AN EXPERIMENTAL DESIGN FOR PRODUCING HOLOGRAMS

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An Experimental Design for Producing Holograms

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DECLARATION

This thesis is my original work and has not been presented for degree in any other University.

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This thesis has been submitted for examination with our approval as University supervisors.

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DEDICATION

I dedicate my entire work to my parents Mr. and Mrs. Fred Ominde for their unsurpassed effort and ever commitment to my life. Your never ending love and encouragement has made me what I am. I am proud of you Mum and Dad. Thank you so much for being so dear to me. May God richly bless you, give you peace at heart and increase your boundaries to surpass all human understanding.

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Psalm 115:1 Not to us, O Lord, not to us but to your name be the glory, because of your love and faithfulness.

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ABREVIATIONS

BR	Bacteriophodopsin
CCD	Charge Coupled Device
CD	Compact Disc
CGH	Computer Generated Holograms
CW	Continuous Wave
DCG	Dichromated Gelatin
ESPI	Electronic Speckle Pattern Interferometry
ESA	European Space Agency
FSL	Fluid Science Laboratory
He-Ne	Helium Neon
HOE	Holographic Optical Elements
Hz	Hertz
JKUAT	Jomo Kenyatta University of Agriculture and Technology
LCD	Liquid Crystal Display
LPSF	Lens Pinhole Spatial Filter
MIB	Munich Innovative Biomaterials
Nd:YAG	Neodymium Yttrium Aluminium Garnet
$Nd:YVO_4$	Neodymium Yttrium Orthovanadate
OD	Optical Density
T	Transmittance
TB	Terabyte = $1 X 10^{12}$ bytes

$\mathbf{U_H}$	Transmitted Beam
$\mathbf{U_o}$	Object Beam
$\mathbf{U_R}$	Reference Beam

ABSTRACT

The challenge of how to differentiate authentic documents from counterfeit supplies has recently increased. The rapid growth and development of modern technology in our markets has made fake currency notes, fake bank credit cards, fake University certificates, and other fake government documents to find their way into our markets. Holography is proposed as a way of countering these forgeries. An experimental set-up to implement holography for both laboratory and commercial use has since been designed and fabricated. Using this setup, holograms of tailor made objects can now be made and attached onto documents to help any user verify the authenticity of the documents.

For the success of this research, local custom made setup was designed and fabricated. A successful advance was the designing and setting up of a tailor made optical table that perfectly suits holographic applications as well as other future experiments in the laboratories. The optical table is made purely from steel and weighs about 325 Kg. It is specially designed with good static rigidity and excellent stiffness. The table has a well damped structure with relatively low mass so that no low frequency resonances (<100 Hz) are present. Preliminary running of holographic set-up was done and from these, the best exposure times for efficient bright hologram was determined.

An intense study of holographic recording is thus presented here. A complete holographic setup has since been made and tested within this region. However, in general the genuine holographic technique documented in this thesis is very promising and can readily be applied in numerous scientific areas like holographic interferometry and holographic data storage as well as for commercial purposes

CHAPTER ONE

1.0 INTRODUCTION

1.1 Overview

Holography is the science of producing holograms. It was invented in 1947 by Hungarian physicist Dennis Gabor (Hungarian name: Gábor Dénes) (Gabor, 1949). A hologram is a record of the interference pattern created when two beams of laser light interfere on the holographic surface. It is a recording of both the phase and intensity of a light beam. Holography is a technique that allows light scattered from an object to be recorded as an interference and can later be reconstructed. A laser source, because of its good coherence, is the preferred light source in recording a hologram. The first holograms that recorded 3D objects were made in 1962 by Yuri Denisyuk in the Soviet Union (Denisyuk, 1962) and Emmett Leith and Juris Upatnieks (Leith *et al.*, 1962). Here, an experimental set-up that can implement holography for both laboratory and commercial use in this region has been designed and fabricated. Holograms can now be made locally and attached onto quality merchandise making it impossible to counterfeit these products. These holograms carry 3-dimensional special information from the company that can be used by any user to verify the authenticity of the documents. An intense study of holographic recording is thus presented in this research.

1.2 Problem Statement

With the rapid growth and development of technology, secure security features that are almost impossible to counterfeit are necessary. Holograms are the new media of 3-D art and are able to perform this task. Holography can also be used during recording of media where the volume of a compact disk is used instead of the surface during recording. Thus, the size of the compact disk can be increased from the current 700 Megabyte to 3.9 Terabyte (Berger, 2003).

General experiments to demonstrate holography especially for undergraduate experiments at Universities are thus desired. Unfortunately this has been a challenge especially in the Sub-Saharan region of Africa because of lack of sufficient funds to purchase the required apparatus or equipments that are quite expensive as well as lack of the well versed manpower to handle these. This study aims at a simple way of designing and demonstrating holography. These holograms can then be widely used, for instance, for demonstration during the training process, or commercially as security features on quality merchandise amongst others.

1.3 Objectives

1.3.1 Main Objective

To design and fabricate an experimental set-up that can implement holography for both laboratory and commercial use in the developing world.

1.3.2 Specific Objectives

1. To design a quick but relatively cheap way of producing holograms especially in the developing world.
2. To design and fabricate a stable optical table for demonstrating and producing holography in local education institutions.

1.4 Justification

Presently, holography is done by well established companies and institutions in the developed world. These include; the MIT Museum, Optware and Maxell Company, In Phase Technology amongst other few organizations. Most African companies and institutions would desire to carry out research and production in this field but are hindered by lack of sufficient resources and the well versed manpower to handle these. Success of this research is a major step forward especially for local companies and institutions. This research gives a local tailor made set-up that can be used in the laboratories to teach and demonstrate the process of holography to undergraduate students in the process of their training as well as a commercial tool for security features on quality merchandise like currency notes, bank credit cards, University certificates, and other government documents.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Development background of holography

Holography originates from the Greek words, holos meaning whole and grafe meaning writing or drawing. It is the science of producing holograms. It is a technique that allows light scattered from an object to be recorded as an interference pattern and later reconstructed. The scattered light from the object has both the intensity and phase variations and therefore the hologram stores both the phase and intensity variation of a light beam. Using the original light source used in recording the hologram, the hologram can be played back or reconstructed giving a 3-D appearance of the original object. The reconstructed image has the perception of depth. The technique of holography can also be used to optically store, retrieve, and process information.

Holography was invented in 1947 by Hungarian physicist Dennis Gabor (Gabor, 1949). The discovery was an unexpected result of research into improving the resolution of electron microscopes in 1947 at the British Thomson-Houston Company in Rugby, England. Using a mercury arc lamp, the non-coherent light source resulted in distortions in his images. These images he called holograms after the Greek words. He realized that his images contained more information than a normal photograph, but also that his discoveries had taken place before the necessary technological equipment had been made. He tried to make his light source coherent by sending the light both through a pinhole and colour filters, but the quality of his first holograms was poor. As a result of his contribution in holography, he received the Nobel Prize in physics in 1971. Holography was made possible by pioneering work in the field of physics by other scientists like Mieczysław Wolfke who resolved technical issues that previously made advancements impossible. The British Thomson-Houston company filed a patent in December 1947 (patent GB685286), but the field did not really advance until the development of the laser. Lacking a proper coherent light source, the interest for holography faded until the invention of the laser by Dr. T.H. Maiman in 1960. The monochromatic and coherent output from the laser made it possible to produce distortion free holograms of high quality. The first holograms that recorded 3D objects were made in 1962 by Yuri Denisyuk in the Soviet Union (Denisyuk, 1962) and by Emmett Leith and Juris Upatnieks in University of Michigan, USA (Leith *et al.*, 1962). Advances in photochemical processing techniques, to produce high-quality display holograms were achieved by Nicholas J. Phillips (Phillips *et al.*, 1976).

Several types of holograms can be made. Transmission holograms, such as those produced by Leith and Upatnieks, are viewed by shining laser light through them and looking at the reconstructed image from the side of the hologram opposite the source. The hologram is viewed with laser light, usually of the same type used to make the recording. This light is directed from behind the hologram and the image is transmitted to the observer’s side. The virtual image can be very sharp and deep (Leith *et al.*, 1962). For example, through a small hologram, a full-size room with people in it can be seen as if the hologram were a window. If this hologram is broken into small pieces or equivalently, the hologram is covered by a piece of paper with a hole in it; one can still see the entire scene through each piece. Depending on the location of the piece (hole), a different perspective is observed. Furthermore, if an undiverged laser beam is directed backward (relative to the direction of the reference beam) through the hologram, a real image can be projected onto a screen located at the original position of the object (Leith *et al*, 1962). A later refinement, the "rainbow transmission" hologram allows more convenient illumination by white light rather than by lasers or other monochromatic sources. Rainbow holograms are commonly seen today on credit cards as a security feature and on product packaging. These versions of the rainbow transmission hologram are commonly formed as surface relief patterns in a plastic film, and they incorporate a reflective aluminium coating which provides the light from "behind" to reconstruct their imagery.

Another kind of common hologram, the reflection or Denisyuk hologram (Denisyuk, 1962) is capable of multicolour image reproduction using a white light illumination source on the same side of the hologram as the viewer. The reflection hologram, in which a truly three-dimensional image is seen near its surface, is the most common type shown in galleries. The hologram is illuminated by a “spot” of white incandescent light, held at a specific angle and distance and located on the viewer's side of the hologram. Thus, the image consists of light reflected by the hologram. Recently, these holograms have been made and displayed in color with their images optically indistinguishable from the original objects (Berger, 2003). If a mirror is the object, the holographic image of the mirror reflects white light; if a diamond is the object, the holographic image of the diamond is seen to "sparkle." Although mass-produced holograms such as the eagle on the VISA card are viewed with reflected light, they are actually transmission holograms "mirrorized" with a layer of aluminum on the back. One of the most promising recent advances in the short history of holography has been the mass production of low-cost semi-conductor lasers (Hariharan, 1996) typically used by the millions in DVD recorders and other applications, but which are sometimes also useful in holography. These cheap, compact, solid-state lasers can under some circumstances compete well with the large, expensive gas lasers previously required to make holograms, and are already helping to make holography much more accessible to low-budget researchers, artists, and dedicated hobbyists (Berger, 2003). The other types of holograms are the ones referred to as Hybrid holograms, that is, between the reflection and transmission types of holograms, many variations can be made. These include:

1. Embossed holograms: To mass produce cheap holograms for security application such as the eagle on VISA cards, a two-dimensional interference

pattern is pressed onto thin plastic foils. The original hologram is usually recorded on a photosensitive material called photoresist. When developed, the hologram consists of grooves on the surface (Berger, 2003). A layer of nickel is deposited on this hologram and then peeled off, resulting in a metallic "shim." More secondary shims can be produced from the first one. The shim is placed on a roller. Under high temperature and pressure, the shim presses (embosses) the hologram onto a roll of composite material similar to Mylar (Hariharan, 1996).

2. Integral holograms: A transmission or reflection hologram can be made from a series of photographs (usually transparencies) of an object which can be a live person, an outdoor scene, a computer graphic, or an X-ray picture (Phillips *et al.*, 1976). Usually, the object is scanned by a camera, thus recording many discrete views. Each view is shown on an LCD screen illuminated with laser light and is used as the object beam to record a hologram on a narrow vertical strip of holographic plate. The next view is similarly recorded on an adjacent strip, until all the views are recorded. When viewing the finished composite hologram, the left and right eyes see images from different narrow holograms; thus, a stereoscopic image is observed. Recently, video cameras have been used for the original recording, which allows images to be manipulated through the use of computer software (Hariharan, 1996).

