is an important claim.
12. ~~~~~ If the angle between the final hologram and the hologram used to illuminate it increases, the output light becomes more and more monochromatic yielding a transmission notch filter. When the angle gets steep enough, there exists cross coupling between the holograms to allow one hologram to be the reconstruction beam for an ELH. (The reference beam is generated by H2 which is reconstructed by an external beam (we show a point source)).
13. The use of the acrylic as shown ~~~~~ which dumps the back reflection of the hologram is ~~~~~ also novel. The hologram is replayed by a beam diverging in the acrylic. The advantage is that it increases the solid angle of the light coming from the source, and removes the back reflected light.
14. For an SRA ideally we want to make it with a convergent reference beam, so we can replay it with a diverging reconstruction beam. Collimated reference and reconstruction beam will also work, but practically, particularly for larger sizes, a point source reconstruction is better. (Otherwise the collimating optics get large and expensive and voluminous.)

## SOME FURTHER NOTES:

1. We have invented not only LCD illumination, but other light panel uses, outlined above (fingers, biosensors, transparency illumination, etc.)
2. Note one of the key features of the invention (for the transmission notch filter) is the use of one hologram to get the light into a second hologram which is true edge-lit.
3. Note that another key feature of the invention is that we are making full color LCD displays by using a mono-chrome LCD panel - eliminating the need for the dyes in the LCD part. We are making multicolor spots from an incoming white beam. These can be done by lamination or ultimately putting all the spots in one hologram. Registration is important.
4. We can also make a white output (with or without spots) or a monochrome output (with or without spots). It is a matter of using the mask or not.
5. The dots can be any size we want. We can produce 5-8 micron dots now. We will soon have 2 micron capability. LCD features are typically in the 80 to 100 micron size.
6. We believe that it is only necessary to depixelate the image if one is magnifying (such as in a virtual reality helmet) or projecting.

## SOME INDUSTRIAL APPLICATIONS

**C.1 EDGE-LIT HOLOGRAMS**

In order to understand how edge-lit holograms can be used to improve Head Mounted Displays, one must first understand what an edge-lit hologram is, and what its advantages are.

**(C.1.1) Background**

Although invented in the late 1940's by Dennis Gabor (who later received a Nobel Prize for his invention), holography has been slow to gain widespread public acceptance. The invention of the laser in the early 1960's touched off an explosion of holographic research throughout the decade. Display holography was made possible by the invention of the laser-viewable, off-axis transmission hologram by Leith and Upatnieks, and the development simultaneously of the white light viewable reflection hologram by Denisyuk in the Soviet Union. Many companies spent millions of dollars researching holography in the 1960's, but significant improvements did not come fast enough to enable widespread public marketing.

A hologram is made by interfering coherent light from an object, the object beam with light derived from the same light source, the reference beam within a recording medium such as a photographic emulsion. Two basic types of hologram existed, the reflection hologram, where the viewer is on the same side of the hologram as the light source, and the transmission hologram where the light source is on the opposite side of the hologram as the viewer. ImEdge Technology, Inc. is producing a third kind of hologram, which is a hybrid between a reflection and a transmission hologram, the edge-lit hologram.

Reflection holograms are white light viewable but are often dark and difficult to see. Transmission holograms typically need a laser to view them, or have reduced vertical parallax, which creates the rainbow which most people are familiar with from holograms such as are found on their credit cards.

Progress in holography over the years has been reasonably steady, with various incremental improvements occurring in optical components, special photosensitive emulsions and their processing chemistries, vibration stability and a growing mastery of techniques by practitioners. More widespread attention to this field has been given more recently, due in no small part to a cover story on holography in National Geographic written by ImEdge's John Caulfield and read by 25 million people.

ITI has researched many of the problems typically associated with holography, and has developed techniques to improve the brightness, eliminate the grainy appearance, provide better contrast, and control the angle of view.

Edge-lit holograms offer significant advantages over standard holograms. Several of these are:

- The incoming or outgoing beam is not obstructed by a viewer, or optics as is the case with some standard holograms (e.g. reflection holograms).
- Improved contrast is achieved since edge-lit holograms are not affected by room light or other outside sources.
- Edge-lit holograms allow displays to be made in a much more compact package than standard holograms.
- Laser light can be used for public or commercial displays safely. It cannot with standard holograms.

#### C.1.2 Holographic Light Panels: Brief Overview

Holographic optical elements (HOEs) are gaining more widespread use. One type of HOE takes light in, operates on that light, and sends light out. Thus we can conceive of a hologram which takes light in (the reconstruction beam, which is the conjugate of the reference beam) and, rather than diffracting light out in a pattern that we perceive as an image, diffracting light out in a prearranged pattern of just light, which is used to perform an illumination function. If we make the hologram an edge-lit hologram, then we have a new, compact, surface emitting light 'source'. This light source can be highly efficient, polarized, monochromatic, multicolored, or white. It can be uniform or patterned, for example, in a way to generate pixels. Therefore it is an excellent way to make a backlight for an LCD panel.

