1971

Non-technical guide to holography and its possible application to theatrical productions

Robert A. Cocetti

The University of Montana

Let us know how access to this document benefits you.

Follow this and additional works at: https://scholarworks.umt.edu/etd

Recommended Citation


https://scholarworks.umt.edu/etd/3097

This Thesis is brought to you for free and open access by the Graduate School at ScholarWorks at University of Montana. It has been accepted for inclusion in Graduate Student Theses, Dissertations, & Professional Papers by an authorized administrator of ScholarWorks at University of Montana. For more information, please contact scholarworks@mso.umt.edu.
A NON-TECHNICAL GUIDE TO HOLOGRAPHY AND ITS POSSIBLE APPLICATION TO THEATRICAL PRODUCTIONS

by

Robert A. Cocetti

B.A., Adams State College, 1963

Presented in partial fulfillment of the requirements for the degree of

Master of Fine Arts

University of Montana

1971

Approved by:

[Signatures]

Chairman, Board of Examiners

Dean, Graduate School

Date: June 4, 1971
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>ii</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Chapter</td>
<td></td>
</tr>
<tr>
<td>I. HISTORICAL BACKGROUND</td>
<td>4</td>
</tr>
<tr>
<td>II. THE LASER</td>
<td>7</td>
</tr>
<tr>
<td>A Concept of Coherence</td>
<td></td>
</tr>
<tr>
<td>Stimulated Emission of Radiation</td>
<td></td>
</tr>
<tr>
<td>Operation of the Ruby Laser</td>
<td></td>
</tr>
<tr>
<td>III. THE HOLOGRAM</td>
<td>19</td>
</tr>
<tr>
<td>Elements of Interferometry</td>
<td></td>
</tr>
<tr>
<td>The Hologram as a Zone Plate</td>
<td></td>
</tr>
<tr>
<td>IV. EXPOSING THE HOLOGRAM</td>
<td>37</td>
</tr>
<tr>
<td>Transmission Holograms</td>
<td></td>
</tr>
<tr>
<td>Absorption Holograms</td>
<td></td>
</tr>
<tr>
<td>Volume Holograms</td>
<td></td>
</tr>
<tr>
<td>V. THEORETICAL STAGE APPLICATIONS OF HOLOGRAPHY</td>
<td>55</td>
</tr>
<tr>
<td>Special Effects</td>
<td></td>
</tr>
<tr>
<td>Background Projections</td>
<td></td>
</tr>
<tr>
<td>Gabor Movie Concept</td>
<td></td>
</tr>
<tr>
<td>VI. SUMMARY AND CONCLUSIONS</td>
<td>66</td>
</tr>
<tr>
<td>APPENDIX</td>
<td>68</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>70</td>
</tr>
</tbody>
</table>
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Double Slit Interference</td>
<td>9</td>
</tr>
<tr>
<td>2. Ruby Laser</td>
<td>17</td>
</tr>
<tr>
<td>3. Characteristics of a Light Wave and Phase Relationships</td>
<td>22</td>
</tr>
<tr>
<td>4. Constructive Interference</td>
<td>26</td>
</tr>
<tr>
<td>5. Destructive Interference</td>
<td>26</td>
</tr>
<tr>
<td>6. Single Slit Diffraction</td>
<td>28</td>
</tr>
<tr>
<td>7. Double Slit Interference</td>
<td>28</td>
</tr>
<tr>
<td>8. Recording a Zone Plate</td>
<td>30</td>
</tr>
<tr>
<td>9. Re-Illuminating the Zone Plate</td>
<td>34</td>
</tr>
<tr>
<td>10. Hologram from a Zone Plate</td>
<td>36</td>
</tr>
<tr>
<td>11. Exposing the Absorption Hologram</td>
<td>40</td>
</tr>
<tr>
<td>12. Viewing the Absorption Hologram</td>
<td>43</td>
</tr>
<tr>
<td>13. Recording the Volume Hologram</td>
<td>47</td>
</tr>
<tr>
<td>14. Non-Pseudoscopic Image-Lens</td>
<td>51</td>
</tr>
<tr>
<td>15. Pseudoscopic Image-Hologram</td>
<td>51</td>
</tr>
<tr>
<td>16. Focused-Image Holography</td>
<td>53</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Young's Fringes</td>
</tr>
<tr>
<td>II. Zone Plate</td>
</tr>
</tbody>
</table>
INTRODUCTION

Holography is one of the newest and fastest growing parts of the science of optics. Its theoretical portions are now over twenty years old, but as a workable tool of science it is barely ten years old.

Holography is an intriguing three-dimensional projection system which uses no lens, no screens and yet is capable of projecting absolutely realistic three-dimensional images complete with parallax and in full color. It requires no special glasses to view the images.

While holography is a tool of science right now, its application to the arts is no more than a step away. Literature, especially science fiction, abounds in theoretical uses of holography in the arts. For instance, Ray Bradbury, writing an advertisement in the Saturday Review for the American Telephone and Telegraph Company, describes a system of home entertainment built on laser holography where the "Ghosts of Christmas Future" visit a home through a television-like medium. Bradbury describes these ultra-realistic images as appearing within the confines of a living room.¹

THX 1138, a science fiction movie of the 25th Century, envisions the use of a "holoroom"—another type of home entertainment center. On a more practical level, Robert Deubel, a partner in Concepts Unlimited, a firm specializing in designing a variety of visual materials for

industrial use, mentions the possibility of holographic projections in the live theater of tomorrow.

Although only scientists are using a hologram now, this slide of three-dimensions of which the laser plays an important light source, would have your audience moving or carousaling around it while perceiving this total three-dimensional light...it is available only at very high cost which neither we nor our clients can afford now, but it will become a thing in the future.²

The May issue of Theater Design and Technology mentions the holographic movie, and this indicates a beginning interest in the field of holographic projections for stage technicians.³

The point is that holography may become a very important tool in the repertory of the scene designer and stage lighting designer. The purpose of this paper is to introduce the general reader to the field of coherent optics using a minimum of highly technical material. The attempt has been to translate, as it were, the language of physics into the language of the stage. In doing so, the theoretical processes which go into the making of a hologram have been described and the laser as a light source has been discussed. Finally, an attempt has been made to determine how holography might be used on stage and which of the multitudinous types of holograms available might be best suited for stage use.

There has been a sub-text of cautious optimism throughout the paper indicating that the widespread use of holography is still a decade or so in the future, and that at least at the present time there is no magic formula for the stage use of holographic projections. There

³ "Recent Developments," Theater Design and Technology, May 1970, p. 36.
are too many questions which cannot be answered by anything short of
direct laboratory experimentation.

This paper has relied exclusively on published reports of
holographic experimentation, extrapolating from them the basic procedures
which, it is hoped, make up the necessary theoretical material for the
stage application of holography. The strict reliance upon published
material, as opposed to experimentation, was made necessary by the lack
of equipment, funding and a suitable place for holographic photography.
In holography, as in few other areas, nothing can take the place of
experimentation. Emmett Leith, one of the very important figures in
the development of holography, observed this fact when writing about
the first public showing of the hologram. "The greatest impact was not
made in any publication, but by our display at the spring meeting, 1964,
of the Optical Society of America. Holograms, it has thus been found,
makethe greatest impression when they are seen rather than merely
described."

This paper has been divided into five chapters. Chapter I is
a brief historical background. Chapter II discusses the laser, how it
is built and how it works and some of the terminology associated
with physics of the laser. Chapter III discusses the hologram,
particularly as it relates to a branch of optics called interferometry.
Chapter IV concerns itself with three major types of holograms; it
contrasts their similarities with their differences, and Chapter V
discusses the possible stage applications of holography using the
technology which is currently available as of this writing.