3. Multichannel holograms: With changes in the angle of the viewing light on the same hologram, completely different scenes can be observed. This concept has enormous potential for massive computer memories (Hariharan, 1996).
4. Computer-generated holograms: Essentially, there are three basic elements in holography: the light source, the hologram, and the image. If any two of the elements are predetermined, the third can be computed. For example, if a parallel beam of light of a certain wavelength is known and a "double-slit" system is obtained, the diffraction pattern can be calculated for. Also, knowing the diffraction pattern and the details of the double-slit system implies the wavelength of the light can be calculated. Therefore, any pattern to be observed can be easily evaluated. After deciding the wavelength to be used for observation, the hologram can be designed by a computer. This computer-generated holography (CGH) has become a sub-branch that is growing rapidly. For example, CGH is used to make holographic optical elements (HOE) for scanning, splitting, focusing, and, in general, controlling laser light in many optical devices such as a common CD player (Schnars *et al.*, 2002).

2.2 The Essential Principle of Holography.

As observed in Figure 2.1, a coherent light beam produced by a laser source is directed to a beam splitter that splits the beam into two coherent beams. One of these beams, the illumination beam (or the object beam) is directed to the object. On striking the object, some light is scattered from it and carries information about the surface of the object. The holographic plate is positioned so that this beam reflected from the object surface falls on it. The second beam referred to as the reference beam, is again directed to the holographic plate. The meeting of the two beams produces an interference pattern. This pattern is what is recorded on the holographic film, and is usually a light field whose intensity varies randomly depending on the surface profile of the object. Viewing the hologram at different angles will give a different view of the object, thus giving a three dimensional appearance (Hariharan, 1996). The exact wavefront produced by an object is duplicated by the hologram.

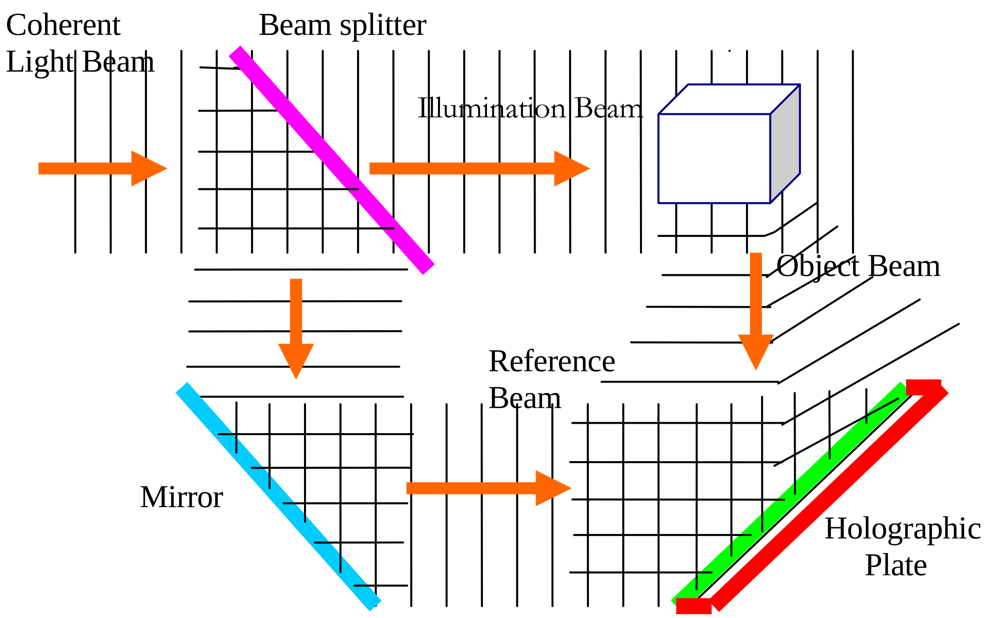


Figure 2.1: Optical arrangement for making a hologram of an object

It can be shown that if the hologram is illuminated by the original reference beam, a light field is diffracted by the hologram which is identical to the light field that was scattered by the object (Hariharan, 1996). Thus, someone looking into the hologram 'sees' the object even though it may no longer be present. This is known as the reconstruction process or simply playing back the hologram.

Figure 2.2 demonstrates the re-construction process. The original reference beam used during recording of object referred here as the reconstruction beam, is made incident to the holographic plate at the same angle as during recording. A light field is then diffracted by the hologram. This field is identical to the light field that was scattered by the object. A virtual image of the holographed subject is then formed.

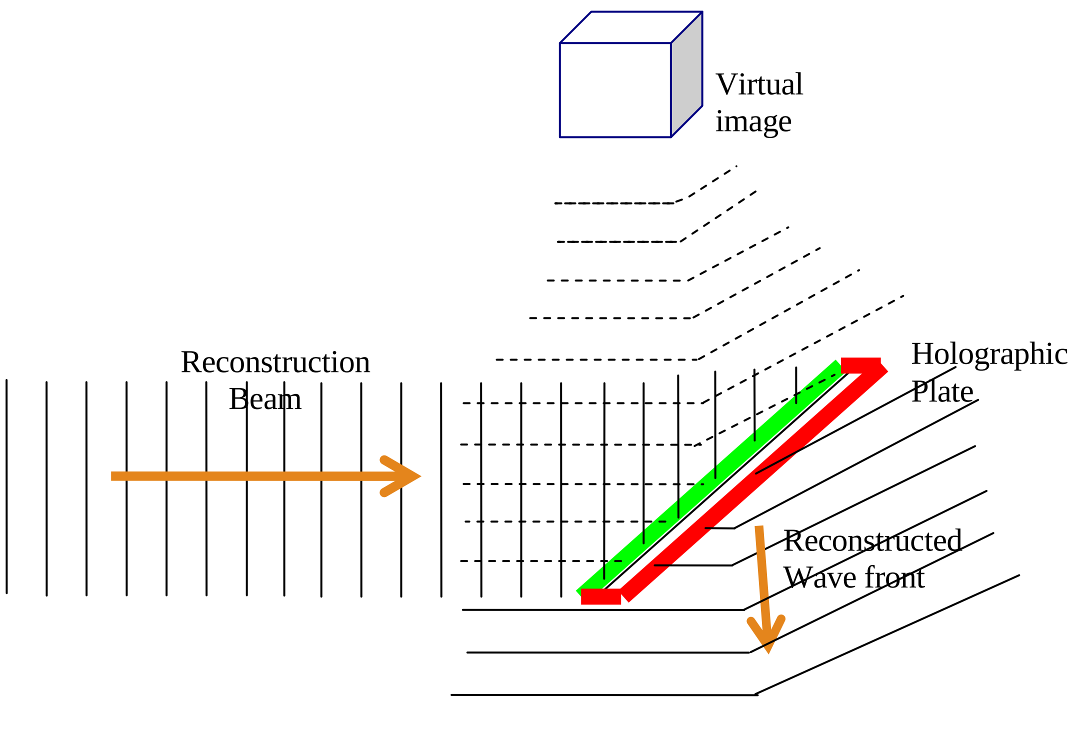


Figure 2.2: Optical arrangement for re-constructing the object beam.

There are a variety of recording materials which can be used, including photographic film. Some of this media used for holography include, the oldest - silver halide film which is a film similar to camera film, but of much higher resolution (Biedermann, 1977). These are excellent for wall pictures, portraits, etc. Dichromate hologram is made of special gelatin emulsion sealed between two glass plates. It is mainly used for small earrings, holo-watches, pendants, etc. It offers really bright and sharp imaging (Meyerhofer, 1977). Embossed holograms are the ones on "silver foil" (Meyerhofer, 1977). Here, photo resist films are used in place of photographic film. The image is recorded on photo-resist with the laser light in a dark room. General procedure for photo resist material development then follows. Once produced, they can then be applied on credit cards, books, stickers amongst other security applications. Embossed holograms often are multi-color. Color information is computer-generated before embossing process. Photo-polymer is a relatively new material. It gives very bright image on a flexible surface (Hariharan, 1996). Used for bright wall holograms, key rings, etc. It may be transparent - which opens new possibilities. The holographic sunglasses are made with photo-polymer (Urbach, 1977). One can look through normally, when on the other side they create extremely bright 3-D image.

An isolation table is essential in the recording of holograms because it eliminates external vibrations. The table can be as simple as floating a slab of granite, marble, or thick steel relative to the types of vibrations one is to eliminate. Its primary role is to act as a shock absorber. The table top should be extremely flat.

2.2.2 A hologram of a plane wave front

A diffraction grating is a structure with a repeating pattern. A simple example is a metal plate with slits cut at regular intervals. Light rays travelling through it are bent at an angle that depends on the wavelength (λ) of the light and a distance (d) between the slits as given by Equation 2.1.

$$\sin\theta = \lambda/d \qquad \text{2.1}$$

A very simple hologram can be made by superimposing two plane waves from the same light source. The first beam, the reference beam, hits the photographic plate normally and the other one, the object beam, hits the plate at an angle θ. The relative phase between the two beams varies across the holographic plate as $2\pi y \sin\theta/\lambda$ (Hariharan, 1996) where y is the distance along the photographic plate. The two beams interfere with one another to form an interference pattern. The relative phase changes by 2π at intervals of $d = \lambda/\sin\theta$ and hence the spacing of the interference fringes is given by d. Thus, the relative phase of object and reference beam is encoded as the maxima and minima of the fringe pattern.

When the holographic plate is developed, the fringe pattern acts as a diffraction grating and when the reference beam is incident upon the holographic plate, it is partly diffracted into the same angle θ at which the original object beam was incident. Thus, the object beam has been re-constructed (Phillips *et al.*, 1976). The diffraction grating created by the two waves interfering has reconstructed the "object beam" and it is therefore a hologram.

2.2.3 A hologram of a point source

Another kind of hologram can be made using a point source of light as object beam and a plane wave as reference beam to illuminate the holographic plate. An interference pattern is formed which in this case is in the form of curves of decreasing separation with increasing distance from the centre.

The holographic plate is developed giving a complicated pattern which can be considered to be made up of a diffraction pattern of varying spacing. When the plate is illuminated by the reference beam alone, it is diffracted by the grating into different angles which depend on the local spacing of the pattern on the plate. It can be shown that the net effect of this is to re-construct the object beam, so that it appears that light is coming from a point source behind the plate, even when the source has been removed. The light emerging from the holographic plate is identical to the light emerging when the point source was there. An observer looking into the plate from the other side will 'see' a point source of light whether the original source of light is there or not.