#### C.2 FLAT DISPLAYS, LCDs

This proposal describes a fundamentally new concept for providing backlighting for flat displays of both the passive and active matrix LCD type. By using an edge-lit hologram as an integral part of the backlighting system, we will show that the light efficiency for LCD panels can be increased dramatically.

For our purposes, we would like to define the flat panel display in terms of the following modules:

- (1) a light source,
- (2) a coupler of the light to the display,
- (3) an active pattern-forming element, and
- (4) output beam conditioners.

In some systems, many of those items are combined or eliminated. An electroluminescent panel, for instance, combines items 1,2, and 3 and omits item 4.

The LCD panel enjoys the distinction of being the best pattern-forming element by combining reliability, and maturity of development with the most satisfying appearance and acceptable cost. Many companies (some of them American!) have wonderful LCD technology. Accordingly, it is our intent to assume that item 3 will be an LCD and to optimize the supporting elements (items 1,2 and 4) for DOD and commercial purposes using our proprietary technologies. Note, however, that should a better pattern forming element be devised which requires backlighting, our technology is adaptable.

The ideal combination of items 1 and 2 would be an ordinary, commercially-available, white light source feeding a passive, flat panel which would emit all of the light (no color filters which absorb significant amounts of light) in RGB pixels matched to the LCD.

The ideal version of item 4 for head mounted and projection displays would be a depixelating diffuser to produce a smooth image of controlled angular extent. We will show below that we can accomplish these goals.

#### C.2.1 LCD Backlighting

All high density gray scale LCD's and Active Matrix Color LCD's require a backlight.<sup>8</sup> Interest in improving backlight performance is increasing rapidly driven by the large world-wide investment in high performance LCD display screens. At the simplest level, all backlights consist of one or more light sources and an optical system.

Today's technology offers four solutions to light sources for backlights: electroluminescent panels, light boxes, edge lights and flat lamps.

Electroluminescent panels are not very power efficient, and suffer from short operation life.

Light boxes use tubular fluorescent lamps, a holder, reflectors and diffusers. There may be several singular lamps or serpentine lamps. Power efficiency is good but it takes a relatively thick box to achieve uniformity. This is totally unsuitable for head mounted displays.

Edge Lights take the light from a fluorescent tube and couple it into the edge of a specially designed plastic (or glass) plate. The plate is optically designed so that light is directed out the front surface. It is possible to have a thin backlight profile but the intensity is limited since the light is generated in one fluorescent lamp and spread out over a relatively large area through these special plates which are not the most efficient means. These are not easily pixellated into ultrasmall spots.

Flat lamps are being developed by a number of companies.

The associated optics for LCD backlighting inherently incur large light losses. These typically include a pair of polarizers and a compensation filter to convert the natural blue of the LCD to a more eye-pleasing black. Combined, these can reduce light throughput by as much as 60%. In the case of color LCDs, the color filter layer absorbs typically 70 - 80% of the light entering

it. In addition, active matrix LCDs (AMLCDs) have a series of windows, surrounded by interstices where the control transistors reside. The ratio of window area to the entire panel area varies with different designs and manufacturers. Typical throughput loss from light that strikes the interstices rather than the windows can be around 50% or more. Overall, of light that is available to go through the LCD panel, only about 15% actually makes it through.

This severe light loss means that brighter lamps are required, which use more electricity, and therefore cost more money, and, in the case of battery operated systems, significantly reduces battery life. For consumer applications, the power consumption of the light source is also strongly restricted, with respect to weight, volume, cost of the power supply unit for the light source and audible noise from the fan for cooling both TFT-LCD's and the light source.<sup>3</sup>

For color active matrix LCD's the color filter array currently represents the largest single component expense. The backlight subsystem is an additional expense for all current LCD designs. Backlighting technology is in a constant state of improvement. New designs are focusing on using a single tube placed along the edge rather than multiple tubes located behind the panel. Tubes are only part of the backlight cost. Inverters, reflectors, light pipes and diffusers also contribute.<sup>10</sup> Today the predominant light source used for backlighting is a fluorescent tube<sup>4</sup>.

The ideal backlight for LCD displays would be a thin film that efficiently converts low voltage direct current into white light with a uniform surface brightness up to 3000 cd/m<sup>2</sup>. There is no such source. Electroluminescent panels are the closest physical approximation to this ideal, but they have relatively low brightness. Flat fluorescent lamps have promise, but have not yet achieved the desired combination of low cost, lightness, reliability and thinness necessary for them to see widespread use. Therefore most of today's high brightness backlighting applications use light sources that are not planar, but which produce sufficient light with reasonable efficiency, e.g. cold cathode tubular fluorescent lamp, and the slightly more efficient hot cathode tubular fluorescent lamp.<sup>5</sup>

### C.3 ITI's Technology

Clearly a need exists for better, more efficient backlighting technology. ITI has spent the past two and a half years developing trade secret and proprietary techniques for producing high quality edge-lit holograms. A detailed background and explanation of edge-lit holograms can be found in Sections III-C and III-F. Briefly, holograms in the past have typically been illuminated by an external source with special characteristics (e.g. collimated light or a distant point source, or a laser). ITI's technology allows light to enter a substrate from the edge. Light travels through the substrate is redirected by a hologram laminated to the substrate. This hologram forces the light to exit the substrate in a controlled direction, with structured characteristics which are determined by how the hologram was made. We call such a holographic system a 'holographic light panel' (HLP).

