Title: HOLOGRAMS AND LIGHT PANELS

Abstract

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.
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HOLOGRAMS AND LIGHT PANELS
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 it's 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\textsuperscript{12}, Bryngdahl\textsuperscript{1}, Stetson\textsuperscript{1}, Lin\textsuperscript{1} 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\textsuperscript{6} and Miller\textsuperscript{7}).

Several years ago Upatnieks\textsuperscript{19,11} 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\textsuperscript{10,11}, 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 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, 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 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 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 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 Du Pont photopolymer and Ilford silver halide material. An interesting and unexpected result was achieved with the Du Pont 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 Leia'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 must 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 need to 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 diffrusing 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 monochrome 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.
BIBLIOGRAPHY

1. H. Nassenstein, "Interference, Diffraction and Holography with Surface Waves ("Subwaves"). I., Optik 29 (1969), 597
2. H. Nassenstein, "Interference, Diffraction and Holography with Surface Wave ("Subwaves"). II., Optik 30 (1969), 44
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.

![Diagram of HLP and LCD](image)

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 teh hologram for uniform illumination across the LCD.

![Diagram of light source](image)

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 monocromatic 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 monocromatic 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.
EXTENSION TO THE SIGNAL GATED
RECORDING PROCESS DISCLOSED IN S.N. 08/011,508

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.

\[ \text{Signal Wave} \]
\[ \text{Recording Medium} \]
\[ \text{Substrate} \]

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 \( \delta_0 \).

\[ \text{Diffuse Signal Wave} \]

The bulk index of the recorder layer is thus increased.

\textbf{THE BULK INDEX INCREASED BECAUSE POLYMER OCCUPIES LESS VOLUME THAN MONOMER.}

\textbf{N.B. WE NOTE THAT SIGNAL WAVE GATED HOLOGRAMS CAN HAVE ZERO NOISE BACKGROUND SINCE INTERFERENCE PATTERNS ARE ONLY PRESENT WHERE THE REFERENCE WAVE IS DIRECTLY TO LEARN IN.
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 *phenol* 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.

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

Whereas *normal* developing agents applied to for example an Agfa-Gevaert 3E65HD 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.
Agfa Gevaert 8075 plate material used for recordings.
We are sending 4 samples of True Edge-lit monochrome holograms to Alabama A&M University. They do not return but will guarantee next day delivery.

They are recorded at 514.5 nm

Fig.

and are played back thus. True conjugate reference

This is not the true conjugate of the original reference, but it works!!!

You will see that the index shift of the Acrylic has turned almost exactly to a slightly incorrect conjugate for replay. This bit of luck is extremely important. But the result clearly works well.
Two major techniques for making illuminators.

1. Holographic illuminators for white spot generation.

Stage (1a) - The making of hologram H1.

Stage (1b) - Replay of H1 into the copy H2.

L1 may need to be at least best form (least spherical aberration) or even aspheric.
Stage (iii) Relay of \( H_2 \).

Point source (white)

Real image of mask.

2. Holographic illuminati or for coloured spot arrays. In the first instance green.

Edge reference

Polymer layer

Image of \( H_1 \)

Conjugate reference

Dyesubstrate

Stage (iv) Forming an edge reference hologram of the spot array image of \( H_1 \).

We do not propose to relay \( H_2 \) directly with white light.
2.

Stage (ii): Fabrication of converter hologram H₁ to replay H₂.

In this stage, we are making an edge reference generator hologram.

The final use of H₁ is as follows:

Near grazing team to use as near edge reference for H₂.
Now we laminate H3 to H2 thus recreating the conjugate reference for H2 using H3. Note that H2 is illuminated over its large area.

The complete relay assembly is as follows:

H3 is laminated to H2 for relay. Note that no relay substrate is involved.

N.B. Because of the large relay angles involved the regenerated edge reference from H3 is nonochronous but matches the nonochronous edge reference requirement on conjugate relay of H2, thus H2 relay in monochrome.
ESTIMATES ON

1. SIZE

Depends on laser power - but suggest up to 10x10 in the first instance.

2. How long to define each optical setup?

With small design and sensitive components, a few days to set up basic file and test - a few minutes to change from strategy 1 to strategy 2. (White [note: color added] text). In many depends on rugged and economic design.

3. What throughput?

Depends on engineering rigidity and time of loading and unloading the recording.

4. First setup linear facility so that laminating is next to recording setup.

Loading in accurate layout. Loading substrate onto recording and 2 min. Exposure 2 min. or less. Unloading 1 min. Result 2 min. @ 10-11 min. /result.