---

1Emmett N. Leith, "Holography: A Status Report," Laser Focus,
February, 1970, Footnote Number 7, p. 35.
CHAPTER I

HISTORICAL BACKGROUND

In terms of a historical perspective the twenty year old
science of holography owes its development to a mere handful of men.
The first of these and the inventor of the principles and theories
involving holography is Dr. Dennis Gabor, who is now serving as a
research scientist with C.B.S. Laboratories. As happens very often in
scientific research, the hologram was an accidental or unintended
offshoot of research into a different field. Gabor's research in the
late 1940's was aimed at a method of improving the resolving power
of the electron microscope—in particular a way around Scherzer's
Theorem which said that it is impossible to eliminate the spherical
aberration in the electron microscope. Gabor felt that it should be
possible to find a way around that difficulty by first taking "a bad
picture, but one which contains the whole information, and correct it
afterwards by a light optical process." As far as the original
project was concerned, Gabor was unsuccessful. But what he did do was
to find a way to capture all of the optical information necessary to
reconstruct three-dimensional objects—a fact which he mentions casually

5 Dennis Gabor, "The Outlook for Holography," Optik, XVIII
6 Ibid.
in his report in *Nature Magazine*. "It is a striking property of these
diagrams that they constitute records of three-dimensional as well as
of plane objects." 7

Gabor had at his disposal a complete body of theory showing
that it was possible to recreate three-dimensional pictures, but his
efforts at the early holograms resulted in very poor images due to the
lack of a good source of coherent light—later supplied by the laser.
Gabor called his optical process a hologram from the Greek word *holos*
meaning whole and *gram*, to write.

Gabor dealt with a type of hologram which would later be called
transmission hologram. Transparencies very similar to 35mm slides
were used as objects to be photographed and the early holography was
in effect a method of duplicating slides.

The hologram was nearly forgotten for a decade. Then in 1960
T. K. Maiman of the Hughes Aircraft Corporation developed the first
workable laser—a source of light whose heart was a small cylindrical
ruby rod. Here for the first time was an "almost perfect source of
coherent light." 8 It was the solution to the problems of coherent
light which had plagued Gabor ten years prior. The hologram was finally
able to produce the kind of image that Gabor had theorized that it
should.

The two men who first showed that holography could produce
nearly perfect optical images were Emmett Leith, a physicist, and
Juris Upatnieks, an electrical engineer. They were jointly engaged

7Dennis Gabor, "A New Microscopic Principle," *Nature*, CLXI
in research at the University of Michigan. The results of their research were published in a series of articles in the *Journal of the Optical Society of America.*

Leith and Upatnieks had not only perfected the transmission hologram but they had also developed the absorption hologram which made it possible to photograph three-dimensional objects (a model train and a pair of statues) and paved the way for the development of color holography.

Another University of Michigan researcher, George Stroke, is usually given credit for a workable method of color holography. Stroke's invention is called volume holography and its major contribution is that it makes possible color holography which can be viewed with a source of white light, unlike earlier holograms which had to be viewed by laser illumination.

These then are the major items of interest to holography, at least as far as this paper is concerned: The laser and the related problems dealing with the concept of coherent light, and the three major types of holograms, the transmission hologram, the absorption hologram and the volume hologram. Each of these will be dealt with at some length and finally an attempt will be made to adapt them to use on the stage.

---


CHAPTER II

THE LASER

The development of holography was impeded by the lack of a good strong source of coherent light from the days of Gabor's early conception of the project until 1960 when the laser was invented. But just what is coherent light, and how does it differ from ordinary or incoherent light, and why is it important to holography?

A Concept of Coherence

The first problem is to define the concept of coherence. There are many ways to speak of coherence, but the literature on lasers generally describes two different kinds: spatial and temporal.\(^\text{11}\) Temporal coherence has to do with monochromaticity or light of a single frequency or single color. There are other considerations, but light that is temporally coherent is commonly monochromatic. The other type of coherence is spatial coherence. This concept says that "there is a correlation between the phases of monochromatic radiation emanating at two different points." Or to put it another way, the light can be thought of as coming from a single point source. Again there are other considerations involved but usually spatial coherence involves a


point source. Ideally, then, light which is coherent both temporally and spatially is light which is emitted from a point source and is of one single color.

The difficulties that are encountered with this definition arise when one considers the light from an ordinary spotlight. It is emitted from a small source (a point source to the lighting designer but not to the physicist) and with suitable filtration it can be made "nearly" monochromatic. This is precisely the kind of light which was used in the early days of holography and still passes in many laboratories for "coherent" light. The problem is that there is a measurable difference between that kind of coherent light and light from a laser. There is a quantitative difference in much the same way that there is a quantitative difference between rainfall and a waterfall.

The refinements and measurements of coherence are made in terms of interferometry, which is the part of optics dealing with the superposition of light waves. (We shall have more to say about interferometry in the next chapter.) For the moment let us say that if a beam of monochromatic light is passed through two very narrow horizontal adjacent slits, S1 and S2 (Figure 1) and is then allowed to fall on a screen behind the slits, the light will arrange itself in a series of horizontal alternating dark and light bands or fringes called Young's fringes after the original experimenter. (See Plate 1)\textsuperscript{13} It is possible to measure the degree of coherence, for coherence is not an "either/or" situation, by relating the relative intensities of the


\textsuperscript{14}Lengyel, Introduction to Laser Physics, p. 26.
FIGURE 1- DOUBLE SLIT INTERFERENCE
PLATE I YOUNG'S FRINGES
light and dark bands. The more coherent the light, the darker the dark bands will be and the greater the contrast between light and dark areas. Light from a laser will give much greater contrast than will light from a lens and filter system. This is one of the quantitative differences.

A second difference involves the concept of a wave train or a "photon." Light propagates or travels in the form of the familiar "sine wave"—the same wave which is used to describe the characteristics of alternating current (Figure 3). A wave train is nothing more than a light wave of a certain finite length. The length of this wave train can be measured by other methods of interferometry. For instance, one can split a beam of monochromatic light into two parts by prisms or mirrors and then bring the two parts together again so that those beams form some interference pattern of alternating dark and light fringes. With a suitable mechanism (the Michelson interferometer) it is possible to measure the relative length of the wave trains. Light from a lens and filter system will have wave trains of a short length and light from a laser will have wave trains which are very long in comparison. The time it takes one of these wave trains to pass a given point is a measure of the temporal coherence.

The advantages that laser light has over other types of light can be seen in these measurements: It is light which is monochromatic or very nearly so; it has wave trains which are very long in comparison to light from ordinary thermal sources; and, these characteristics show

---

up in superior reading in interferometric devices. It shall be shown later that holography is merely an extension of interferometry.

This is why the greater coherence of laser light is important to holography. How it is created at the atomic level is indicative of some of the other differences between laser light and light from ordinary sources.

Stimulated Emission of Radiation

The word "laser" is itself an acronym. The letters stand for "Light Amplification by Stimulated Emission of Radiation." This is a good description of lasers—if you know what "stimulated emission of radiation" is.

Elementary physics tells us that the atom is composed of a nucleus containing protons and neutrons and a group of electrons surrounding and orbiting that nucleus. Roughly speaking the electrons rotate around the center of the atom in elliptical orbits. The electrons have a negative charge and the protons have a positive charge. There is in general one electron for each proton and the total charge of an atom is therefore zero.

The electrons in the outer shell or orbit will remain there as long as no external energy is applied to them. Atoms are then said to be in a stationary or ground state. If, however, sufficient energy of some kind is applied to an atom, be it from heat, collisions from outside electrons from electron guns, or possibly some source of electromagnetic radiation, that atom may absorb some of the energy from that external source. This will cause one of the electrons in the outer orbit—the
one having the highest energy already—to rise to a new state with still higher energy. The electrons will not stay in these excited states for long, and when they fall to their original level, they will release the energy that they have gained, sometimes in the form of light. This bundle of energy or "photon" makes up light and other radiant energy. This is the process of spontaneous emission.

When an atom absorbs radiation and an electron in the outer orbit rises to a new state or energy level, it does so in predictable steps. This is important because it allows scientists to determine what materials are capable of sustaining laser action and what frequencies of light can be expected from which materials. This phenomena can be shown experimentally by enclosing mercury gas in a glass box. If the gas is bombarded by an electron gun whose voltage can be continuously varied, there will be no absorption of energy and hence no light if the bombarding voltage is anywhere below 4.8 electron volts (eV). When the voltage reaches 4.8 eV, light in a narrow frequency band is emitted. Only this frequency is emitted until the voltage is increased to 6.7 eV and then light of another frequency appears. A third frequency appears at 8.8 eV, and at voltages beyond that the atom is disrupted to the point that electrons leave the atom and ionization takes place.