Therefore, the most basic HLP consists of light travelling through a substrate, and then being emitted by the hologram to illuminate an object such as an LCD (active or passive) panel. ITI has developed a patent pending technique to use a white light illumination source and have the hologram emit light within a narrow wavelength band. This is a white-to-monochromatic system. It is also possible to create a white-to-white system, that is, white light illuminating source, and white light emitted by the HLP, by using a two hologram system. Here the light source illuminates a hologram on the face of the substrate which couples the light into the substrate. The light travels through the substrate and gets emitted by the output hologram. The output holograms can be made to couple the light out with reasonable uniformity (see Section III-D) and significant efficiency (theoretically approaching 100% at a given wavelength).

For AMLCDs, the next step to improving efficiency would be for the output hologram to emit light only where the AMLCD windows are and not in the location of the interstices. ITI has already demonstrated a prototype of such a device. In this prototype, light input to the edge of a plastic substrate strikes the output hologram, and is emitted in a checkerboard pattern. ITI has one prototype consisting of approximately 1600 1.4mm square monochromatic pixels, where light from each pixel focuses approximately 3 millimeters into space above the plane of the hologram. The machine used to make the mask for this hologram has the capability of producing pixels in any pattern (lines, triads, checkerboard, etc.) down to 0.2 micrometers per pixel. It should be emphasized that considerable efficiency is gained by only sending through the windows, and not at the interstices between the windows. In addition, by only sending light through the windows of a TFT-LCD, the temperature rise associated with such systems is diminished because the illumination energy normally absorbed by the interstices is eliminated.

Going one step further, ITI has already begun experiments, but requires funding assistance, toward making the pixel array noted above in RGB colors. Therefore, the most expensive and light inefficient component of an LCD display, the color filter layer can be eliminated! This reduces costs and enhances efficiency.

Another feature that has been discovered regarding ITI's edge-lit holograms, is that they maintain at least some degree of polarization. If the polarization ratio can be sufficiently controlled, this would eliminate one of the polarizers commonly used in LCDs, allowing a further light throughput gain.

Taking the ultimate step, ITI has also begun experiments on a technique to modulate the pixels in the hologram. If this concept is successful, it could lead to the elimination of the LCD itself!

ITI's holograms are made in photopolymer. Once the master is made and registered to a particular LCD model is perfected, replication of the holograms should ultimately prove to be very inexpensive, certainly compared with current AMLCD manufacturing costs.

These advantages over current backlighting technology offer the potential for significant efficiency improvement.

#### C.4 DEPIXELLATION

One of the biggest problems associated with head mounted displays, or projection systems is that the pixels in these systems are optically magnified, causing annoying 'pixellation' in the displayed images. Professor Phillips has invented and can produce a photopolymeric microlens structure which is registered with the pixels (or stripes, where needed) for a given LCD system, which effectively merges the red, blue and green subpixel images into white, yielding the most effective depixelating system that we have seen. We propose to marry our hologram technology with this depixelation technology in order to achieve the highly effective, efficient and clear display imagery necessary for successful head mounted displays.

### Detailed Technical Approach

ITI has already developed successful techniques for making edge-lit holograms. Several types we have achieved include:

- true edge lit, waveguide hologram
- true edge-lit, no bounce hologram
- 2 hologram, face-lit, waveguide hologram
- 2 hologram, face-lit, no bounce hologram
- steep reference angle hologram.

Since the quality of image bearing holograms is quite subjective, no formal measurements have been made of the samples we have produced. However, Holographic Light Panel quality must be objective, and correspond to strict, measurable specifications. Our technical plan, then, involves utilizing and enhancing the techniques we have already developed to make light panel samples, carefully measuring their characteristics, as noted in Section III-A2, and then optimizing our processes to achieve results as close to the desired specifications as possible. While we have already made impressive proof of concept samples, considerable work still needs to be done to achieve holograms optimized for LCD applications.

Some of the history and background behind our present technical status is described in Section III-F. We will describe here some of the characteristics necessary for a successful backlighting system, as noted in Section III-A2, and how we propose to approach achieving these goals.

#### UNIFORMITY

It is important for each area of the backlight HLP, or each pixel with a pixellated HLP to emit the same amount of light as any other area or pixel, within a given tolerance, e.g. 10% or 20% differential, depending on the application. Fortunately, the eye is very forgiving of such luminance differences, which would tend to make looser tolerances more acceptable than with some other features.

In order to achieve uniformity in our hologram outputs, we propose the following concept. In particular, as light travels through a substrate, or a waveguide, or a hologram at an oblique angle, it gets absorbed along the way, according to Beers Law, so that the part nearest to the light source sees the most light, and the part furthest away sees a significantly depleted amount of light. This can be a factor in both the recording and the playback of the hologram. The problem is what we call illumination depletion. It is possible in principle to precompensate for this problem during the recording. The primary goal of this component of the technical plan is to perfect that precompensation method. Four distinct tasks can be identified as necessary to the accomplishment of this component of the plan.