This would be greatly reduced by high-speed contact copying, for example.

4. MATERIALS IN THE MAN ARE

(a) Photopolymer - (DuPont)
(b) Laminating materials (virtually negligeable compared to DuPont).
(c) Active display substrates.
6. Throughput in first 5 years. We might consider that illuminators and displays figure here.

Without mass production one recognition might yield 6 results/hour. But if we can laminate, de-lamination, leaving on to 100 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.
A basic diagram of a two component hologram assembly with aberration from transverse chromatic aberration.

1. Hologram element (off-axis zone plate).

Making of hologram element.

Replay by light from point source.

Chromatic properties on replay.

When lens 2 is replayed by lens 1, wavelength and angle adjust to give lateral acromaticism.
In these preceding diagrams, the reference angle θ is kept small enough so that the hole edges are not especially wavy with selective

We now reconsider the recording geometry so that the reference does not enter from air!

New, the angle of attack θ is beyond that attainable by allowing the reference to enter the recording layer from air.

Theoretically, replay of H1 should be as follows:
However, if the 'replayed reference' is coupled directly into an H2 as before, the extreme reference angle can be invoked thus

\[ \text{Source} \]

\[ H_1 \rightarrow \text{The gap will be set to zero by} \]

\[ \text{laminating} \]

\[ H_1 \text{ on to } H_2. \]

In such an example, chromatic selectivity is now high.

E.C.O. illuminators - Making strategies

1. (a) Making of holographic aperture generator
(b) Copying of H₁ into an H₂ narrow band illuminator

LENS

H₁

H₂

CONJUGATE
REFERENCE

FOCAL POINT.

REPLAY OF H₂ — BROAD BAND

AXIAL IMAGE OF APERTURES.

POINT WHITE SOURCE

NOTICE: THAT A SINGLE HOMOGRAN (H₂) IS USED IN THIS CASE.
(A) Recording of a monochromatically deflatable monochrome array.

(B) Recording of extreme external reference hologram for regeneration of conjugate reference of H2.
Display of H₂ by H₃.

We might need to use some tricks to prevent 'zero order' light from lamp leaking through.

For example:

N.B. All significant rays are beyond the critical angle.

Note that the extra light gathering by the refractive interface might be very useful.

In effect, lamp looks closer.
7.

To summarise, we need to make holograms and supports or spaces in the following categories:


2. Dual hologram monochrome converter system again using convergent reference in manufacture.

3. Basic hi array holograms - these could protect any shape or elemental feature - round or rectangular.

4. General displays

What about colour?

At the moment only green is understood.

The h2 replaced by hi scenario opens the door to overlayed next appropriate array.

Say we use 3 hi's for the primary and record hi using simultaneously red.

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 (cool green only for example).
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:

\[ \text{LINEAR LAMP} \quad \text{(LINE DIFFUSED)} \]

IT WILL NOT REPLAY A TRUE PARALLAX HOLOGRAM BECAUSE OF THE RAY DIRECTION FROM THE SOURCE EDGE OF HOLOGRAM

ONLY RAYS EMITTED INTO THE LAYER AT RIGHT ANGLES TO THE EDGE ARE RELOTTED.
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.

- Pixelated beam (PB)
  This is good for LCD displays: flat panel televisions, 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.

(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.

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. I 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 monochrome 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 depixel-late the image if one is magnifying (such as in a virtual reality helmet) or projecting.
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 hologram that is a transmission notch filter.

2. A pair of holograms, the first hologram adapted to direct light into the second hologram for single pass illumination thereof.

3. A pixelated display comprising an electronically controlled pixelated switching panel and a hologram adjacent to and illuminating said panel.

4. The display defined in claim 3 wherein said panel is a liquid crystal panel.

5. The display defined in claim 3 wherein said hologram produces a continuous white light over substantially its entire surface.

6. The display defined in claim 3 wherein said hologram produces pixels of white light.

7. The display defined in claim 3 wherein said hologram produces a multiplicity of three primary color pixel arrays.

8. The method of making an achromatic hololens comprising the steps of:

   A) recording an off axis zone plate hololens;
   B) recording a second off axis zone plate hololens;
   C) laminating the said zone plates in a back to back relationship.

9. A single pass edge-lit holographic panel.
**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, and continues
to the hologram. The object beam (OB) passes through
beam expander BE, 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.

These diagrams were taken from Practical Holography by Graham Saxby, Prentice Hall, 1988.
**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-halation. (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