The inference drawn from this behavior is that the mercury atoms can only absorb discrete chunks of energy; that the atom is initially in

---


17 An electron volt is an extremely small unit of energy used when dealing with atomic and subatomic energies.

a "ground state" and is excited by absorption of 4.8 eV to a "first excited state"; by absorption of 6.7 eV to a "second excited state" and so on. The electrons eventually fall back into their stable orbit leaving the atom in its ground state. When it does so it emits a bit of light which is characteristic of the energy separation between the ground state and the excited state. For example, the frequency emitted by mercury atoms when they absorb 4.8 eV has been found to be far in the ultra-violet range.

All atoms have this same characteristic color emission. Each atom has a peculiar set of energy levels and these energy levels identify atoms in the same way that fingerprints identify people. The yellow light emitted when ordinary table salt is burned is characteristic of the sodium atom, for example.19

The laser operates according to these same principles except that it must include one more process. This is the creation of a population inversion. The normal state of electrons is that there are always more at the lower levels or states than at the higher levels. All the electrons are at the lowest level only at a temperature of absolute zero—minus 273.1 degrees Centigrade. At temperatures above absolute zero electrons tend to spread themselves over the set of allowed states so that they range from the highest to the lowest energy level but with the lowest levels always containing more electrons than any level above it. (In the usual case there will be so many more in the ground state than in any other that we can assume that they are all in the ground state.) The first step necessary to create laser action is to invert that

19 Ibid. p. 59.
trend so that one of the energy levels contains many more electrons than the ones below it. This is called a population inversion. This is accomplished by submitting the laser material to a high level of excitation. There are many possible ways of accomplishing this, e.g., electron bombardment, as previously mentioned, or possibly a high intensity light discharge. The creation of a population inversion is necessary because electrons in a high energy level give up a photon of light as they fall to a lower level while those electrons in the lower states can absorb that light. For "stimulated emission" to take place it is necessary that there be many more electrons in a position to give up radiation than there are to absorb that radiation.

Now suppose that while the population inversion exists a photon of light from some source is directed toward that group of electrons. When it collides with them there is the probability that it will cause another photon to be emitted which will travel in the same direction at the same time as the first, and the triggering photon will continue on its way unchanged. Those two photons will collide with others and create other photons, each of which will be of the same frequency and in phase with the other two. (Two waves are in phase if the peaks and valleys of one coincide with the peaks and valleys of the other.) This is the process of light amplification by stimulated emission of radiation.

All that is necessary now to make a laser is to find a suitable material and to design a container which augments that amplification process and helps to control the eventual light emission.

Material which is suitable for sustaining laser action has the capacity of remaining in the inverted state for a (relatively) long time.
Ruby is such a material. Ruby can be molded or machined in the shape of a rod which can be designed to contain within itself the means to contribute to the laser action. Because of its simplicity of design and operation, the ruby laser has become the standard textbook laser.

Operation of the Ruby Laser

The ruby laser as developed to T.H. Maiman was one of the first operating lasers. Ruby is essentially aluminum oxide with a very small percentage of the aluminum atoms replaced by chromium atoms. The chromium atoms are the only ones actively involved in the laser process. Maiman took a solid ruby rod and wrapped a xenon flashtube around it (see Figure 2). This tube was one of the photographer's flashtubes. The flashtube will supply the external radiation to excite the chromium atoms. As the flashtube is discharged the chromium atoms absorb the energy emitted by that discharge. This high level of excitation creates a population inversion. As normally happens some of the chromium atoms release energy spontaneously in the form of red light. If this light were allowed to escape, there would be only small amplification of energy and light travelling in all direction would be amplified the same. However, the ruby rod is constructed so that both ends are polished and mirrored— one partially and the other completely. The first photons which are spontaneously emitted in the right direction (along the axis of the cylinder) are thus trapped in the optical cavity of the ruby rod and as they are reflected back and forth between the polished ends, they trigger other electrons in the inverted state to emit photons of their own. The partially reflective end allows some of the light to escape.
FIGURE 2 - RUBY LASER - AFTER PIKE, P. 127 -
Practically all of the light emitted was stimulated by the few initial spontaneous photons, and all the photons are in phase and of the same frequency as them. Since the light is created by electrons falling from one particular energy level to another, the light is monochromatic or temporally coherent. Furthermore, the ends of the ruby rod are precisely machined and designed so that as the light waves travel back and forth inside the rod they all remain in phase or in step. This accounts for the relatively long wave trains of laser light and its spatial coherence.  

The process of light amplification by stimulated emission of radiation creates a light which differs markedly in four respects from normal light. Laser light differs in divergence, temporal coherence, spatial coherence and intensity. Temporal and spatial coherence are characteristics which are crucial to holography, and as shall be seen in the next chapter holography is able to use the high intensity of the laser beam to its advantage. Thus the laser beam forms a nearly perfect light source as far as the holographer is concerned.

---


22 Ibid. p. 114.
CHAPTER III

THE HOLOGRAM

According to Dennis Gabor

holography is the art of photography by coherent light, in which a record of the wave coming from an object is fixed in the [photographic] plate by interference with another wave, the 'reference wave.' The 'frozen' wave is then revived by illuminating the photograph, called a 'hologram' with a wave which can, but need not be the same as the reference wave, and need not even have the same wavelength.

Essentially this chapter will be devoted to taking this definition word for word and discussing holography in that manner, using Gabor's definition as a starting point.

Gabor says that holography is the "art of photography" implying some connection between holography and normal photography. Photography is a means of "writing pictures," but there are some interesting similarities and differences between holography and photography. The major similarity is that both of them use a light sensitive film to record reflected light waves from an object or scene. Both of them capture information about a scene from light waves that are reflected from that scene. But, that is where the similarity ends. Here are a few of the differences. First, holography need not use a lens in the process of recording an image—that is, unless one can keep from thinking of the holographic plate itself as a lens—whereas the lens is an integral

---


19
part of the normal photographic process. The second difference is that, in general, holography uses coherent light in the recording process and in normal photography the type of light used is of relatively little importance. Furthermore, holography uses a system of mirrors to direct a portion of the laser light to the film plane, bypassing the object to be photographed. This difference has to be diagrammed to be intelligible, (see Chapter IV) but some arrangement of mirrors or prisms used to direct the beams of light is essential to holography.

The final two points of difference between holography and photography have to do with the photographic negative. In ordinary photography the negative is a film image wherein the light and dark portions of a scene are reversed; that is, the light areas appear dark and dark areas appear light. When the "positive" is made, those light and dark areas are again reversed so that the final print portrays the scene as originally seen. In holography only one image is made and that image serves as both positive and negative, there being no distinction in holography.

The final difference is that in normal photography the negative or the photographic plate resembles the original scene. In holography the hologram bears no resemblance at all to the original scene. In fact all holograms, regardless of type or object portrayed, look alike—a "uniform gray sheet." 25


In normal photography the camera comes equipped with a lens and this lens focuses an image of the scene on the film plane. At the film plane the film records the varying intensities of the light by the action of the silver salts. These silver salts respond most to light of the greatest intensity and least to light of the least intensity. The result is that the negative becomes an impression of the focused image of a scene in varying degrees of brightness. It is at this point—the interaction of the light waves and the film—that the greatest differences between holography and photography exist. But, in order to understand them, one must become acquainted with the rudiments of interferometry—and this comprises the bulk of the remainder of Gabor’s definition:

"...fixed in the plate by interference with another wave."

_Elements of Interferometry_

Figure 3 is a representation of a sine wave; it is the simplest mathematical model for electromagnetic waves. As far as we need be concerned right now there are four important things about that wave: the wavelength, the amplitude or intensity, the frequency, which is mathematically related to the wavelength, and the phase. In Figure 3 the distance from point M to point N is called the _wavelength_. It is the distance from the peak of one crest to the peak of the next crest. In that part of the electromagnetic spectrum which we can see, the visible light portion, the wavelength varies from 16 millionths of an inch at the violet end of the spectrum to about 78 millionths of an inch at the red end.