#### Task 1

Task 1 is the quantification of the output pattern of the hologram. We will record a standard hologram, illuminate it in a standard way, and plot the output intensity with

specially designed equipment. The hologram we will record will have a plane wave as an object. This means that the field of view for the reading equipment will not be a problem. Readout will be via an optical fiber connected to a detector. The optical fiber will be translated under computer control in x and y to plot out the output intensity pattern.

#### Task 2

We must record a precompensation mask. Remembering the previous discussion, we understand that we must record a hologram with a uniform plane wave. The reconstructed pattern will then be used to expose a photographic mask. There are many ways we can vary the linearity and base density of that recorded pattern.

#### Task 3

Task 3 is to record the plane wave through various precompensating masks. Obtaining the proper exposure will be a significant concern.

#### Task 4

Task 4 will be to quantify the 2-dimensional output pattern derived in this manner. In principle, this pattern will be quite uniform. In practice it will inevitably require considerable experimentation to perfect this technology.

This cycle of precompensation, recording, and quantification will be repeated as needed until we have perfected the ability to record holograms of plane waves in this manner. It remains then to go through the cycle several more times recording various objects, to convince ourselves that the precompensation mask made for plane waves is adequate for recording extended objects. We have no reason to doubt this, because the subtle errors it will introduce are likely to be totally lost to the human eye. That is, the eye is very tolerant of small gradual variations of illuminations.

### DIFFRACTION EFFICIENCY / LUMINOSITY

At a given wavelength, it is well known that holograms have the capability of achieving nearly 100% efficiency. That is, nearly 100% of the incoming light can get channeled into one of the first diffraction orders. Achieving high diffraction efficiencies in holography is dependent on many factors, such as the material used, the exposure density, the processing chemistry, the vibrational stability of the system, and the index of refraction modulation achieved in the material. We have the advantage of having Prof. Phillips on our team, who is one of the most skilled and knowledgeable holographers in the world. We have successfully achieved very bright edge-lit hologram prototypes, but their actual efficiency and luminosity have not yet been quantified. This quantification is an important part of the effort proposed here, and is commonly done by comparing the light emitted by the hologram, collected by a radiometer, with the light entering the hologram. One great advantage that we have is that even if our holograms only achieve modest efficiency, we believe that the comparative gain over current systems, whose efficiency is very poor (see Section III-C), will be significant.

### PIXEL RESOLUTION

In order to produce pixellated HLPs, we have developed special techniques for making masks which are used as the object for our holograms. Larger masks are computer generated, smaller feature masks are made by standard high resolution printing techniques, or electron beam lithography. This is a straightforward process. Masks can easily be made to match any known LCD pixel array pattern, down to a feature size of around 0.2 microns, which is much smaller than any feature required for current high resolution LCD technology.

### VIEWING ANGLE

Holograms inherently have a limited angle of view. The deeper the image, or the smaller the construction aperture, the smaller the region where the image is viewable. In the case of HLPs, the image is either the extent of the exiting light field, or the image of the pixel mask. Images in the plane of the hologram exhibit the widest viewing angle. Restricting the angle of view is quite straightforward, using known techniques for aperturing the object beam used in the construction of the hologram. In the case of Head (or Helmet) Mounted Displays, typically only a small viewing angle is required. The smaller the viewing angle, the more efficient the display, since more light is channeled to a smaller solid angle. One of the ways that we will be able to control the viewing angle, making it smaller or larger, according to desired specifications is by the special photopolymeric gradient index microlens diffusers that Prof. Phillips has developed and patented. By varying the size and thickness of the microlenses and the gradient index variation, we can achieve a wide range of viewing angles, which can be tailored, for example, to maximize in the horizontal plane and minimize in the vertical, or achieve peak transmission in any desired direction.

### RGB PIXELS

Techniques for making full color holograms have been known for many years. Recently, both the Russians and the Japanese have made some excellent image-bearing full color holograms. However, since edge-lit holograms require light to travel along a much longer path length in the holographic medium than standard holograms, we need to develop new techniques or special materials in order to achieve full color. DuPont has a polychromatic photopolymer, which has the capability of achieving good full color standard holograms, and the capability to "tune" the colors by allowing post-processing monomer migration. In early experiments with this material we have not met with great success for edge-lit holography. However we are working closely with DuPont, and they are developing special photopolymer formulations for us to our specifications, specifically for use with edge-lit holography. The materials issue is really the key to achieving success at making an RGB pixellated HLP. There are several techniques that we will explore, including working with the new DuPont materials, and creating special masks to allow us to expose red, a blue and a green mask image in the same hologram. We will devise special techniques to allow proper registration of each mask. If we are unsuccessful with this technique, there are several others we will try, including differential swelling and shrinking of localized areas of the hologram, which will create variations in interference fringe spacings, which translates to different color outputs in different areas of the hologram. Another technique would be to laminate three holograms together in registration.