This sort of hologram is effectively a concave lens, since it 'converts' a plane wavefront into a divergent wavefront (Phillips *et al.*, 1976). It will also increase the divergence of any wave which is incident on it in exactly the same way as a normal lens does. Its focal length is the distance between the point source and the plate. A hologram of a complex object can be considered to be a set of point sources

2.3 The Theory of Holography

A light wave can be modeled by a complex number U which represents the electric or magnetic field of the light wave (Hariharan, 1996). The amplitude and phase of the light are represented by the absolute value and angle of the complex number. The object and reference waves at any point in the holographic system are given by U_O and U_R respectively. The combined beam is a superposition of the object and reference beam and is given by $U_O + U_R$. The energy of the combined beams is proportional to the square of the magnitude of the total electric field amplitude as given by Equation 2.2.

$$|U_O + U_R|^2 = U_O U^*_R + |U_R|^2 + |U_O|^2 + U^*_O U_R \quad \ldots\ldots 2.2$$

If a photographic plate is exposed to the two beams, and then developed, its transmittance, T, is proportional to the total light energy that was incident on the plate, and is given by:

$$T = K\,[U_O U^*_R + |U_R|^2 + |U_O|^2 + U^*_O U_R] \quad \ldots\ldots 2.3$$

Where, K is a constant.

When the developed plate is illuminated by the reference beam, the light transmitted through the plate, U_H is given by;

$$U_H = TU_R = K\,[U_O U^*_R + |U_R|^2 + |U_O|^2 + U^*_O U_R]\,U_R$$

$$= K\,[U_O + |U_R|^2 U_R + |U_O|^2 U_R + U^*_O U^2_R] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.4$$

It can be seen that U_H has four terms. The first of these is KU_O, since $U_R U_R^*$ is equal to one, and this is the re-constructed object beam. The second term represents the reference beam whose amplitude has been modified by U_R^2. The third term also represents the reference beam which has had its amplitude modified by U_O^2; this modification will cause the reference beam to be diffracted around its central direction forming a cloud around the hologram called halo. The fourth term is known as the 'conjugate object beam'. It has the reverse curvature to the object beam itself, and forms a real image of the object in the space beyond the holographic plate.

Early holograms had both the object and reference beams illuminating the recording medium normally which meant that all the four beams emerging from the hologram were superimposed on one another (Denisyuk, 1962). The off-axis hologram was developed by Leith and Upatnieks to overcome this problem (Leith *et al.*, 1962). The object and reference beams are incident at well-separated angles onto the holographic recording medium and the virtual, real and reference wavefronts all emerge at different angles enabling the re-constructed object beam to be imaged clearly.

It should be clear from this why a hologram is not a 3D photograph. A photograph records an image of the recorded scene from a single viewpoint, which is defined by the position of the camera lens. The hologram is not an image, but an encoding system which enables the scattered light field to be reconstructed. Images can then be formed from any point in the reconstructed beam either with a camera or by eye

Since each point in the hologram contains light from the whole of the original scene, the whole scene can, in principle, be re-constructed from a single point in the hologram. To demonstrate this concept, you can break the hologram into small pieces and you can still see the entire object from each small piece. If you envisage the hologram as a 'window' on the object, then each small piece of hologram is just a part of the window from which you can still view the object even if the rest of the window is blocked off. However, resolution is lost as you decrease the size of the hologram - the image becomes 'fuzzier'. This is a result of diffraction and arises in the same way as the resolution of an imaging system is ultimately limited by diffraction where the resolution becomes coarser as the lens or lens aperture diameter decreases.

2.4 Hologram Classification

There are a few characteristics, which are used to classify different types of holograms. These classifications are determined by the recording geometry (optical set-up), on how the reconstruction beam is modulated to diffract the image and it depends on the thickness of the holographic emulsion.

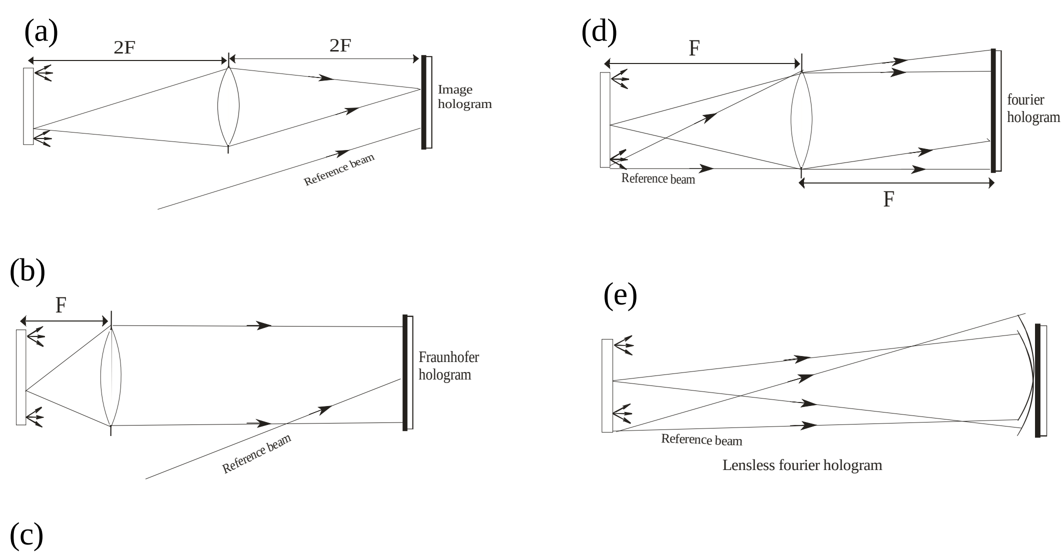
2.4.1 Recording geometry

The recording geometry decides whether the hologram will be classified as a transmission or a reflection hologram. If the two interfering waves (object and a reference beam) illuminate the emulsion from each side of the film, it is classified as a Lippman or reflection hologram (Gabor, 1949). They are also called “white light” holograms, as they can be observed under ordinary white light conditions. These holograms should be seen as a light reflection from the film plate. It has its name due to the reflection of light from the film.

The other type is called transmission hologram (Gabor, 1949). The two recording waves illuminate the film from the same side, and due to the recorded structure in the emulsion these holograms must be viewed with a coherent light source (laser). To view the hologram, the reconstruction light source must illuminate the film from the opposite side of the observer; hence the illumination light will travel through the emulsion and recreate the object (and therefore its name). The geometrical set-up also determines whether the hologram is a Leith-Upatnieks (the first to use this technique) “off-axis” hologram or a Gabor “in-line” hologram (Hariharan, 1996).

The difference between them are self-evident, as the in-line hologram use ~ 0° between the two interfering waves, and the off-axis holograms are all other recording geometries that use angles between the two interfering waves different from 0°.

The last classification due to the recording geometry is a consequence of the curvature of the interfering wavefronts at the hologram plane **(**Ostrvsky *et al.*, 1990). The curvature of the waves at the hologram, define where the minimas and maximas of the fringe pattern in the emulsion are created. The distance from object to film and the possible optical elements positioned between film and object, partly determine the name the respective recording receives. The different types are called "Image", "Fraunhofer", "Fresnel" and "Fourier" holograms. The recording geometry for the different holograms is shown in Figure 2.3.



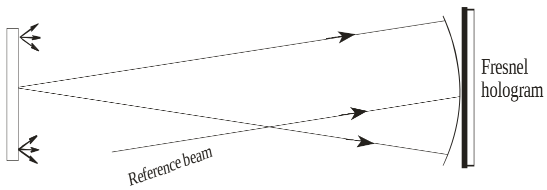


Figure 2.3: Holographic Recording Geometries **(**Ostrvsky *et al*, 1990). F represents the lens focal length, (a) Image hologram, (b) Fraunhofer hologram, (c) Fresnel hologram, (d) Fourier hologram and (e) Lens less fourier hologram.

A hologram recorded at an infinite distance from the object (Fraunhofer diffraction region) or projected to be at an infinite distance (using a lens), is called a Fraunhofer hologram. The object wave is evolving as parallel light onto the holographic film. The far-field condition is fulfilled if the distance from the photographic plate to the object is large compared to the dimensions of the object, **(**Ostrvsky *et al.*, 1990) given by:

$$Z_o >> \frac{(x_o^2 + y_o^2)}{\lambda} \quad \ldots\ldots 2.5$$

Here x_o and y_o, represent the two dimensions of the surface of the object.

The common Fresnel hologram is formed when the object is in the near-field diffraction region. Generally, the field at the hologram plane is the Fresnel diffraction pattern if the object is reasonably close to the recording medium. Smith (1977) showed this distance to be typically 10 times the object diameter or less from the film. If both waves lie at infinity, or have the same curvature of the wave front (lensless Fourier hologram), the complex amplitude of the waves at the hologram plane, are the Fourier transform of the original object and reference wave. This normally restricts the object to be of limited size or in a single plane. The Fourier holograms are usually produced, by placing the object and the spherical reference wave at the focal plane of a lens.

2.4.2 Modulation of the incident beam

The second classification of holograms depends on how the illuminated hologram modulates the diffracted beam that reconstructs the object. This classification reveals how the incident light is directed and modulated to form the virtual (or the real) image of the object. In this classification, holograms are put in two categories. The created structure within the emulsion can be a variation of the index of refraction (phase recording) (Hariharan, 1996), or a variation of the medium's density/opacity (amplitude recording), or even both. In phase modulation materials, the refractive index is modulated throughout the emulsion due to the two interfering waves. After developing, a pure phase modulated material does not absorb any of the incident light and produce very bright images. The illumination wave is forming the virtual and real object image as a result of how different light rays are refracted through the emulsion. In the amplitude modulating materials the absorption constant changes as a result of the exposed light (exposure being, intensity multiplied with time). On reconstruction, the film absorbs a considerable amount of the light, reducing the efficiency of the image. Many holographic materials can be transformed from a developed amplitude hologram to a phase hologram by a chemical bleaching procedure. The bleaching chemicals and the procedure are often different for each particular film.

2.4.3 Thickness of the film medium

There are thin and thick (volume) holograms, a classification that depends on the average spacing of interference fringes, Λ, in the hologram to its thickness d. A Q parameter is used to separate the two regimes. The parameter Q is defined by Equation 2.6:

$$Q = \frac{2\pi\lambda_{o} d}{n_{o}\Lambda^{2}} \qquad \text{.......... 2.6}$$

Where:

λ_o is the recording wavelength

d is thickness of the emulsion

n_o is the refractive index of the emulsion

Λ is the grating period (number of fringes per length)

If this parameter is larger than one for a specific film, it is considered to be a volume hologram. If it is less than one, then it corresponds to a thin hologram. These criteria are not always adequate, (Hariharan, 1996). The major difference between the two emulsion types is the depth of the reconstructed image. Very thin holograms (such as rainbow holograms on credit card) will provide little depth, while a thick hologram recreates the object with greater depth.

2.5 Holographic films

The most important properties of holographic materials are sensitivity, diffraction efficiency (modulation capability) and recyclability (Biedermann, 1977). The film should ideally be sensitive at all wavelengths of the electromagnetic spectrum to render recording by any light source. Such a material has yet not been made. Standard holographic films like Silver halide and Dichromatic gelatine has some but not all of these qualities. Silver halide materials can be made extremely light sensitive and dichromatic gelatine can obtain extreme diffraction efficiency, but neither of the films can be recycled nor sensitized at every wavelength (although the visible light spectrum can be covered with pan-chromatic film). Sensitivity and resolving power is a trade-off with all films, as both depend on the photosensitive grain size in the emulsion. Another problem working with holography is that not all the different types of emulsion are commercialised. For our project, a few commercialised films were considered. These were; silver halide, dichromatic gelatin and thermoplastic film plates.