---

AMPLITUDE $A$:
DISTANCE ABOVE X-AXIS

Y-AXIS

WAVELENGTH

M O P N

OUT OF PHASE:
PEAKS AND TROUGHS DO NOT COINCIDE

F

EYE

FREQUENCY:
NUMBER OF TIMES PER SECOND
PAST THIS POINT: $F$

FIGURE 3- CHARACTERISTICS OF A LIGHT WAVE AND PHASE RELATIONSHIPS
The distance \( A \), which is the maximum height of the wave above the \( x \)-axis, is referred to as the amplitude. The intensity or brightness of the light wave is directly related to the amplitude: the intensity is the amplitude squared. The higher the wave above the \( x \)-axis the brighter the light. This is the portion of the wave that black-and-white photography responds to—the amplitude or the intensity. Figure 3 is a representation of the light wave as if its motion had been stopped by the action of an ultra-high speed camera. The frequency is a measure of that motion, being the number of times per second that the peaks of the wave move past a given point, \( P \). Light waves oscillate or pulse in a manner similar to that of alternating current. The peaks and troughs are periods of the greatest intensity, and the points at which the wave crosses the \( x \)-axis are periods of darkness. But the speed at which this wave vibrates (about a million billion times per second) is so great that our eye integrates or smooths out the variations in the wave. The ordinary individual is not aware of these fluctuations any more than he is aware of the pulses of alternating current. But the fact that the fluctuations do exist is most important to the discussion of interference or superposition, a more descriptive term.

The other wave characteristic which must be considered is called the phase. Neither our eye nor the photographic film of a camera is sensitive to the phase of a light wave. The phase has to do with its location in time; e.g., in Figure 3 the wave starting upwards at \( P \) is slightly ahead in phase of the wave starting upwards at \( O \). These two waves are said to be "out of phase" with respect to one another. Two waves are said to be in phase when the peaks and troughs of one of them
corresponds with the peaks and troughs of the other. Colloquially these waves are said to be "in step."

Phase can also be thought of as the time lag or differential between two electromagnetic waves. This time lag can be (very roughly) compared to a sound recording process in which one microphone records one simple sound. The recording mechanism will respond only to the intensity of that sound (its amplitude) and when the recording is played back only that intensity will be reproduced. The location of that sound in space will have been lost. Now if a stereophonic recording is made of that same simple sound, the two microphones will record the sound at slightly different times. The sound will reach one microphone at a certain time, and some time later the sound will reach the second microphone. It is this difference in time or phase which establishes another dimension in the recording process and makes it possible in a stereophonic recording to locate a sound in space. Similarly it is holography's ability to capture the phase information of light waves which allows it to add one extra dimension to the photographic process. The phase information is captured through the "interference" of which Gabor speaks.

Interference or superposition has to do with the interaction of the phase differential between two beams of light. Interference is defined as "the modification of intensity obtained by the superposition of two or more beams of light." With the help of some diagrams and a couple of experiments easily performed at home, this concept will become clearer. Notice that the definition of interference does not

---

limit interference to coherent light, but rather says that it is applicable to all light. However, the most dramatic examples of interference or superposition are created by coherent light and this is also why the best holography is done by coherent light.

Figure 1 is a diagram of the simplest type of superposition. Take, for example, two waves A and B. If they are in phase, their peaks and troughs coincide and their wavelengths are the same, they can interfere constructively: their amplitudes will add together to form a new wave C whose amplitude is the numerical sum of the amplitudes of A and B. If the two waves are out of phase—their peaks do not coincide—they will interfere destructively: A new wave C will be formed whose amplitude is the difference between A and B (Figure 5). 28

The idea of constructive and destructive interference forms the basis of the phenomena of interference patterns—layers or fringes of alternating light and dark regions. These interference patterns can show up as horizontal or vertical arrangements of light and dark layers, or they can be arranged in concentric circles.

Light is generally thought of as travelling through space in the form of ever widening concentric spheres. Light waves in such instances are called spherical waves and often give rise to interference patterns of the concentric circle variety. Sometimes however it is convenient to think of or to work with light waves that are planar or travel as a series of planes. In this case it is usually assumed that the source of that wave is at an infinite distance away so that the wave fronts

Figure 4 - Constructive Interference

A + B = C

Figure 5 - Destructive Interference

A - B = C
are part of a sphere whose radius is infinite. It is possible to get light of this kind from a laser.

If such a wave were allowed to strike an opaque plate (such as exposed photographic film) that had one transparent slit etched into it (see Figure 6) a tenth of a millimeter or so wide, the waves would be diffracted, i.e., some of the light waves would be bent away from the normal, as it passed through this very narrow opening. This is due to the wave nature of light. Part of the wave is bent so that if one were to look at the light pattern on the other side of the opaque screen, he would see a wide shaft of light instead of the thin shaft that he might expect. Now if the opaque screen with one horizontal line was replaced by a similar screen with two slits etched into it and a beam of monochromatic light was allowed to strike the plate as in Figure 7, an interference pattern of alternating bands of light and dark fringes would result on a screen on the other side. The explanation for the interference pattern is that the light from the two slits arrives at the screen S at slightly different times, having different distances to travel. Because of this time lag or phase difference, the waves will interfere. For instance, if the peak of one wave reaches a point as the peak of another wave reaches the same point, the waves will interfere constructively creating a bright spot. If the peak of another wave and the trough of another wave reach the same point at the same time, the waves will interfere destructively creating a dark spot. The light and dark regions will be arranged in horizontal layers or fringes and this particular arrangement is called a grating.29

29 Ibid. p. 11.
- Figure 6 - Single Slit Diffraction -

- Figure 7 - Double Slit Interference -
This experiment can be approximated rather well at home with a slide projector, gelatin slide (Brigham gelatin Number 67, for example) and aluminum-foil-pinhole opening that can be used to approximate coherent light. The only other piece of equipment needed is an exposed piece of film that has two lines or slits etched in it. The slit can be made by a knife blade guided by a straight edge so that the slits are about one millimeter apart. By holding the film plate close to the eye and then by looking at the filtered light source, the interference fringes can be seen. In order to see interference patterns of spherical waves, it is necessary to replace the slits on the film plane with pinholes. Light which has been diffracted through a pinhole will exhibit diffraction just as the light did when it passed through a narrow slit. However, in the case of a pinhole the image on the screen behind will be that of a much larger circle than would be expected. If the light that illuminates the pinhole is from a laser, then as it passes through the pinhole it will change from approximately a plane wave to a spherical wave: It propagates itself through space as a series of ever widening concentric spheres. If the size of the opaque card that contains the pinhole is decreased so that some of the laser light is allowed to pass around it (Figure 8) then interference can be established between the plane waves of the laser light passing around the outside of the card and the spherical waves of the light passing through the pinhole on the inside of the card, and the resulting interference pattern will be a series of light and dark fringes arranged as a series of concentric circles. This circular arrangement of

---


Figure 8 - Recording a Zone Plate
interference fringes is called a zone plate. (Plate 2) Another home experiment will show the interference patterns between spherical waves and plane waves. The only equipment that is required is a flashlight, a piece of aluminum foil, a bathroom mirror and some kind of dusting or talcum powder. Cover the end of the flashlight with the aluminum foil and poke a small hole through the foil so that the light from the flashlight leaves through the tiny pinhole. Dust the mirror with the powder and then hold the flashlight at eye level close to the side of the head. Shine the light directly into the mirror. The interference pattern in this case is caused by the reflection of the light from the back part of the mirror or the silvered part and the glass surface to the front of the mirror. It will show itself as circular patterns of light and dark fringes on the mirror. The powder merely aids in seeing the faint rings. These rings are called Whewell's or Quetelet's fringes.32

The Hologram as a Zone Plate

Returning for a moment to the concept of a zone plate, recall that it is made by the interference between a spherical wave created when light is passed through a pinhole in a piece of cardboard and the plane wave passing around the cardboard undeviated or unchanged. This interference pattern takes the shape of a series of concentric circles in alternating patterns of light and dark (Plate 2). If this interference pattern was recorded on photographic film which was then properly processed and this negative containing a zone plate was illuminated with a laser similar to the one used to expose the film, a very interesting thing would happen.