### COUPLING TECHNOLOGY

The least understood aspect of this work is the coupling of light into the waveguide light panel. Theoretical analysis by Prof. Caulfield shows that the only way to avoid lateral chromatic dispersion altogether is

- use a grating (hologram) input coupler, and
- arrange the illumination beam, the input hologram, and the output hologram so that light enters and leaves the hologram in the same direction (probably normal to the waveguide).

Taking this as our goal, the unanswered questions include these:

- In what ways do point and line sources differ in their net coupling efficiency?
- In what ways do the angular divergences in the two directions (in-plane and out-of-plane) impact efficiency?
- How are all of these parameters affected by waveguide geometry and mode structure?
- How does the hologram design impact efficiency? How close to 100% of the input light can we get out of the hologram?
- What kind of optics should we use? What beam conditioning elements?

This part of the total program will be performed by and at Alabama A&M University (AAMU). The first step will be a complete modelling of the illuminator system. This can and will involve computer ray tracing, but it must also explicitly include the mode structure of the waveguide.

A recent PhD project under Prof. Caulfield (the AAMU PI) provided for the first time, the analytical tools to handle thick waveguide holograms in a rigorous manner. We will apply this methodology (see appendix) to the illuminator hologram. Modelling the source, the beam conditioning, the source optics, and the coupler will be complicated by the fact that there are so many choices.

For instance, we have

- filament systems (line, coiled, etc.)
- arc lamps
- LED's (singles, arrays)
- laser (diode, gas, solid)
- etc.

Within limits, each can be shaped by

- lenses (refractive, reflective, diffractive, holographic, etc.)
- stops, slits, pinholes, etc.

Thus besides building up the models, we must develop some preferences and rules of thumb to help us decide which systems should be modelled.

Once we can model a total system, we can at least partially optimize it. Both simulated annealing and genetic algorithms will be so slow as to be totally impractical, but steepest ascent can be used to find the local optima of the systems initially modelled. Thereafter we can downselect to a few of the locally optimized systems.

Through continuing interaction with the other team members, we should have a good system ready to test soon after the optimization is complete.

The next AAMU task is to design and assemble tests to verify system performance. As all metrology is circular, these test must trace back to primary or secondary standards. That is, they must be quantitatively and absolutely calibrated.

Next, in collaboration with its partners, AAMU will assemble multiple couplers of each type on multiple holograms. These will then be tested, and the results will be compared with theory. Inevitably, this requires some adjustment of both test and theory to accomplish full reconciliation.

Finally AAMU will use all of its experience and analysis to that point to "optimize" the couplers for any particular applications ARPA and other team members suggest.

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It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above construction, articles, and methods without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described, and all statements of the scope of the invention which, as a matter of language, might be said to fall therebetween.

Having described our invention, what we claim as new and desire to secure by Letters Patent is:

CLAIMS

1. A metal halide sensitized medium recording a phase modulated image wherein voids in the medium modulate the image and the medium is substantially free of the metal of the metal halide and the metal halide itself.

2. The medium defined in claim 1 wherein said voids are greater in volume at the antinodes in the recorded image than at the nodes thereof.

3. The method of recording a phase modulated image in a metal halide sensitized recording medium comprising the steps of:

- A. exposing said medium to an image;
- B. developing said medium by converting exposed metal halide grains to metal grains; and,
- C. bleaching and hardening said medium to remove said metal grains and form voids therein.

4. The method defined in claim 3; and the additional steps of:

- D. uniformly exposing said film to activate substantially all of the remaining metal halide grains therein;
- E. developing said film to convert substantially all the remaining metal halide grains therein to metal grains; and,
- F. bleaching said medium to remove said metal grains and form voids therein.

5. The method defined in claim 4 wherein said medium is gelatin and said hardening is accompanied by release of chromium ion at said metal grains.

6. The method defined in claim 3 wherein said medium is gelatin and said hardening is accompanied by release of chromium ion at said metal grains.

7. The method defined in claim 6 wherein said bleaching step is accompanied by use of a Dichromate.

8. The method defined in claim 7 wherein said Dichromate is Potassium Dichromate.

9. The method defined in claim 8 wherein said bleaching step is accomplished using a Persulphate.

10. The method defined in claim 4 and the additional step of:

G. amplifying said voids by applying a Propanol to said medium.

11. The method defined in claim 3 and the additional step of:

D. fixing said medium.

12. The method defined in claim 11 wherein said medium is gelatin and said hardening is accompanied by release of chromium ion at said metal grains.

13. The method defined in claim 12 wherein said bleaching step is accompanied by use of Dichromate.

14. The method defined in claim 12 wherein said bleaching step is accomplished using a Persulphate.

15. The method defined in claim 11 and the additional step of:

G. amplifying said voids by applying a Propanol to said medium.

16. A bleaching and hardening solution for forming a phase modulated image in a metal halide recording medium comprising:

- A. a dichromate; and
- B. a persulphate.

17. The solution defined in claim 16 further comprising:

- C. a hydrogen sulphate.