2.5.1 Silver-Halide in gelatin

Silver halide materials have been used for several years now. It is used in ordinary photographic as well as in holographic films to record all types of radiation. Photographers and holographers have more practical experience with this material than any other, (Kasap, 2001). Silver halide materials are versatile, commercially available in numerous sizes and qualities and they can be handled and processed with a minimum of equipment. These films are suitable for making both amplitude and phase holograms (not a mix of both, however), and possess a sensitivity unequalled by any other material. A typical peak sensitivity of a film from Slavich (type PFG-01 pr.2004-03-29) is 80μJ/cm^2 (this film has 3000 lines/mm) (Biedermann, 1977). This film requires wet processing, which is a major drawback. This limits its practical applications to standard holography, frozen fringe and average-time holography. During exposure, a few μm displacement of the film from its original position would rule out the possibility of achieving interference patterns from the two beams. A Silver halide emulsion consists of microscopic crystals of silver halides, predominantly silver bromide (AgBr), encapsulated in gelatine. The index of refraction of gelatine is about 1.5, while AgBr is around 2.25.

In order to decrease scattering from the embedded crystals, the particles must be made much smaller than the wavelength of light according to Rayleigh theory of scattering. Typical values of grain size in the emulsions intended for holographic use are in the order of 0.03 – 0.08 μm (Biedermann, 1977). Emulsions with larger grains yield the highest sensitivity, but have less spatial efficiency (resolution). Films made of small silver halide grains provide better spatial efficiency, but will lack some sensitivity and will require a longer exposure time. There is a trade off between the film speed and the resolution.

During exposure, the absorption of a photon by a grain in the emulsion will free an electron as shown in the following reaction:

$Br^- + h\upsilon \rightarrow Br^+ + e^-$ 2.7

This free electron will then move through the crystal lattice. At one of the crystal imperfections, which have to be distributed suitably through the emulsion, it is trapped and attracts an interstitial silver ion, occupying holes between the larger metal atoms or ions in the crystal lattice:

$e^- + Ag^+ \rightarrow Ag$ 2.8

Lifetime of this single silver atom is about 1 – 2s, but it will trap another liberated electron and keep increasing, repeating the process if offered more electrons during its lifetime. A larger silver speck of two or more atoms is stable, but to make a latent image it has to be a speck of at least three or four atoms. These silver specks are often referred to as the latent image, because they can be converted into a hologram by wet processing. Processing techniques using Silver halide recording materials are then applied, (Singstad, 1996).

Most commercial silver halide emulsions have a typical spatial frequency (resolving power) around 3000 - 5000 lines/mm, depending on sensitivity region. Agfa-Gevaert, which has been the largest manufacturer, has stopped producing their quality 8E75HD, which had about 5000 lines/mm with peak sensitivity in the red region. Eastman Kodak still produces their BB-640 (sensitivity region 580-650nm), which has the same spatial resolution, while Slavich produce PFG-03M (ultra-fine grain), which has more than 5000 lines/mm at spectral sensitivity range

600-680nm (Slavich, 2004). Silver halide films are produced both in selected sensitivity ranges and as pan chromatic plates (full visible spectrum). Good quality holograms have been made using products from Slavich and this is what we have used during our study.

2.5.2 Dichromated gelatin (DCG)

Dichromatic gelatin and other dichromatic colloids are among the oldest photographic materials (Meyerhofer, 1977). Many different colloids have been used to make photosensitive layers; albumen, sodium, fish glue etc. Dichromated gelatin is an important holographic material due to its almost ideal properties for phase holograms. It record information either as variation of index of refraction or as a thickness variation, or as a combination of the two. The main reason why DCG have not been widely used is despite their promise, the difficulty of obtaining reproducible results and problems related to the distortion of the photosensitive layer from exposure to developed image.

A colloid is defined as “a substance that consists of particles dispersed throughout another substance” This material can produce holograms with diffraction efficiency at almost the theoretical limit (Meyerhofer, 1977). It has low noise and good image quality. It has been one of the best materials to make holographic optical elements, like gratings and lenses. A disadvantage is the low sensitivity, which creates a need for a powerful light source. Currently Slavich offers DCG films designed to make phase recordings with a resolving power of more than 5000 lines/mm (Slavich, 2004). The sensitivity of the same material is between 100-250mJ/cm^2. This is ~ 10^3 times less sensitive than the silver halide materials. We did not investigate any of these DCG films as they offer no new functionality compared to the silver halide films we already had.

2.5.3 Thermoplastic Recording

Thermoplastic (or "Photo thermo-plastic") is a material that is recyclable, and which requires no wet processing (Lin *et al.*, 1970). It is reasonable sensitive across the entire visible spectrum and can yield fairly high diffraction efficiency. The film surface needs to be sensitized to light by applying a high voltage prior to exposure, as shown in Figure 2.4.

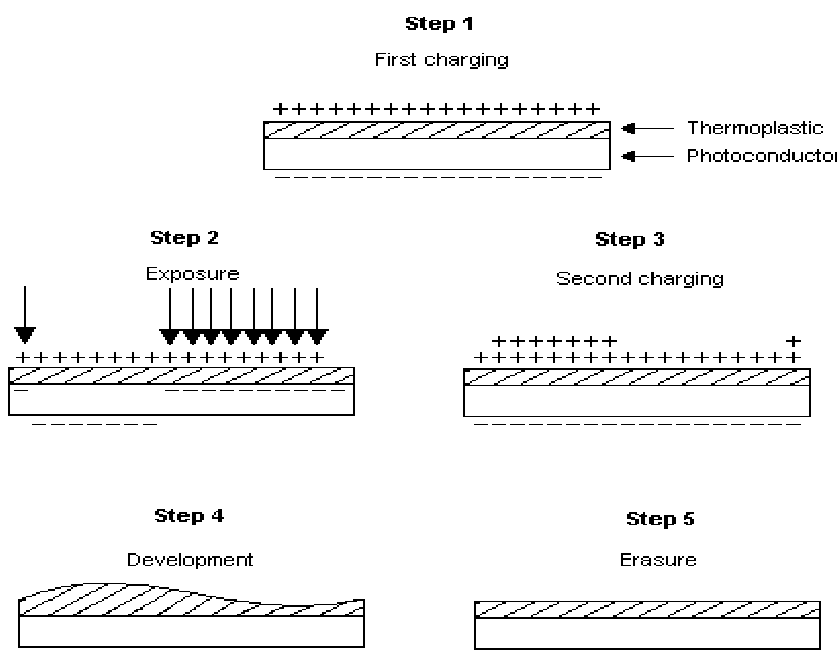


Figure 2.4: Record-erase cycles for photothermoplastic recording material (Lin et al, 1970). Step 1 – sensitizing film by applying high voltage; step 2 - exposure to light generating charge carriers on photoconductive layer; step 3 – additional charging creating a latent image; step 4 – heating the thermoplastic close to its softening temperature; step 4 – heating the film and illuminating it by white light.

This should be performed with a "corona device" which sprays positive ions across the surface of the film. The film is now sensitized and all exposed light will change these charge carriers on the surface. An exposure to light will generate charge carriers in the photoconductor layer, and these will migrate to the oppositely charged carriers and neutralized these. This will reduce the surface potential. Another strong recharging of the film, additional charges are deposited wherever the exposure had resulted in a migration of charge resulting in a spatially varying electric field pattern. This represents a latent image. The thermoplastic can now be heated near its softening temperature using a current passing through the material. This will deform the thermoplastic layer according to the electric field. It will be thicker in all unexposed areas and thinner in the illuminated areas. After cooling the film is relatively stable and is not further affected by light. The film can be heated again and illuminated by white light to erase all prior recordings.

According to (Hariharan, 1996) commercial Thermoplastics have a life time of more than 300 cycles but Urbach (1977) reported much higher numbers like 50 000 cycles or even 80 000 in an inert atmosphere. Using a special substrate, a diffraction efficiency of as high as 60% has been reported, (Urbach, 1977). Its resolution can be 4000 lines/mm and it is reported to have a high sensitivity. The drawbacks of Thermoplastics are its need for complex apparatus to control the aforementioned charging (high voltage) and the development (strong current). It is sensitive to dust and abrasion and has a tendency to form ghost images due to charge trapping in the emulsion. We would also like to add that purchasing such a film and the necessary equipment especially the strong corona device is quite costly.

2.5.4 Digital Holography

Digital holography is quite different to standard optical holography. This technique was studied to see if it could be used in this study. It involves digitally reconstructing the object wave from a digital picture. Digital holography differs from traditional holography, by substituting the holographic film for an electronic recording medium (Kebbel *et al.*, 2001). There are no wet processing (silver-halide emulsions) or need for a high voltage source (order of thousand volts for a thermoplastic material). The recording medium used in digital holography is typically a scientific CCD camera, which stores the hologram electronically. It depends on budget and application which CCD camera to choose. Key specifications are wavelength sensitivity/region, the needed sensitivity level (bright objects or single photons), pixel resolution and frame-rate required. The most important specifications for the application of tracking moving particles will be lighting level and frame-rate. These are coupled in the sense that enough light must reach and illuminate the CCD-array to obtain a quality picture. If the tracer particles have moved a large distance during the recording of one picture, the image will be diffused/blurry and difficult to retrieve information from.

Using this technique, 3D televisions could be obtained in homes one day (Earthlink, 2004). The definition of digital holography is not standardized and the classification of it varies with research groups. Some define it as ESPI (electronic speckle pattern interferometry) while others (Schnars *et al.,* 2002) will claim and use the term for digital recording and numerical reconstruction of holograms on a computer. In recent years, digital holography has been used and improved in various applications. Examples of such are deformation analysis and shape measurement (Osten *et al.*, 2001), particle tracking (Adam *et al.,* 1999), microscopy, (Kebbel *et al.,* 2001) and measurement of refractive index distributions within transparent media (Dubois *et al.,* 1999). Most of the scientific work has been done on transparent media and digital holography under microgravity conditions, i.e. in space. The last is a technology that has been wanted onboard the International Space Station for experiments for the Fluid Science Laboratory (FSL) under the European Space Agency (ESA). They write about digital holography on their web site: It provides a refocusing capability of small objects in the experimental volume regardless to the focus plane of the optical set up. By this way, tracers in a fluid physics experiment could be tracked in the liquid volume giving rise to potential 3D-velocimetry map determination (FSL, 2004). Note that making holograms in space compared to normal gravity experiments is very different. Under microgravity conditions the tracing particles will be extremely slow and the exposure time can be increased without the problem of generating bad images. A short digression is that the German mission HOLOP-D2 used a thermoplastic film camera from Steinbichler Optotechnik Gmbh to achieve real-time recordings under microgravity in mid 1990's. It is unknown to us whether they also used numerical reconstruction techniques. Today they offer digital holographic services.

2.5.5 Bacteriorhodopsin

While studying recent publications dealing with real-time holography, another material was discovered that had not been used before (Seitz *et al.*, 2000). It is called Bacteriorhodopsin (BR) and is a living organic medium. According to the only commercial vendor of these films, Munich Innovative Biomaterials (MIB) GmbH – a BR film can be rewritten as many as 10^6 times without any degradation of quality. MIB list (MIB, 2003) that the BR films are especially well suited for applications in high performance data processing, holographic recording, data recording, volumetric optical memories, etc. It has a good resolution, typically >5000 lines/mm and a large damage threshold (Table 2.1). Seitz *et al.* (2000) reported that the BR film has sensitivity suitable to generate a full holographic modulation with $100\mu W/cm^2$ of light, but the article does not mention the length of exposure. Nevertheless the same authors used a frequency doubled $Nd:YVO_4$ at 532nm at 2W power to perform their experiments.