Plate II Zone Plate
Suppose that the laser light illuminating the zone plate entered it slightly off-axis (slightly above or below and off to one side of a line drawn perpendicular to the zone plate and passing through its center). Part of that laser light would pass through the plate undeviated, part of it would be deviated upwards, and part of the wave would be deviated downwards as in Figure 9. This deviation is caused by the diffraction of light as it passes through the narrow fringes of the zone plate. Those waves which are deviated upwards are also deviated outwards so that the effect is one of a cone of light apparently emanating from a source of light at the apex of that cone, PV. "These waves form what is called a virtual image of the original point light source P (virtual because in the reconstruction no source really exists there)."\(^{33}\) Thus a viewer with his eye in the region indicated in the upper right corner of Figure 9 would imagine that he saw the original light source, PV, in its original position.

With any diffraction pattern waves are diffracted both upwards and downwards, and because the recorded pattern is circular the upwards waves diverge and the downwards waves converge or meet at a point. In this particular example the downwards waves converge to form a conjugate image, that is, an image which is the same distance from the zone plate as the virtual image but on the side away from the light source. This particular image is called the real image because a white card placed at the point of convergence would show a true concentration of light. Thus the zone plate is a hologram in miniature for what it has done is to record a picture of a point source of light, P. By illuminating that

negative with coherent light it is possible to reconstruct the image
of that original point source as the virtual image, PV, in Figure 10.
This is the virtual image and it is seen by looking through the hologram
so that it appears on the same side of the plate as the light source.
PR represents the real image of the hologram and it is a real (as
opposed to apparent) source of light. The real image is always seen
on the side of the plate away from the light source.

The next step in building a hologram from the concept of a zone
plate can be shown by replacing the card with the single point source
in it with, say, three cards each having a pinhole in a different
vertical location and each a different axial length away from the
photographic plate. The resulting zone plate when properly exposed
and illuminated will reproduce the image of the three pinholes in their
proper three-dimensional perspective. 34

In a hologram of three point sources, three separate zone plates
are created—one for each of the point sources. Now, any object or
scene can be considered to be nothing more than a nearly infinite number
of point sources of light, each of which will create its own zone plate
when exposed to coherent light, and each of which when reilluminated can
be placed in its proper three-dimensional perspective. The point
sources of light can be "frozen" in the photographic film and then can
be "revived" by reilluminating the hologram with coherent light.

CHAPTER IV

EXPOSING THE HOLOGRAM

There are three different kinds of holograms being studied today. They are the transmission or in-line hologram, the absorption hologram and the volume hologram. Volume holograms are sometimes called reflection or deep holograms. The differences among these three types of holograms, in general, are the differences in the relative positions of the reference and illuminating beams.

**Transmission Holograms**

The transmission hologram was the first type to be invented. It is in fact the hologram which Gabor used in his early experiments. It is also probably the least important from a theatrical point of view, its use being limited to laboratory experiments and classroom demonstrations. The transmission hologram is limited to photographing objects which are partially transparent, partially opaque and relatively simple. It is for this reason that normal photographic transparencies are ideal objects for experimentation.\(^{35}\) The relative position of the laser light, the transparency and the hologram is in a straight line, hence the name "in-line" holography. The light from the laser is "transmitted" through the transparency and the interference takes

---

place on the film plane between the light that passes through the transparency undeviated and the light that is diffracted by the opaque elements in the transparency. It is for this reason that not every transparency is suitable for experimentation. The best results have been obtained by using transparencies which have dark objects (lettering) on a transparent background.

As a classroom tool, the transmission hologram may be very useful and instructional. George Stroke, for example, has shown that it is possible to expose transmission holograms using very low power lasers and ordinary Polaroid cameras and film.

**Absorption Holograms**

The first major improvement over Gabor's transmission hologram came when Emmett Leith and Juris Upatnieks devised the absorption hologram. Their major contributions to holography were to pioneer the use of laser light for illumination and devising the idea of splitting that beam of laser light into two different parts—a reference beam and an illuminating beam. This creates the situation, as explained previously, where two beams of light are allowed to interfere and the resulting interference pattern is captured on photographic film.

Once the theoretical processes are understood, the actual making of an absorption hologram is a rather simple and straightforward project.

---


It requires eight pieces of equipment: a laser, a beam splitter, two diverging lenses, two high quality mirrors, a film holder and film and a target platform or some means to stabilize the object to be photographed.38

The film most commonly used today is Agfa-Gevaert 10875 emulsion which is the first commercial film made especially for holography. Although Kodak's 649-F spectroscopic film is still popular, the Agfa film is much faster (more sensitive to light so that shorter exposures are possible) and much more sensitive to red light. Sensitivity to red light is important because both the Helium-Neon and the Ruby laser emit light in the red region and these are currently the most popular lasers for holographic experimentation.

The equipment is arranged according to the diagram in Figure 11. The beam splitter separates the laser beam into two parts: the reference beam which is called "path one" in the diagram and the illuminating beam which is labeled "path two." The reference beam should be about three to four times the intensity of the illuminating beam and the length of the two paths should be about equal. For the absorption hologram the beams meet at the film plane at an angle of about 60 degrees.

The system must be aligned before any film is placed in the holder, and the method of doing this is to place a white card in the film holder and adjust the mirrors and lenses so that the reference beam just covers the film plane. Then by blocking the light from path

Once the alignment is completed, the other crucial factor in successfully making holograms is stability. Movement on the order of one wavelength of light (1/100,000th of an inch) is enough to ruin the delicate interference patterns on the film plane. Movement of this magnitude can occur from such sources as cars traveling past the building or even from movement within the room caused by breathing, so a very solid surface is a necessity. One method used successfully by some researchers is to use a large inner tube with a plywood top three to four feet square on it. Several heavy weights placed on the plywood insures a stable upper surface and the inner tube itself acts as a shock-mounting device which effectively insulates the hologram recording from external movements.

Lasers generally require a short period of warm-up which allows the components to stabilize. As it should be kept operating continuously, some sort of mechanical shuttering device is necessary. A piece of black cardboard or paper works well. The cardboard is merely placed in the beam path to shut off the light and is removed to turn it on.

Since photographic film is involved in the holographic recording process, the room must be darkened at all times while the film is being handled. Thus, once a stable base is available and the optical system

\[39\text{Ibid. p. 31.}\]
is aligned, exposing the hologram is simply a matter of mechanically
shuttering the laser light, placing the film in the holder and then
removing the shutter for one or two seconds. Replace the shutter
and develop the film according to directions, and once the film has
dried it is ready to view as no other processing is necessary.

Figure 12 shows the viewing arrangement. This viewing arrange-
ment merely reconstructs the photographic alignment. The hologram is
placed between the viewer and the light source. The virtual image
should be easily visible behind the hologram in the same relative position
that it was in during the recording session. The hologram plate forms
a window and the virtual image is seen as if looking through that
window; the real image can be seen (with much greater difficulty) on
the side of the hologram away from the light source. It is projected
cut in front of the hologram.

While the best results are obtained by viewing the hologram
with the same light that exposed it, satisfactory results can be obtained
by nearly any monochromatic or quasi-monochromatic source. For instance,
a slide-projector lens can be covered with a piece of aluminum foil
which has a pinhole poke in it. Brigham theatrical gelatin number 67
closely approximates the red light from the He-Ne lasers and provides
some degree of temporal coherence. A hologram which has been exposed
by a He-Ne laser can be satisfactorily viewed with this arrangement in
a darkened room.

Viewing the absorption hologram can best be described by
imagining that one is looking through a window which is placed in front

---

This is a typical exposure for a He-Ne lasers and Agfa 10275
film; exposure for different films and different lasers will require
experimentation.
Figure 12 - Viewing the Absorption Hologram
of the scene. The hologram is the "window glass" and the complete three-dimensional image is seen behind it.

In this respect it is as if one were looking at the actual object. However, the image is slightly grainy and is more transparent than opaque. In a hologram of a pair of dice and a pencil which is standing in front of the dice, for instance, the images form a line-pencil, die, die. When the observer moves his head, the apparent position of the pencil with respect to the dice changes (parallax). The observer may also see different views of the face of the dice. He would be limited to the same extent that a window ordinarily limits view. The image of the hologram is monochromatic for holograms which are played back by light from a single laser. For instance, holograms which are exposed by the Helium Neon laser will have a definite reddish cast to them.