18. The solution defined in claim 17 wherein the proportion of said hydrogen sulphate in said solution is much less than said dichromate.

19. The solution defined in claim 16 wherein said dichromate is potassium dichromate.

20. The solution defined in claim 19 wherein said persulphate is potassium persulphate.

21. The solution defined in claim 16 wherein said persulphate is potassium persulphate.

22. A hardening bleach for a gelatin phase modulated image recording medium comprising a dichromate.

23. A regenerative bleach for a metal halide phase modulated image recording medium comprising a persulphate.

24. A bleaching and hardening solution for forming a phase modulated image in a metal halide recording medium comprising, in proportion:

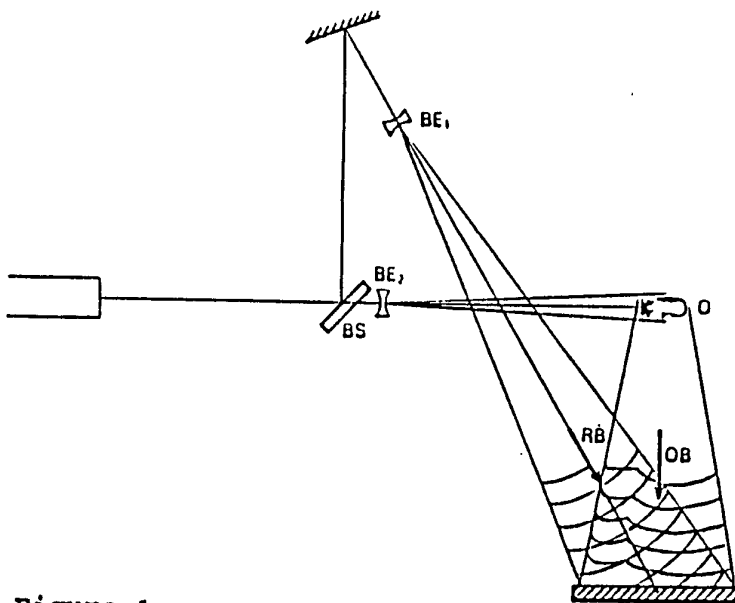
X-Dichromate, about 10 grams;

X-Persulphate, about 20 grams;

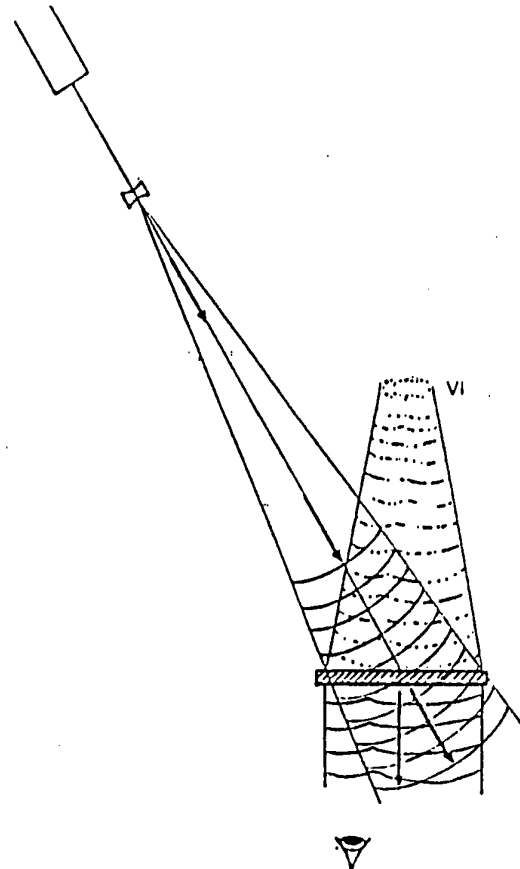
X-Hydrogen sulphate, about 2 grams; and

pure water to 1 Litre;

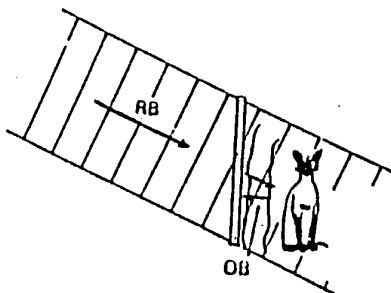
where X is an alkali metal.

**Figure 1**

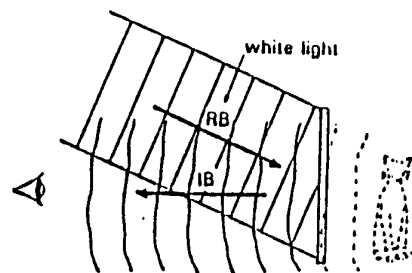
A simple transmission hologram geometry. The laser beam is split by the beamsplitter (BS). The reference beam (RB) bounces off a mirror and passes through beam expander BE<sub>1</sub> and continues to the hologram. The object beam (OB) passes through beam expander BE<sub>2</sub> and strikes the object. Light reflects from the object to the hologram.