Table 2.1: Key properties of Bacteriorhodopsin films (MIB, 2003)

Key- properties of Bacteriorhodopsin - Films	
Spectral Range	400 – 650 nm
Achievable Resolution	≥ 5000 lines/mm
Light Sensitivity	1 – 80mJ/cm^2 (B-type recording) 30 mJ/cm^2 (M-type recording)
Reversibility	> 10^6 write/erase cycles
Photochemical Bleaching	> 95% in selected films
Diffraction Efficiency	1 – 3%
Polarization Recording	Possible

A nice explanation for how the bacteriorhodopsin molecules are affected by light is explained by the Board on Army Science and Technology (BAST, 2004). Scientists using bacteriorhodopsin for bioelectronic devices exploit the fact that the protein cycles through a series of spectrally distinct intermediates upon absorption of light. A light-absorbing group (called chromophores) embedded in the protein matrix converts light energy into a complex series of molecular events that store energy. This complex series of thermal reactions causes dramatic changes in the optical and electronic properties of the protein. The excellent holographic properties of bacteriorhodopsin derive from the large change in refractive index that occurs following light activation. Furthermore, bacteriorhodopsin converts light into a refractive index change with remarkable efficiency (approximately 65 percent). The protein is 10 times smaller than the wavelength of light, which means that the resolution of the thin film is determined by the diffraction limit of the optical geometry rather than the "graininess" of the film. The optical properties of the material change in response to the incident light. The BR molecules undergo a transition through a series of molecular states upon absorbing a photon. This photocycle can be simplified as there are mainly two states in which bacteriorhodopsin occupy for any length of time.

According to the outlined theory developed by (Seitz *et al.,* 2000), there are four parameters that characterize the photoresponse of a BR film. These are the optical density (OD), light sensitivity, bleaching ratio and the thermal decay time. The OD describes the number of light sensitive molecules per area, and how much absorption to expect at different wavelengths. Light sensitivity is a dynamic variable describing how the OD changes according to the light exposed. Bleaching ratio is a parameter describing the absorption changes to the initial OD, i.e. how many molecules have been converted from either state. The last parameter thermal decay time is a chosen time limit. It can be the time required to thermally convert 50% (Seitz *et al.,* 2000) or 63% (MIB) from the excited state back to ground state. The complex derivations of these will not be included in this thesis. Expressions for all of these parameters exist (Seitz *et al.*, 2000) and can be used for a theoretical approach if this will be of interest at a later stage.

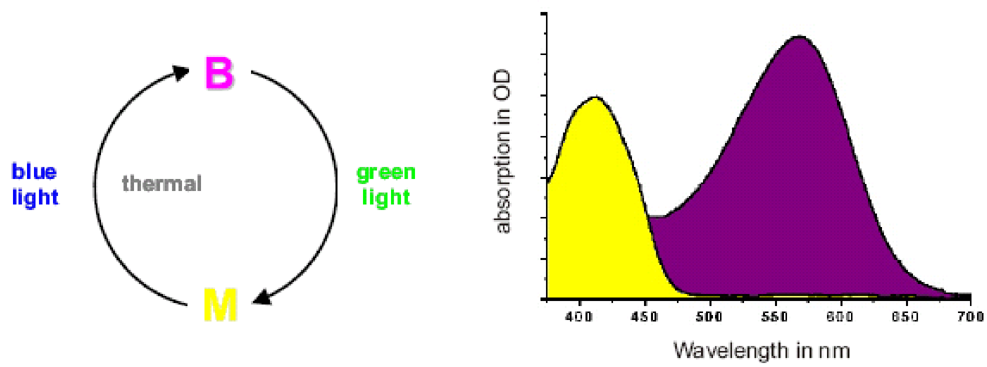


Figure 2.5: Simplified photochemical cycle and absorption spectrum for Bacteriorhodopsin (MIB, 2003). B-state is the ground state while M-state is the excited state with absorption peaks at 412 nm.

This absorption spectrum for the MIB films indicates that there are two absorption regions at which the film should be addressed. The peak sensitivity of these regions are at 568 nm for molecules in the initial B-state and 412 nm for molecules in the M-state. By illuminating the film with light at a wavelength within these two distinct regions, a hologram can be recorded at one wavelength and erased with light within the other sensitivity region. Recording with light between 500 – 650 nm has so far been the most common, as the prices for laser sources in the 400 – 450 nm regions have been quite expensive. The inverse approach is to first photo chemically induce the molecules to the M-state using one light source within the

500 – 650 nm region, and then use a laser source in the 400 – 450 nm region to make the hologram (M-type recording, due to the initial M-state).

If a film of this recording material was to be purchased, the laser source to experiment with B-type recording would have been available. A light source to photochemically convert the excited molecules back to the ground state would have to be acquired.

2.6 The theory of optical tables.

It is often necessary to conduct optical experiments or take measurements in a vibration-free environment. However, largely uncontrollable sources of vibrations such as air conditioners, heat pumps, road and rail transportation systems are just a few mechanisms that contribute to an unavoidable vibration background noise that is coupled to the foundations and floors of surrounding buildings. Optical systems comprised from multiple components that must be individually mounted and aligned in a precise and rigid fashion are particularly vulnerable to vibration-induced performance degradation. Many types of experiments are impossible or severely hampered by small vibrations. For example, many laser applications require a beam waist of a few micrometers; if the position of this spot is critical to system performance (e.g., using an ion laser to pump a jet stream dye laser), then vibrations with amplitudes in the micrometer range can inevitably cause experimental failure. Since visible light has a wavelength of approximately 0.5 micrometer, interferometry-based experiments (including holography) may also be impossible to perform in the presence of vibrations, even if they are sub-micron in amplitude. Optical and/or mechanical machining or probing of semiconductor wafers requires similar stability. If an experiment utilizes mechanical elements that move or vibrate, it is often necessary to vibrationally isolate these components from all other critically aligned optical elements.

The surface on which an optical system is mounted must satisfy several basic requirements. It must provide a rigid base on which optics can be mounted and aligned reliably with both long-term stability and no inherent vibrational resonances. It must not only successfully damp any vibrations caused by motorized or moving parts in the experiment, thereby preventing these vibrations from influencing critical optical elements, but also isolate the experiment as a whole from ambient background laboratory vibrations. If these criteria are not met, undesirable effects often result. An individual component, or the system as a whole, may not function properly. Valuable data may be buried in random noise, or data may be totally misunderstood and incorrectly evaluated due to vibrationally induced noise. In the latter case, poor data can lead to frustration, hinder timely progress, and consume resources, which is particularly costly when the system is a laboratory prototype of a production assembly. Ideally, an optical table should maintain a rigid and flat upper surface without being overly massive.

2.6.1 Sources of Vibration

Vibration, which is commonly referred to as noise, can be segregated into three main categories: seismic (ground) vibrations, acoustic vibrations, and forces applied directly to the load on the working surface. Seismic vibrations include all sources that make the floor under the experimental setup vibrate. Common seismic vibration sources are foot traffic, vehicular traffic, wind blowing the building, and building ventilation fans, to name a few. Many of the sources that generate seismic vibrations also generate acoustic vibrations. The difference is that acoustic vibrations are a measure of the effects of air pressure variations on the experiment. The final contributor to vibration is forces applied directly to the load on the working surface; these are vibration sources that are directly coupled mechanically to the experimental setup but not transmitted through the table supports. Examples include vibrations resulting from a moving positioning stage with a sample on top of it or the vibrations transmitted to the working surface via vacuum system tubing.

2.6.2 Vibration Characteristics

Vibrations can be classified as either random or periodic. Periodic noise obviously includes the constant vibrations caused by a continuously running vacuum system, but it also includes the vibrations caused by the fans of an air handling system that turn on and off based on the temperature of the room. Random vibrations are classified as vibrations from unpredictable sources like wind blowing a building or a jack hammer crew digging up a water main in the street. In addition, it is important to know the frequency and amplitude of the vibrations. Typically, the frequency of the vibrations will range from 4-100 Hz.

The primary goal of a well designed optical table is to eliminate relative motion between any two (or more) components on the surface of the optical table. However, before the design of optical tables can be discussed, it is necessary to examine the underlying theory of vibrations and the nomenclature commonly used to discuss tabletop vibrations: compliance, vibrations, resonance, and damping.

2.6.3 Compliance

In the case of a constant (static) force, compliance is defined as the ratio of the linear or angular displacement to the magnitude of the applied force. In the case of a dynamically varying force (vibration), compliance is defined as the ratio of the excited vibration amplitude (angular or linear displacement) to the amplitude of the force causing the vibration. Any deflection of the tabletop is evident by the change in relative position of the components mounted on the table surface. Therefore, by definition, the lower the compliance value is, the closer the optical table is to meeting the primary goal of optical table design, minimized deflection (FSL, 2004). Compliance is frequency dependant and is measured in units of displacement per unit force (meters per Newton).

There are two basic goals that guide the design of the optical tables made: the natural resonances of the table should be as high as possible and the table should be well damped. The advantage of designing a table with resonances as high in frequency as possible is that the amplitude of the vibrations is proportional to 1/cf at the peak of a resonance. Here, f is the frequency of the forcing function and c is a parameter describing the damping properties of the system.

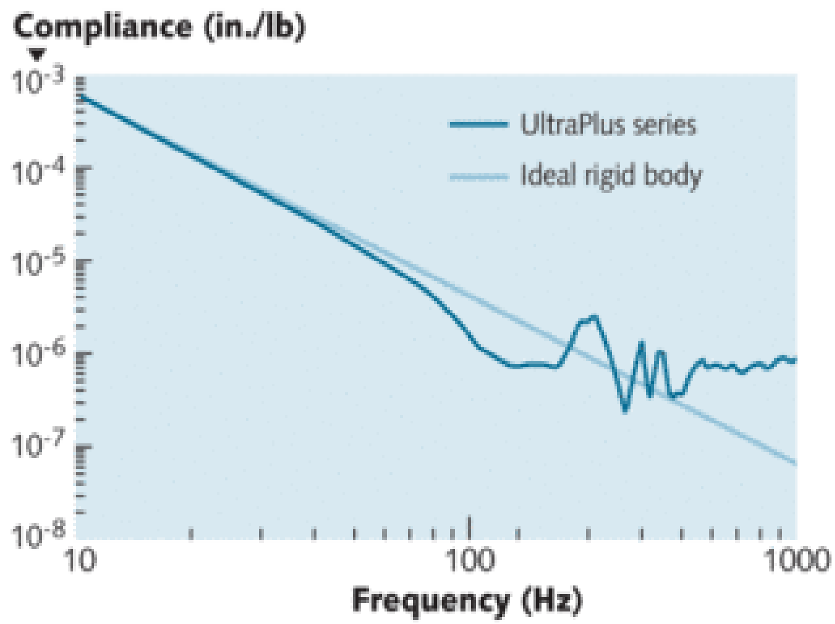


Figure 2.6: Compliance curve of an optical table. (FSL, 2004)

This displays the displacement of the optical table (ultra plus series type) under an excitation force across a range of frequencies, compared to that of an ideal rigid body. The table will ideally match the rigid-body line up to about 100 Hz which is in the high-frequency territory. Peaks in the curve represent natural modes of the table when subjected to various frequencies. The compliance curve is used to evaluate the performance of an optical table; this charts the natural vibration modes of the table under a static load as a function of frequency (Figure.2.7). The three basic requirements for an optical tabletop are therefore: Good static rigidity (i.e., stiffness), Low mass so that no low frequency (<100 Hz) resonances are present. Note: Low frequency resonances have large amplitudes, and most laboratory background vibration noise occurs at low frequencies and finally a well damped structure.