**Volume Holograms**

It is possible to record holograms in full color using the techniques of the absorption hologram. Three successive exposures are made using light from three primary-colored lasers. Leith and Upatnieks succeeded in doing this in the early 1960's. However, the problem arises that during playback all three of the lasers must contribute to the illumination; three lasers were required to expose the hologram and three lasers are required to play it back. Shortly after Leith and Upatnieks' success with recording the absorption hologram, a group under the guidance of George Stroke devised a method of recording a

---

slightly different kind of hologram—the volume or reflection hologram. The only difference in recording technique was that the researchers split the original laser beam into two parts, but they directed them so that the beams met at the film plane on different sides of the plate. The single great advantage of volume holograms is that they not only can, but must, be played back in white light. The recording must be done with lasers, but lasers have been eliminated from the playback.

Theoretically the volume hologram is an extension of a now very old principle which was first discovered by Nobel-prize winning physicist Gabriel Lippman in 1891. What Lippman essentially did was to place a plate of photographic film in front of a highly reflective surface. Instead of mirror he used liquid mercury. When the film was exposed to coherent light, the light was reflected off the mercury behind the film and the same sort of interference between light waves occurred as was mentioned in Chapter III, only in this case it takes place within the thickness of the film plane. Light waves travelling into the film from the front side interfere with the light waves reflected off the mercury on the back side. Where the waves interfere constructively, there is an increase in amplitude and a corresponding denser exposure. At the areas of destructive interference the film will be lightly exposed. This interference takes place within the volume or depth of the film plate, and to the microscopic eye it might look like a series of venetian blinds arranged in successive parallel layers. When the plate is developed and illuminated by white light,

---

\[h^2\] Stroke, "Holography," p. 81.

\[h^3\] Born and Wolf, Principles of Optics, p. 280.
the venetian blind arrangement reflects only light waves of the frequency originally illuminating it. The Lippman layer "thus acts as a selective reflector for the light of the wavelength used to prepare it." This means that if a developed plate is illuminated by white light, then only light of a single frequency will be reflected from that plate.

Now, if the same idea is used to prepare a hologram, the mechanics of its exposure indicate that one of the beams should enter from the front side of the film and the other beam from the back side of the plate (Figure 13). Note that in the earlier discussion of holography it was tacitly assumed that the hologram was a two-dimensional plane, and that the interference phenomena took place on the surface of the film. Now with volume holography it is necessary that the interference takes place within the film. For example, Kodak emulsion 649-F is 17 microns thick, a micron being 1/1000th of a millimeter. Relative to the wavelength of light, say 0.5 microns, there is a considerable depth for interference to take place.

The volume hologram can be exposed to one wavelength of laser light and it will, when played back by white light, act as a selective reflector for that one wavelength and reconstruct a hologram in that one color. If, however, that exposure is made with a three-color beam, or with three lasers of the primary colors, a volume hologram will selectively reflect those three colors from the component parts of the white light beam and a full-color three-dimensional picture will result—from ordinary black-and-white film. The brightness of the image is

Figure 13 - Recording the Volume Hologram
actually enhanced directly “by the number of colors superposed during the recording.”

Thus the volume hologram offers some very exciting possibilities. It must be played back or viewed in white light, and it can reproduce full color pictures. However, to give full color reproductions it must be recorded using light from three different lasers or perhaps a multi-mode laser which can produce light in a variety of frequencies.

It is a little more difficult to describe the image of the volume hologram than it is to describe the image of the absorption hologram. The absorption holograms have been popularized in the non-scientific magazines. The volume hologram has remained largely in the laboratory. However, it is possible to report that it is nearly impossible to distinguish between the photograph of a hologram and the photograph of the original object when they are placed side by side.

Leaving the volume hologram for a moment, there are several other areas which are worth exploring. One of these is the “phase-modulated hologram” or as it is more commonly referred to, a phase hologram. “Bleaching an absorption hologram is an obvious method for obtaining a phase hologram.”

---

5 Stroke, "Holography," p. 82.

6 Ibid.


However, regardless of the causes of the phenomena, it is a well-established fact that the phase hologram forms a much brighter image than does an unbleached absorption hologram.

The bleaching agents range from the simple kind of bleach in Kodak's chromium intensifier as used by Cathey\footnote{Cathey, "Phase Holograms", p. 157.} to a special ferricyanide bleach devised by Burckhardt and Doherty.\footnote{Burckhardt and Doherty, "Bleach Process," p. 2479.} All of these reports stipulate that the hologram used to make phase-contrast holograms is of the absorption variety. Reports on bleaching volume holograms have generally been unavailable perhaps because the volume hologram is particularly sensitive to emulsion shrinkage, and photographic emulsion does shrink when a hologram is bleached.\footnote{D.H. McMahon and H.J. Caulfield, "A Technique for Producing Wide-Angle Holographic Display," \textit{Applied Optics}, IX (January, 1970), p. 92.}

Thus far it has been the virtual image of the hologram which has received the greatest share of the research; but there have been attempts to utilize the real image of a hologram, and these may turn out to be of some interest. Recall that the virtual image is the image on the same side as the light source and that it is seen as if looking...
through a window. The real image, on the other hand, is the image seen on the side opposite the source of light and is projected in front of the hologram. It is generally of much poorer quality than the virtual image and is much harder to see. Furthermore, the image is pseudoscopic.

The term pseudoscopy refers to the inversion of an image so that front becomes back and back becomes front. This can be explained by referring to Figure 14. The normal lens images a scene of points A and B so that if A is to the left in the original scene and B is to the right, then in the lensed image of the scene that same relationship holds: A is to the left and B is to the right. But in holography (Figure 15) the real image which is projected out in front of the hologram inverts the position of A and B. Instead of A-left, B-right, the relationship is B-left, A-right. Viewers of this real image will see objects in the rear become objects in the foreground and vice versa. It is this phenomenon that has been given the name pseudoscopic image.52

Leith and Upatnieks report an even more remarkable property of this real image, referring to Figure 15:

When one observes the virtual image, he will see object B in front of object A, and when the two objects are in line, object B will obscure object A as indeed it should. To observe the real image, the eye is placed to the right of object A in which object A is closer to the eye than is object B. As the observer moves his head, the parallax between B and A is in accord with their positioning. The curious feature is that when the objects A and B are brought into alignment, it is the object A rather than B which is obscured. The near object disappears and one sees the far object through the hole created by the disappearance of the near object.53


Figure 14 - Non-Pseudoscopic Image - Lens

Figure 15 - Pseudoscopic Image - Hologram
In order to circumvent this problem most of the research done on projected real images has been done with a single symmetrical object which is generally circular in shape such as a champagne glass. With this type of image there is no problem at all with front and back. There is only one object and the object is symmetrical front to back so that virtual and real images are exactly alike.

There is a possible way out of the difficulty presented by pseudoscopic imaging and that is to make a pseudoscopic image out of the original pseudoscopic image. In this case the result is a pseudoscopic-pseudoscopic image which is in effect a view of the original object as originally seen. With this process, any scene, including unsymmetrical ones, can be used as an image.