**Figure 2**

Illuminating the processed hologram with a replica of the reference beam provides a virtual image (VI) occupying precisely the space of the original object.

**Figure 3**

Denisyuk (single beam) reflection hologram. In making the hologram the reference beam (RB) passes through the emulsion and illuminates the object to form the object beam (OB), which is incident on the emulsion on the side opposite to the reference beam.

**Figure 4**

The reflection hologram is replayed by a reconstruction beam (RB) on the same side as the viewer; the image beam (IB) is reflected from the hologram.

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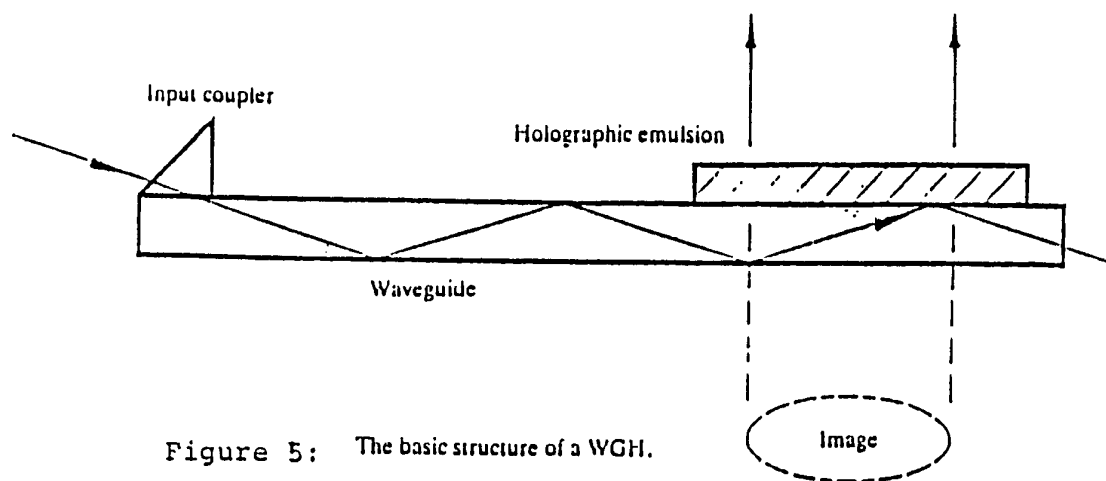


Figure 5: The basic structure of a WGH.

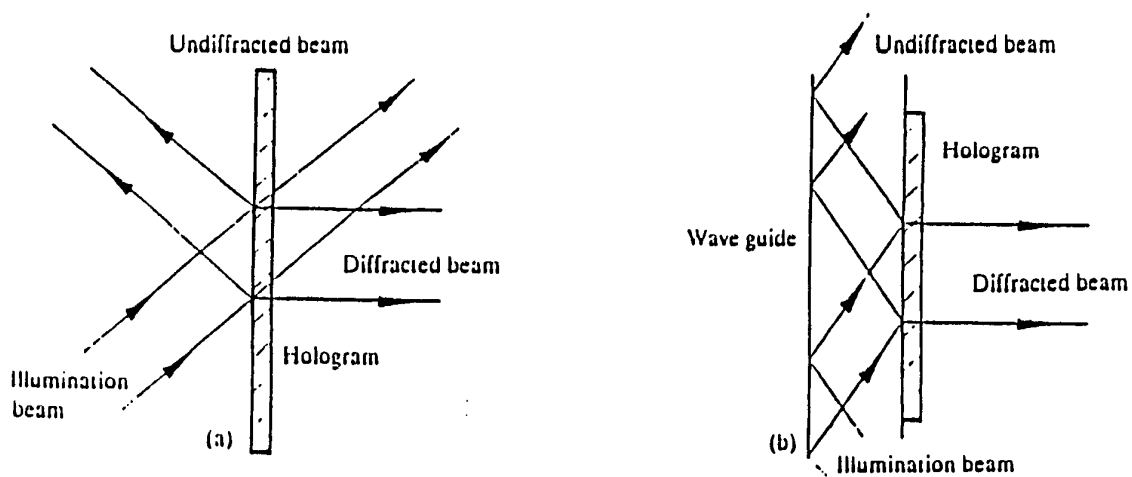


Figure 6: (a) Image reconstruction by a conventional hologram. The undiffracted beams increase the brightness of the background. (b) Image reconstruction by a WGH. The undiffracted beam is confined in the waveguide.

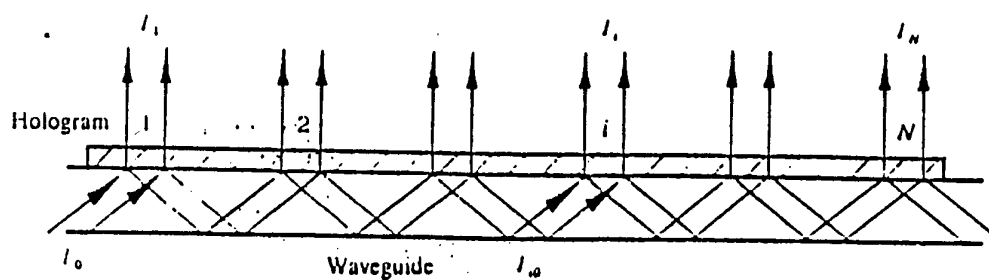


Figure 7: Multiple utilization of the illumination beam by a WGH.