For many years, scientists performed delicate optical experiments on home-built tables, which were usually quite massive. These optical tables were constructed from granite, concrete, wood, steel, and many elaborate composite structures in attempts to improve performance while keeping weight at a realistic level. Each of these materials has advantages and disadvantages. The disadvantages of granite and concrete are that the slabs tend to absorb water vapor, which causes them to deform. Steel has two distinct drawbacks: a high density and a tendency to resonate at several vibration frequencies after 100 Hz, with very little natural damping. The performance of wood is surprisingly good; however, it has a tendency to warp with time and/or exposure to moisture.

2.6.4 Damping

Damping refers to any process that causes an oscillation in a solid body to decay to zero amplitude. It is a very important phenomenon in vibration suppression or isolation in real systems because it causes energy to be diverted from vibration to other sinks. Materials such as wood and rubber have a large amount of natural damping. The microstructure of a well-damped material is such that deformations cause strains in the material that rapidly convert the mechanical vibrations into other forms of energy such as heat. Metals manifest a small amount of internal damping. This is principally due to the small amount of friction present at grain boundaries.

For a typical rectangular tabletop, the lowest frequency vibrations (in order from lowest to highest frequency) are the long, torsional, and short bending modes. In Figure 2.6, these bending modes are illustrated along with the first overtone of the long bending mode. Each of these independent modes has a characteristic resonant frequency, for example, Ambient horizontal vibrations tend to occur at lower frequencies than vertical floor vibrations (1 to 20 Hz versus 10 to 50 Hz) and are therefore more difficult to isolate, which gives rise to a corresponding peak in the compliance curve. Therefore, to avoid any resonant effects from induced floor or tabletop vibrations, which generally range from 4-50 Hz, the resonant frequencies of the table need to occur at frequencies above the frequency of the vibrations created by sources in the vicinity of the table. For example, the steel optical table designed, resonant frequencies occur far past 100 Hz, implying all vibrations below 100 Hz will be comfortably damped.

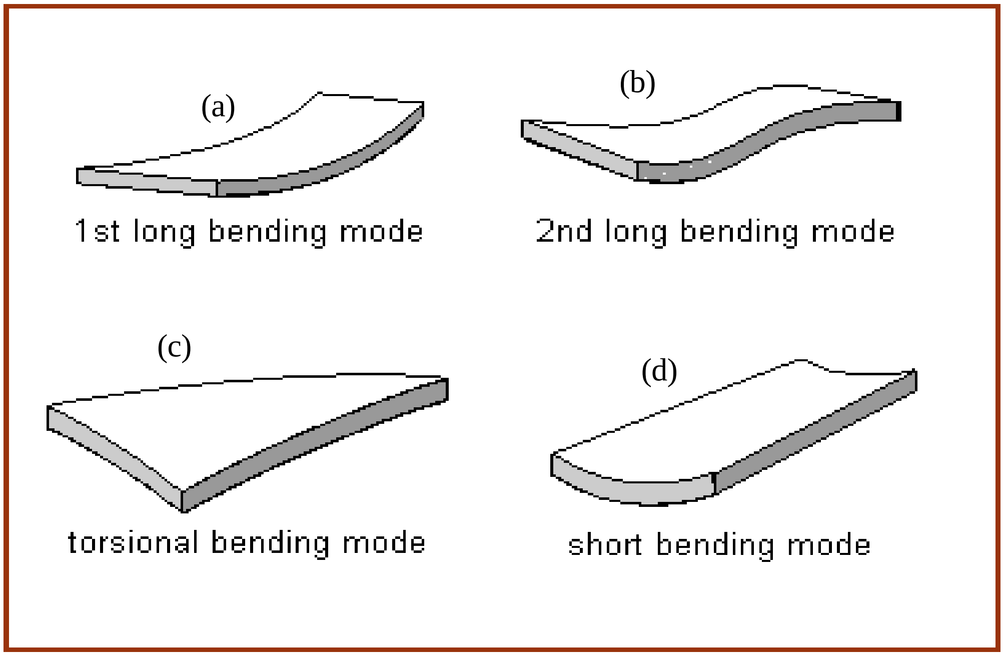


Figure 2.7: Vibration modes of an optical table

2.6.5 Honeycomb Theory

If the interior support structure consisted of planes of parallel steel sheets bonded to the top and bottom solid steel plates, this would effectively make the table into a series of I-beams oriented along the long direction of the steel sheets as shown in Figure. 2.8. (a).

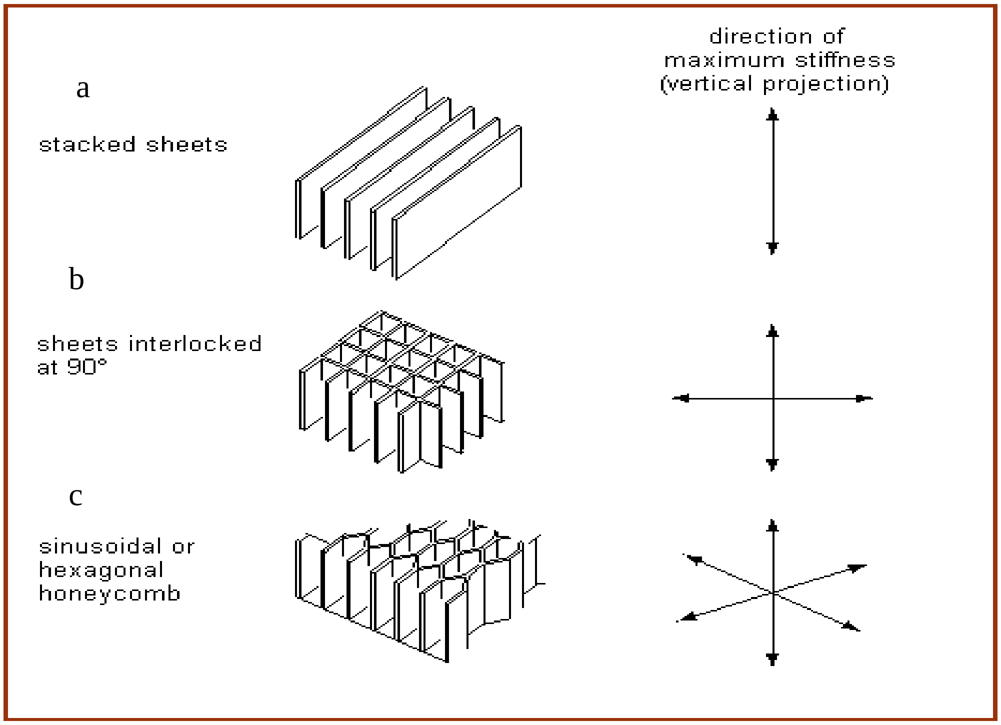


Figure 2.8: Planes of stiffness: (a) stacked sheets; (b) interlocked sheets (c) sinusoidal or hexagonal honeycomb sheets.

This geometry would dramatically increase the stiffness of the table along this direction due to the shape of the I-beam. In order to create this I-beam-type structure along two axes, the plane sheets could be interlocked. At this point, the table would be most susceptible to bending along a plane at 45° with respect to either of the planes of parallel sheets, which means that the table's resistance to torsion bending has not be significantly improved.

Therefore, to resist the long, short, and torsion bending modes, the sheets in the structure must be oriented at intermediate angles. if the idea of adding new sets of parallel planes is projected forward, the resulting optical table would just be a solid steel object with a high mass and very little natural damping mechanisms. The most practical solution to the need for a light structure that provides stiffness along several planes is to create an interior with interlocked honeycombs.

In Summary, the optical table should be a stiff, low mass structure. The compliance characteristics of an optical table should be as near as possible to that of an ideal rigid body. The table resonances should be shifted to as high a frequency as possible in order to minimize the number of common vibration sources that produce vibrations at a resonant frequency. The table should have internal damping mechanisms that minimize the table's compliance at resonant frequencies and damp all vibrations in the shortest possible time. The characteristic damping time is referred to as Impulse Decay.

2.7 Applications of Optical Holography

2.7.1 Security holograms

Security holograms are very difficult to forge because they are replicated from a master hologram that requires expensive specialized and technologically advanced equipment (Hariharan, 1996). This implies that using this technology, special holograms of say emblems carrying special information about a company can then be made and widely used on quality merchandise for example Currency notes, Title deeds, University certificates, Car Log books amongst many others. Currently, few international currencies such as the Brazilian note, British pound, Canadian dollar notes, and Euro notes are inserting these special holograms on their notes (Holophile, 2004). Holograms can also be used on credit and bankcards as well as on other quality products. For example, the hologram on a Nokia mobile phone battery shown on plate 2.1, this is intended to show the battery is 'original Nokia' and not a cheaper imitation.

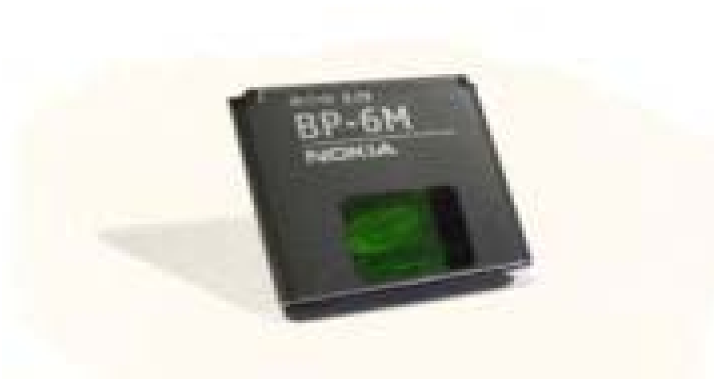


Plate 2.1: A Hologram on a Nokia mobile phone battery.

The low resolution of camera hinders perfect visibility of the Hologram although the aspect of depth characteristics of the hologram is evident.

2.7.2 Holographic Interferometry

Holographic interferometry (Schnars *et al.,* 1994; Powell *et al.,* 1965) is a technique which enables static and dynamic displacements of objects with optically rough surfaces to be measured to optical interferometric precision (i.e. to fractions of a wavelength of light). It can also be used to detect optical path length variations in transparent media, which enables, for example, fluid flow to be visualized and analyzed (Dubois *et al.,* 1999) . It can also be used to generate contours representing the form of the surface. It has been widely used to measure stress, strain, and vibration in engineering structures (Kuznetsova *et al.*, 2007)

2.7.3 Holographic data storage

Holography can be put to a variety of uses other than recording images. Holographic data storage is a technique that can store information at high density inside crystals or photopolymers (Osten *et al.,* 2001). The ability to store large amounts of information in some kind of media is of great importance, as many electronic products incorporate storage devices. The advantage of this type of data storage is that the volume of the recording media is used instead of just the surface. In 2005, companies such as Optware and Maxell have produced a 120 mm disc that uses a holographic layer to store data to a potential 3.9 TB (terabyte), which they plan to market under the name Holographic Versatile Disc as compared to the current discs of only 700 MB (megabyte). Another company, InPhase Technologies, is also developing a competing format (Berger, 2003).