There is one other approach used to the satisfactory recording of real-image holograms and that process has become known as focused-image holography. It eliminates pseudoscopic imaging by exposing, in effect, the real image. The name is derived from the fact that the hologram is taken of an object which is first focused by a normal converging lens and the hologram is taken of that focused image. Referring to the diagram in Figure 16, suppose there is a scene of two objects A and B. They are focused through the lens to form the real image to the right A and B. Now note that the laser light from the bottom right is directed to the original scene and that the reference beam is diverted from that. Once this hologram is exposed, the objects will stand out in front of the hologram or film plane in their proper relationship.\textsuperscript{5h}

\textsuperscript{5h}Ibid. pp. 80-81.
These are the basic elements of holography. The absorption and the volume hologram represent the two most important types, and they can be exposed emphasizing either the virtual image or the real. The next chapter will deal with the possibilities of utilizing any combination of these four on stage. It will further explore the strengths and weaknesses of each type.
CHAPTER V

THEORETICAL STAGE APPLICATIONS OF HOLOGRAPHY

There seems to be a rather arbitrary division of projections into three separate categories which could be stage applications of holography. The class called special effects is one of them. This category might include such applications as projecting the ghost of Hamlet's father in a production of Hamlet; projecting an image of a knife in Macbeth's "Is this a knife I see before me?" or some other similar type of projection. Special effects could also include some kind of background projections of realistic (for example) outdoor scenes which do not comprise the main elements of a set. The second category could contain such applications as using projections on geometric shapes or planes such as is done with great success by Josef Svoroda. In this case projections become a part of the design in the sense that they add interest to pre-existing geometrical shapes. The third category would use holograms as the sole means of design. In this case the hologram forms the entire background; for instance, a production of Winnie the Pooh might use a holographic projection of a forest which encompassed the entire stage. Episodic plays such as Danton's Death might make use of a great number of projections, each of them being the major scenic element in the production. Full-stage effects could be

55 See Glenn Looney, "Josef Svoroda Retires?", Theater Crafts, January/February, 1971, p. 26 for examples of his work.
motion-picture sized and could give the playwright the freedom of a 
screenwriter in terms of location.

**Special Effects**

In the special effects category one of the most obvious uses of 
holograms could be to utilize their "window" property and actually 
replace whatever material is being used for a window—plexiglass, screen 
or whatever—by a hologram. Theoretically, at any rate, it should be 
possible to look through that window and see whatever realistic or 
impressionistic scene the designer might choose to use. If holograms 
were used this way on stage the viewing position in terms of observer, 
holographic plate, and image are in the same relative position as the 
absorption hologram: observer, hologram, image.

This application is not without its problems and following is 
a list of the five most obvious and crucial problems.

(1) The absorption hologram for best results should be played 
back by laser light. This practice is at least dangerous, at most 
expensive and troublesome.\(^{56}\)

(2) There is a definite size limit to the absorption hologram—
at least when exposed according to the directions given in Chapter IV. 
For instance, Agfa's 10B75 emulsion comes in 70mm rolls. This is the 
size of standard 120 film—2\(\frac{3}{4}\)\(\times\) \(2\frac{3}{4}\)\(\)\. Reports are fairly common of 
absorption holograms being made on \(4\)\(\times\) \(5\)\(\) film and some have been 
exposed which are as large as \(11\)\(\times\) \(14\)\(\)\. However, this is still far 
too small to be useful on stage.

\(^{56}\) See Appendix for a list of precautions to be followed when 
dealing with laser light.
There is a critical angle of view beyond which either of the images cannot be seen. For instance, consider a straight line formed by the light source and the geometrical center of the hologram. The viewer's eye must be slightly off to one side of that line and slightly above or below. This critical angle subtends only a few degrees so that even if all of the other problems could be solved (and for the most part they can), this still indicates that the absorption hologram as typically exposed is inadequate for use on the stage because of its limited visibility.

Absorption holograms are generally exposed with only one source of light so that the image is monochromatic. A hologram exposed with the He-Ne laser which operates in the deep red region of the spectrum (6328 Angstroms) will have a definite reddish cast to it. This factor, of course, may or may not be objectionable.

There is a considerable amount of expense and precision needed to make a hologram. There is about $200 worth of equipment needed to make the hologram described in the preceding chapter not including the laser, and these holograms are clearly not suited for use on the stage. There is also the very real problem of time, money, equipment, and a suitable place to work—one that is free of dust, vibrations, and intrusions. That certainly is not descriptive of the typical scene shop.

Thus, while it is theoretically possible to use the absorption hologram as a window, for instance, practical problems tend to limit its usefulness. However, some of the limitations ascribed to the absorption hologram in terms of angle and view can be solved, as will be shown momentarily.
The "window" effect uses the virtual image of the absorption hologram. The other type of special effects projections would probably use the real image of either the absorption hologram or the volume hologram.

The volume hologram offers a means of solving at least some of the problems inherent in the absorption hologram. For instance, the volume hologram is played back by white light, eliminating the hazards and expense of using a laser on stage. The color of the volume hologram can be controlled so that anything up to and including full-color images are possible. However, this size limitation is still present and it is apparently even more of a problem with the volume hologram than with the absorption hologram.\(^5^7\) The critical angle of view still remains a problem.

Towards the end of investigating more thoroughly the feasibility of using the type of holographic projection typified by the projection of the ghost of Hamlet's father, letters were sent to nine companies which deal with custom holography.\(^5^8\) Each of the companies was asked "...could you tell me if it is possible to make a three-color volume hologram of a man which would project the real image a distance of say 20 feet so that the projected image would appear life-sized?"

Of the three answers which were returned, none is encouraging. Charles K. Febber of G-C Optronics in Ann Arbor, Michigan wrote: "It is possible to project the real image, in color, 20 feet, as you asked.

\(^5^7\) McMahon and Caulfield, "Wide-Angle Holography," p. 92.

You would need a hologram about 5 times larger than the man or roughly the size of a commercial movie screen in a movie theater. The cost would be prohibitive.  

The manager of the Advanced Optics Group at KMS Technology Center attempted to explain the need for the large sized hologram.

With respect to projecting a real image of a man over a 20-foot distance, I do not personally believe that such an image would appear life-like. As you are probably aware, the hologram plate must always subtend the line drawn from the viewer's eye to the object. For a real image, in other words, a line drawn from the viewer's eye must pass through any point on the real image and then through the hologram plate. Thus, a person standing twenty feet from your real-image man, which in turn is spaced 20 feet from the holographic plate, would require a hologram forty feet tall. This is the big disadvantage of real image holograms. With a virtual image, a line must always be drawn from the person's eye through the hologram plate to any point on the image. In this case, the viewer can look through a ¼-inch hologram plate and see a 20-foot image beyond the plate. In any case, we do not have the facilities for making such large holograms.

John Gillespie of the Jodon Associates was more to the point:

"...We do not feel that the state-of-the-art has progressed to this extent."

It is important to note that the difficulties expressed by Febber and Thomas are inherent in the projection of real images from either absorption of volume holograms.

It seems then that projected real images provide very limited projection possibilities. However, there are some interesting questions


60 Letter from C.E. Thomas, KMS Technology Center, March 1, 1971.

regarding these problems. One of them concerns an application called "holosigns." These are traffic signs apparently now in use by the state of Massachusetts which utilize certain properties of holography. Inventor Harry Forster describes a projector system wherein a box on a hillside projects an image to a point over the traffic lanes of a highway. "...the box contains an incandescent light bulb, an arc lamp, or some other conventional light source...and an aperture plate that others would call a phase hologram." Other than that, Forster is not saying any more about his process. In face he regards it as a secret. Neither has information from the Patent Office regarding this application been received as yet.

The point is that there is apparently some way out of the difficulty of projecting real images (assuming that this is ultimately what Forster has done) over long distances without the need for huge projection plates, and furthermore these images can be seen in daylight—a fact of more than incidental interest to the scene designer.

The conclusion seems to be that, given the present state-of-the-art, holographic projections for special effects, as they have been defined here, is not quite practical as yet.


63 Perhaps an unwarranted assumption in view of the source and lack of information.
Background Projections

One of the most promising applications of holography for stage use today seems to be in the second category, where projections are used to fill up geometrical shapes, and that combinations of shapes and projections is the scene design.

The reason for the optimism in this area is work being done on holographic projections in terms of large displays and display devices. D.H. McMahon and H.J. Caulfield have succeeded in devising a hologram which can be used (for instance) for table top models of terrain. The plate of glass usually covering a three-dimensional model of the terrain is merely replaced by a large hologram of that terrain. This hologram is capable of being viewed by a large number of people and it can be viewed over an angle of 62 degrees just as if one were looking at a glass covered three-dimensional model. It is illuminated from beneath by laser light.