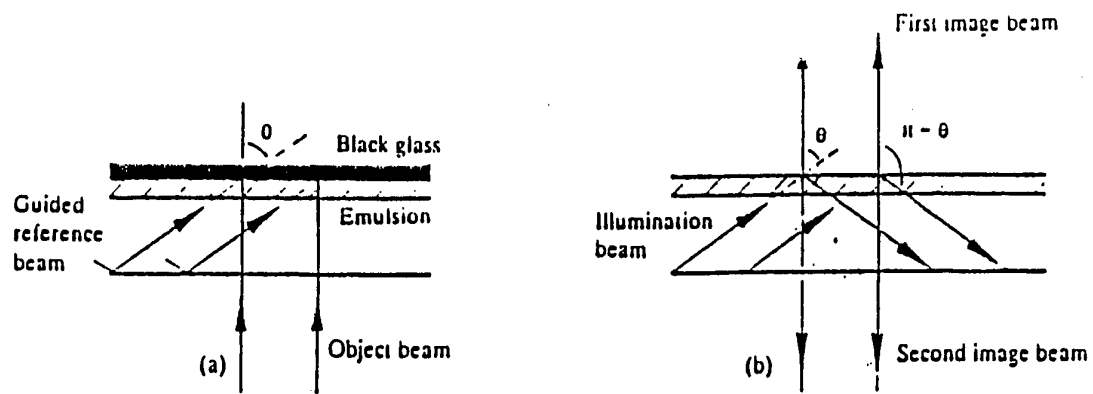


Figure 8: (a) Recording a WGH with a vertically incident plane wave. The black glass is used for anti-halutation. (b) The twin image effect of WGH reconstruction.

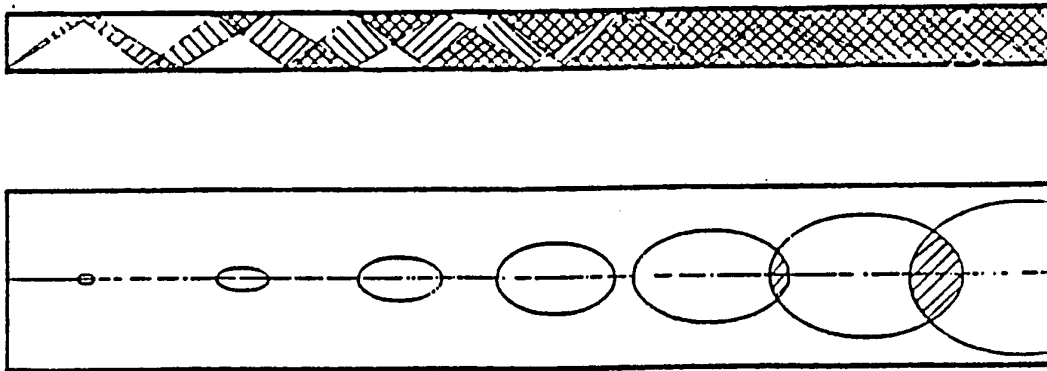


Figure 9: The propagation of a diverged beam in a waveguide. The shaded area is where multimode blurring occurs.

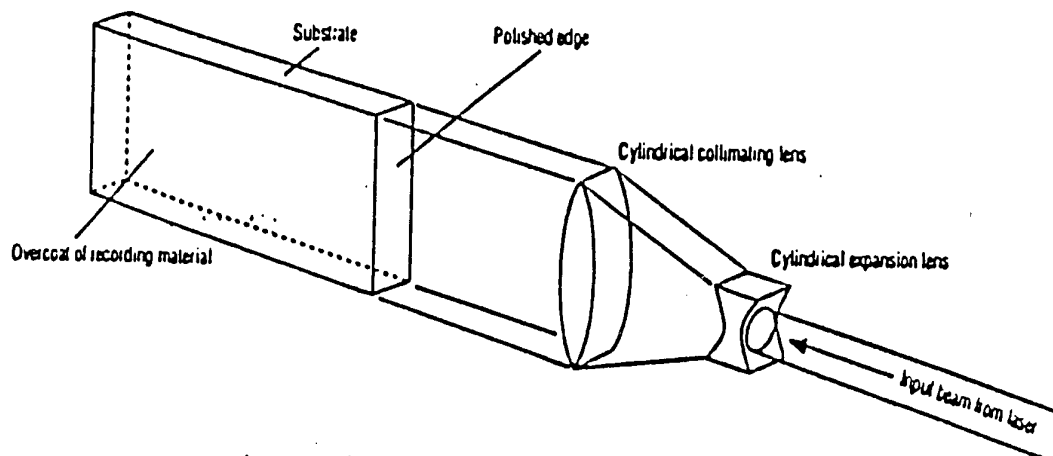


Figure 10