2.7.4 Interferometric microscopy

The hologram keeps the information on the amplitude and phase of the field. Several holograms may keep information about the same distribution of light, emitted to various directions. The numerical analysis of such holograms allows one to emulate large numerical aperture which, in turn, enables enhancement of the resolution in optical microscopy (Jones *et al.,* 1989). The corresponding technique is called interferometric microscopy. Recent achievements of interferometric microscopy allow one to approach the quarter-wavelength limit of resolution (Jones *et al.*, 1989).

2.7.5 Dynamic holography

The previous discussions describe static holography, in which recording, developing and reconstructing occur sequentially and a permanent hologram is produced. There also exists holographic materials which do not need the developing process and can record a hologram in a very short time (Kebel *et al.*, 2001). This allows using holography to perform some simple operations in an all-optical way. Examples of applications of such real-time holograms include optical cache memories, image processing (pattern recognition of time-varying images), and optical computing (Kuznetsova *et al.*, 2007).

The amount of processed information can be very high (terabit/s), since the operation is performed in parallel on a whole image. This compensates the fact that the recording time, which is in the order of microseconds, is still very long compared to the processing time of an electronic computer. The optical processing performed by a dynamic hologram is also much less flexible than electronic processing. On one side one has to perform the operation always on the whole image, and on the other side the operation a hologram can perform is basically either a multiplication or a phase conjugation. A particularly promising application is optical phase conjugation. It allows the removal of the wavefront distortions a light beam receives when passing through an aberrating medium, by sending it back through the same aberrating medium with a conjugated phase. This is useful for example in free-space optical communications to compensate for atmospheric turbulence (the phenomenon that gives rise to the twinkling of starlight) (Ryf *et al.*, 2001).

2.7.6 Holography in art

Holographic art is often the result of collaborations between scientists and artists. A small but active group of artist use holography as their main medium and many more artists integrate holographic elements into their work (Holophile, 2004). For example, the MIT Museum (Leith *et al.*, 1962) has extensive collections of holography and on-line catalogues of art holograms.

2.7.7 Supermarket Scanner.

Supermarket scanners read the bar codes on merchandise for the store's computer by using a holographic lens system to direct laser light onto the product labels during checkout (Adam *et al.*, 1999). Holographic lenses are holograms in which the "object" is a mirror or a lens. A flat mirror as an object produces a diffraction grating. A lens or a concave mirror as the object produces a hologram that behaves like a lens. These holographic lenses are lighter than traditional lenses and mirrors and they can be designed to perform more specialized functions. A Holographic scanner is a type of scanner in which a beam of light is deflected by a rotating hologram so that it scans a plane in a multitude of directions. Some of the light reflected from an object is returned via the hologram and brought to focus on a sensor as indicated on Figure 2.9. They are widely used for reading bar codes at retail checkouts.

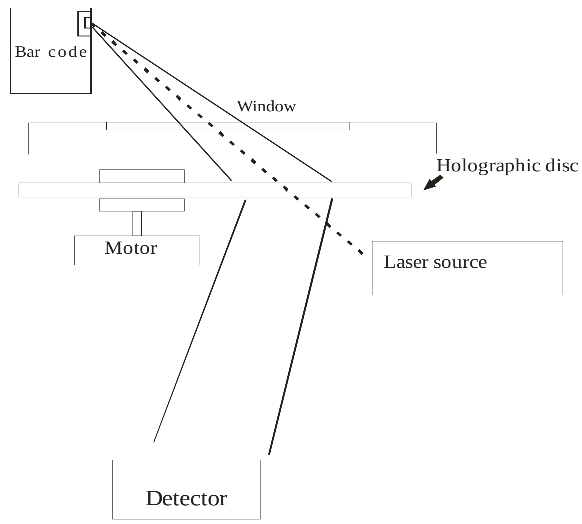


Figure 2.9: Holographic Scanner Setup.

2.8. Mass replication of holograms

An existing hologram can be replicated, either in an optical way similar to holographic recording, or in the case of surface relief holograms, by embossing. Surface relief holograms are recorded on special films called photoresists or photothermoplastics and allow for cheap mass reproduction. Such embossed holograms can then be widely used, for instance as security features on credit cards or quality merchandise.

The first step in the embossing process is to make a stamper by electrodeposition of nickel on the relief image recorded on the photoresist or photothermoplastic. When the nickel layer is thick enough, it is separated from the master hologram and mounted on a metal backing plate. The material used to make embossed copies consists of a polyester base film, a resin separation layer and a thermoplastic film constituting the holographic layer. The embossing process can then be carried out with a simple heated press. The bottom layer of the duplicating film (the thermoplastic layer) is heated above its softening point and pressed against the stamper so that it takes up its shape. This shape is retained when the film is cooled and removed from the press. In order to permit the viewing of embossed holograms in reflection, an additional reflecting layer of aluminium is usually added on the hologram recording layer.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Fabrication of optical table

A custom made optical isolation table was designed and fabricated specifically for the hologram set up as shown in the steps below;

A 6mm thick steel plate was picked for this setup. This plate provides a stiff and flat working surface. In order to fit well on the laboratory table as well as give enough room for future experiments, a 1500mm by 600mm steel plate was cut out. Keen care was observed so as not to loose the flatness of this plate. A mercury level helps determine when either of the bending modes occurs.

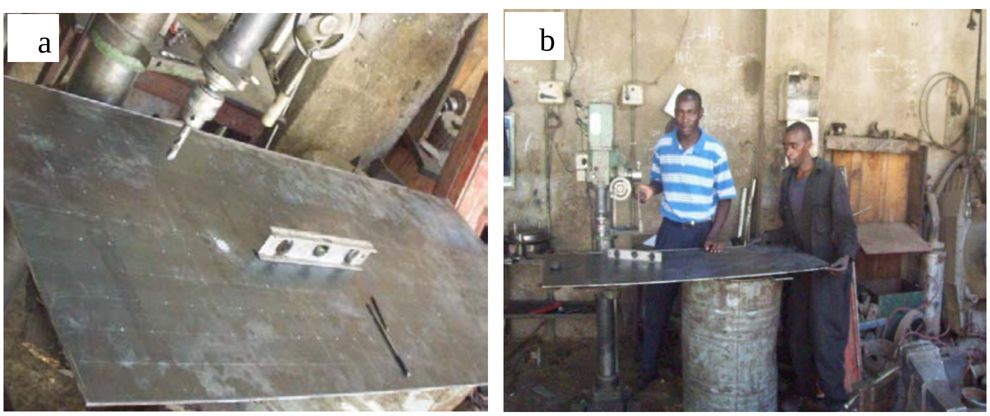


Plate 3.1: Cutting and leveling of optical table top plate: (a) Table top flatness being investigated using a mercury level; and (b) marking of holes on table top.

Marking of the top steel plate was the next step. Here precise and accurate 50mm spacing between holes was determined before marking the whole plate as observed on Plate 3.1. This is an international standard for optical tables in order to fit well all kinds of optic bases available.

Φ5 holes were then drilled carefully throughout the 6mm thick steel top plate, taking extreme care on their precision as portrayed on Plate 3.2 below:

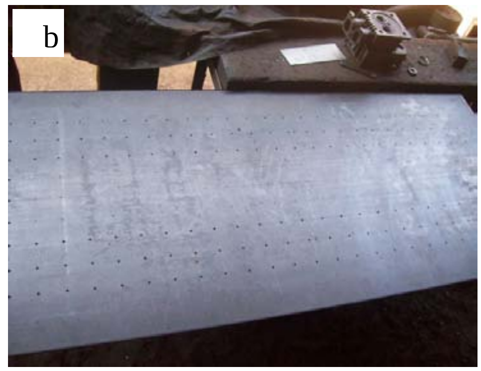


Plate 3.2: Measurement and drilling of holes in the optical table: (a) Measurement of table top dimensions; and (b) Spatially drilled table top.

Using an M6 bit, the Φ5 drilled holes were tapped to give them a final 6mm diameter. This exercise was done manually as observed on Plate 3.3. Regular greasing was done on the holes to give them a clear smooth finish.

Plate 3.3: Threading of the optical table base setup: (a) Greasing M5 holes before drilling; and (b) Manual tapping of table top using M6 threads.

In order to greatly increase the dynamic rigidity of the optical table without significantly increasing the mass of the optical table, interior honeycomb structures were employed. The honeycomb structure naturally damps table vibrations as well resists the long, short, and torsion bending modes. To commence with, the stacked structures were welded on the top plate before carefully adding the interlocked honeycombs sheets as portrayed on Plate 3.4.

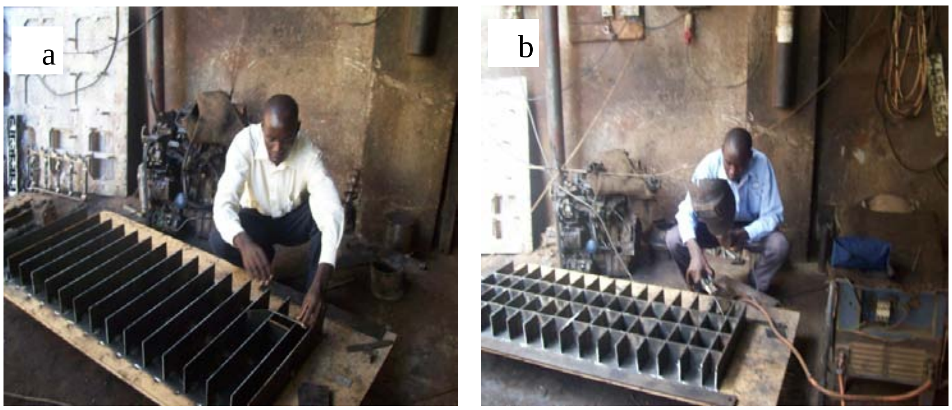


Plate 3.4: Stacked and interlocked honeycombs sheets being welded onto the base plate: arrangement of (a) stacked sheets; and (b) interlocked sheets on the table.

Filing was the next activity once the honeycomb structures had clearly been welded onto the base plate. Here, any uneven surface or traces of welds on the top surface was gotten rid of so as to leave the surface extremely flat to hold the bottom plate without wobbling

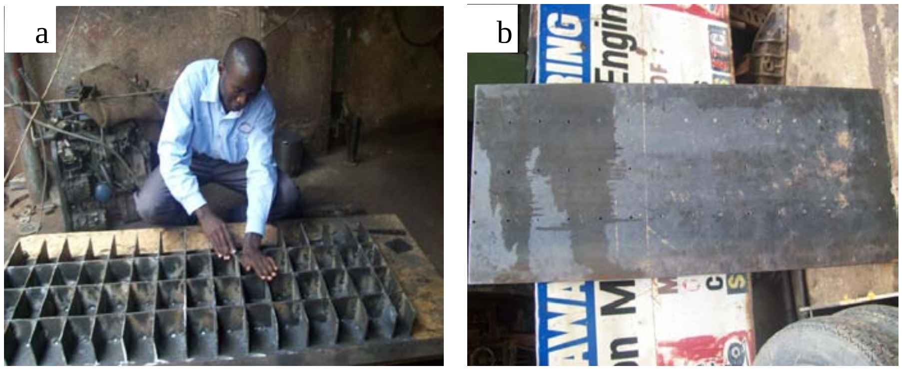


Plate 3.5: Filing of Honeycomb surface and the completely drilled bottom plate: (a) filling of interior honey comb structures; and (b) drilled bottom plate.