The problem in exposing this kind of hologram is to move the object to be holographed close to the hologram plate and still find some way of getting a reflected beam and reference beam to the photographic plate. McMahon and Caulfield claim that for large holograms techniques of volume holography cannot be used because of the "emulsion shrinkage which occurs on development" disrupts the image. They have, however, succeeded in recording holograms which could be incorporated into Svoboda-like designs. The holograms can be large and

---


65 Ibid. p. 92.
they can be viewed over a wide angle. While they must be played back by laser, it might be possible to use some sort of quasi-monochromatic light to achieve an acceptable image. Unfortunately, these wide-angle images seem to be a little more difficult to expose than the conventional absorption hologram.

The McMahon-Caulfield hologram seems to be a fairly solid design possibility. Either upstage or throughout the depth of a stage, holograms could be arranged in various planes. One possible arrangement would be to replace a backdrop with a honeycomb of holographic panels. Illumination could be from the rear by ordinary ellipsoidal spotlight. As that back wall or series of panels is illuminated, the virtual image would appear in its customary place—behind the hologram. Different colored gelatin might be used for different effects. One other curious property of the hologram might be utilized in this application. A hologram can record several different images on one piece of film by rotating the film plane around its axis. A scene change could be as simple (or as complex) as rotating a hologram about some axis. Finally, there is no reason why the McMahon-Caulfield hologram could not be used for a "window" as envisioned in the special effects section.

Gabor Movie Concept

The third category of holographic projections—projections which cover the entire stage and impart a movie screen quality—is probably the most exciting, most feasible and the most expensive. Research along

this line is being conducted by Dennis Gabor. Projections of this type will be particularly important to theaters which are electronically oriented such as those envisioned by R. Buckminster Fuller as being the theaters of the twentieth century. 67

Gabor’s new concept is a three-dimensional projection system built upon holography which is suitable for movie-theater sized projections. Unlike the kinds of holography which have been dealt with here, it uses two projectors (one for each eye) and a screen. It is the screen which is the hologram. It apparently projects something like a volume hologram in both color and black-and-white. While the device has been issued a patent number (3,679,111), it is probably not quite perfected for commercial use. 68

In Buckminster Fuller’s theater, for instance, the walls could be made of whatever material Gabor’s scheme requires. Holographic capability could be built into the theater. Thus it would be possible, as Deubel imagined, to have “your audience moving and carouseling around it while perceiving this total three-dimensional light.” 69

In addition to the technical problems of exposure, visibility and placement, there are other problems which will present themselves as holograms are used on stage. Just as a normal two-dimensional slide looks one way when it is viewed at home and then quite another way when it is finally seen as part of a production, so too will holography


68Details of this projection system are available in a poorly written article in Industrial Photography, April, 1970, pp. 26-27.

look quite different when it is combined with the other elements of a stage production: actors, costumes, and lighting.

One of the very serious considerations will be stage lighting. It appears that the same kind of precautions will have to be taken with holographic projections as are taken with two-dimensional projections. The scenery will tend to be dark; dark carpeting or floors will help reduce unwanted reflected light. Lighting cannot be from a flat frontal angle; it must come from a high angle. The illumination will in general be subdued, and lighting instruments will have to be angled very carefully.

The actor's relation to the holographic projections is still another matter for consideration. This is much more difficult to assess because of the lack of facilities and equipment. For instance, how will an actor look in front of the hologram and how he will look within the hologram? These are questions which will have to be answered when this equipment is ready for stage use.

Up until now the question of using holographic projections on stage has largely been an academic one. The assumption was that holography still needed a considerable amount of development. This may now have changed with the recent publication of a news item stating that the Festspiele in Munich, Germany is producing Mozart's *Wunder Flute* (Magic Flute) using laser holography.70 There is no indication of either the kind of hologram or the type of application. Their reported budget is 20,000 marks (about $5,000) and this is not very much money at all in terms of what American researchers have been talking about. While the

---

The Festspiele production has at least indicated that it is possible to use holography on stage, it has raised more questions than it has answered. For instance, how many images were used and what kind of images were they? What was the quality of the image? What size were they and how successful was the application? What did the 20,000 marks pay for in terms of hardware, etc.? Finally, did the German designers find a totally new approach to holography; have they merely used existing techniques and lived with the limitations, or have they discovered some ingenious way around them?

These questions should be answered when and if the Festspiele productions techniques are published. This report should give researchers some definite guidelines to go by and it should point the way toward more productive research in holographic projections for the stage.
CHAPTER VI

SUMMARY AND CONCLUSIONS

Early in the history of two-dimensional slide projections, designers must have felt that the two-dimensional slide would be the ultimate form of scene design. As holography becomes more and more familiar to this current generation of designers, the same feeling may hold for holography: it will be the ultimate form of scene design. Such a feeling may be more optimistic than is warranted because holography, as a scene designer's tool, is beset with numerous technical problems. While it may not supplant the normal three-dimensional (and two-dimensional) forms of scenery, it may, like two-dimensional projections before it, form an important adjunct to the scene designer's art.

Certainly there are several things which are clear from the preceding discussion: (1) that holography can find a suitable niche in the scene designer's kit, and (2) that there can be no substitute for experimentation in determining the actual form that holography might take on stage. It will take actual physics laboratory work and on-stage experimentation before very successful holographic projections can be used on stage. This will require the close cooperation between a well-equipped physics laboratory and an interested theater. It will also require a good deal of time and money in order to find the best combination of holographic forms and illuminating lights that will mean
success in this kind of projection. This research will also undoubtedly uncover new storage mediums (other than photographic film) which may solve some of the problems caused by photographic film.

It also seems quite reasonable that some interested organizations (the United States Institute of Theater Technology is a logical one) might initiate a series of workshops or lectures on the feasibility of using holograms on stage. One advantage that such an organization has over a typical small college is the prestige to invite the Leith’s, the Strode’s and the Gabor’s to lecture and participate in workshops.

Finally, it seems that the advent of lasers and holography will breed a new generation of electronic instruments for the theater from laser-operated televisions to light shows the like of which has not yet been seen. One of the ultimate outcomes of this kind of activity will be that the scene designer and the scenery technicians will need a nodding acquaintance with the areas of science that affect these instruments. The field of science may play an ever increasing role in the development of new forms of theater.
APPENDIX

CAUTION LASER

1. Never look directly into the beam of any laser either with the naked eye, a telescope or binoculars.

2. Do not rely on sunglasses or other tinted materials to protect the eyes. Only specially designed filtering mediums should be used, and these vary with each laser wavelength.


4. For general experimenting, room lighting should be high (200 foot candles) in order to keep the eye pupil small and reduce the possibility of retinal damage.

5. Be careful of reflecting surfaces. Laser light can be reflected from any shiny surface, and that reflection can be as dangerous as the original beam.

6. Lasers are operated by high voltage electrical discharges, so beware of electrical hazards.

7. Do not operate a laser in rain, snow, fog, or heavy dust. Here again the danger of reflective radiation is apparent.

8. Do not track vehicular or airborne traffic with a laser.

9. Do set up an operating procedure check list and follow it each time.

10. Know the potential hazards of the particular type of laser being used; there are many different kinds.

---

Hologram Recording

Bill of Materials

<table>
<thead>
<tr>
<th>Item</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>He-Ne laser complete with laser tube, housing, and postage.</td>
<td>$65.75</td>
</tr>
<tr>
<td>Metrological Instruments, Inc.</td>
<td></td>
</tr>
<tr>
<td>143 Hardin Avenue</td>
<td></td>
</tr>
<tr>
<td>Bellmawr, NJ 08030</td>
<td></td>
</tr>
<tr>
<td>Automatic Power Supply including postage</td>
<td>$18.50</td>
</tr>
<tr>
<td>Model 60-625 holography kit, mounting holders or optical components,</td>
<td></td>
</tr>
<tr>
<td>and shock mounted rigid base with three triangular tracks including</td>
<td>$103.00</td>
</tr>
<tr>
<td>postage.</td>
<td></td>
</tr>
</tbody>
</table>

---

BIBLIOGRAPHY

Books


Magazines


and ______. "Reconstruction with Continuous Tone Objects." *Journal of the Optical Society of America*, LI (December, 1963), pp. 1377-1381.


Miscellaneous


Thomas, C.E. EMS Technology Center, Personal Letter, March 1, 1971.