Another 6mm thick 1500mm by 600mm steel plate was cut out so to act as the bottom plate. This plate provides a stiff and flat bottom surface that fits well on the laboratory table. To avoid wobbling between this surface and the honeycomb structures, holes were drilled through the plate to coincide the honeycomb welded joints as observed on the Plate 3.5.

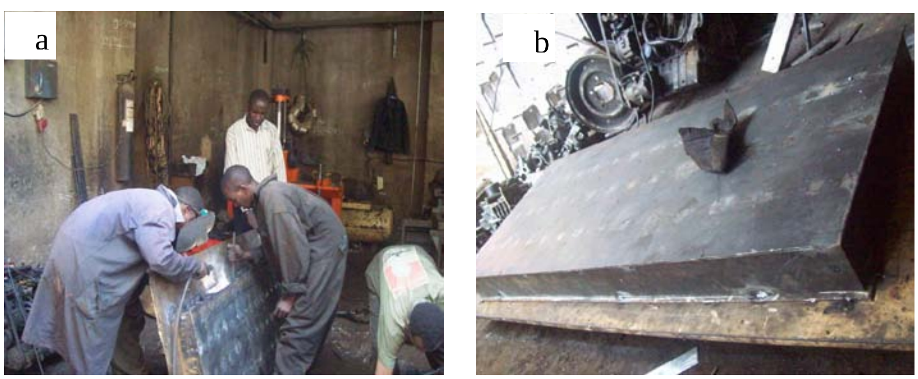


Plate 3.6: Welding of the rear sides of the optical table and the bottom plate: (a) welding of bottom plates onto honey comb structures; and (b) completely welded optical table.

Using the drilled holes, the interior honeycomb structures were joined with the bottom plate through welds before joining the rear side plates as observed on Plate 3.6.

Once the complete optical table setup was welded, the next step was to test all threaded holes with M6 screws as shown on Plate 3.7 below, so to ensure of there precision and verify there were no variations as a result of the heat generated during the welding process. The optical table handles were then fabricated. Here, straight metal rods were subjected to very high temperatures of heat before bending them to form joints as shown on Plate 3.7. This handles were then affixed through welds onto the optical table.

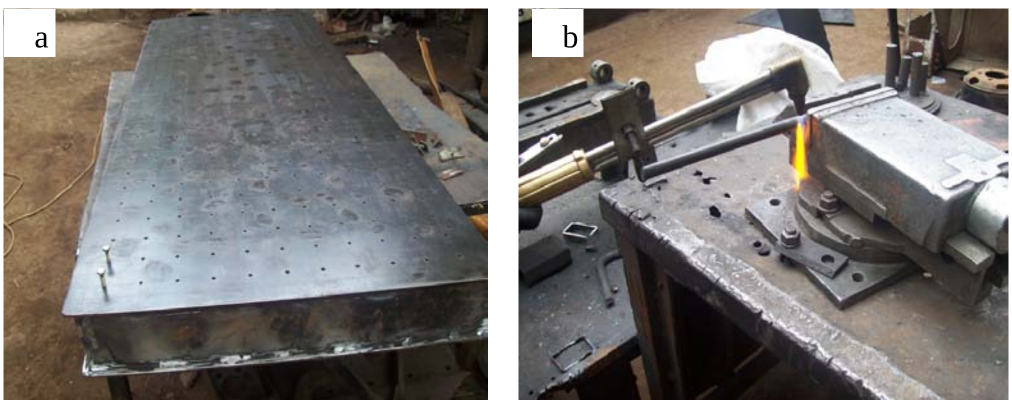


Plate 3.7: Testing top plate with M6 screws and later making optical table handles: (a) testing of optical table with M6 screws; (b) bending of metal rode to form handles

The optical table was finally painted silver on the top and black on the sides (3 coats) as portrayed by Plate 3.8 before being transferred to the laboratory for use.

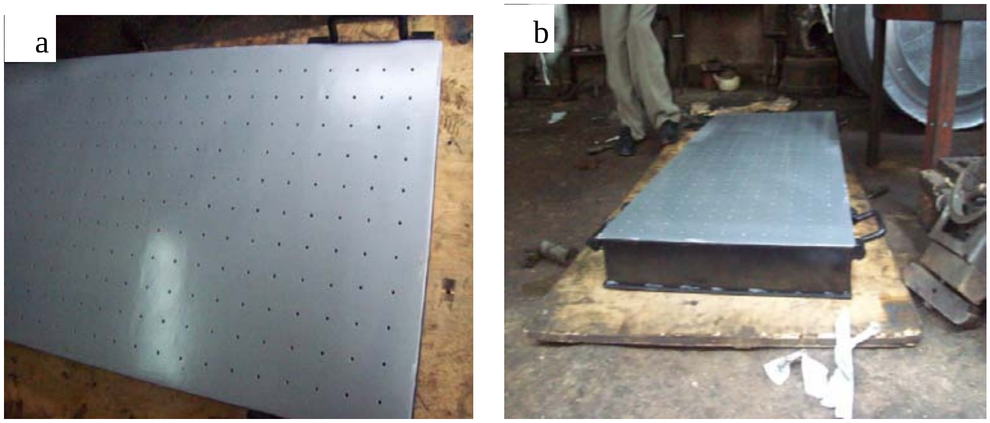


Plate 3.8: Completely painted and cleaned optical table ready for use: (a) a completely painted table top surface: (b) finished optical table for use.

3.2 Setting up of optical table

Plate 3.9 shows a photograph of optical table setup in the laboratory.

Plate 3.9: Completely set optical table in the laboratory.

A rubber material was placed in between the optical table and the laboratory base table to help damp vibrations. This rubber base also helps setting up a firm contact that helps to get rid of wobbling of the table as the lab base table was not flat.

3.3 Laser Analysis.

A well collimated monochromatic single mode, coherent laser source is required in order to obtain best results; unfortunately this was not the case for this setup. Beam analysis to study these characteristics was thus done on the three laser sources that were available using the spectrum analyzer, power meter and Michelson interferometer experiments and the results discussed later in this thesis. The laser beam spectral composition, that is, waist, power and interference fringes were thus respectively obtained and analyzed.

3.4 Laser alignment

A perfectly aligned laser beam from the source is always desired for any precise optical experiment. Laser alignment is an imperative aspect for it helps to minimize aberrations as a result of mismatched beams. Laser alignment was thus done to make sure the beam off the laser source was perfectly aligned and parallel with the base set-up. This involved first marking a point on a screen, say point (c), as observed on Plate3.10. Now using both the near field and far field, the beam was adjusted making sure the laser beam off the source strike the same spot, (c), along the straight line without deviations both when close to the source and a distant away. Once this is observed, it verifies that the laser beam off the source is perfectly aligned and parallel with the base set-up.

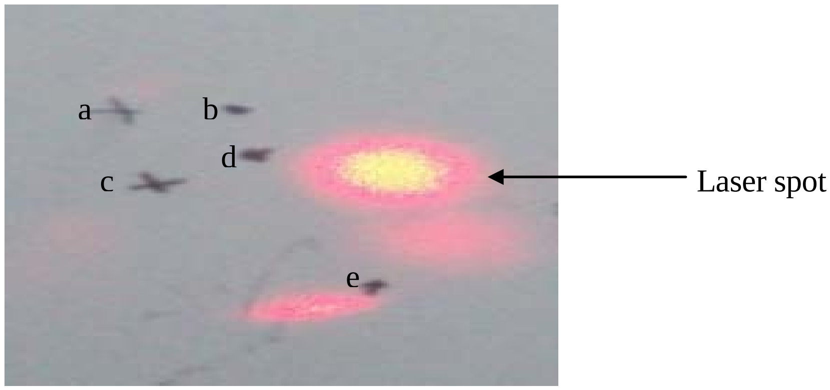


Plate 3.10: Laser alignment setup photograph

The marks (a), (b), (c), (d), and (e) represent the position of the laser spot on the viewing screen at different positions in the near and far field from the source during the alignment. Also on the photograph is the actual laser spot during one of the instance.

3.5 Michelson Interferometer

The first optical arrangement setup was a Michelson interferometer. This was set up on the optical table to help detect any vibrations that occur on the table surface (or any optical components that are moving). No optical component including the object scene should move during the exposure of the hologram. The Michelson interferometer setup was arranged as shown on Figure 3.1:

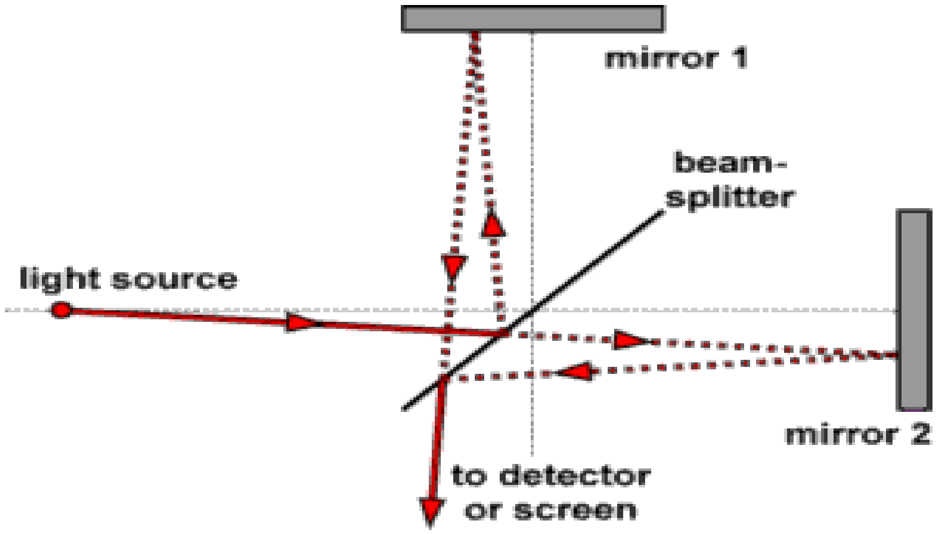


Figure 3.1: The Michelson interferometer setup. The light source usually a laser sends the beam to the beam splitter creating the two arms as shown in the figure. Mirror 1 and Mirror 2 reflects the incident beams back into the beam splitter.

The laser source centered at one end of the table, positioned at a height above the optical table that allowed the beam to be slightly above the table surface. The beam was allowed to illuminate the beam splitter BS where it was split into two beams. One beam was then transmitted through the beam splitter to mirror 2 and the other beam reflected to mirror 1. The distance, or path length as it is called, between each mirror and the beam splitter should always be the same. These distances were determined with a tape measure or string, and this can be as long as possible for the table size. The interferometer's sensitivity increases the farther the mirrors are from the beam splitter. Both mirrors then reflected their respective beams back to the beam splitter as indicated on Figure 3.1. Part of mirror 2's reflected beam was reflected by the beam splitter to the screen S and part of mirror 1's reflected beam transmitted by the beam splitter to the screen S. The idea here is to have the two beams overlap at the beam splitter surface. This is achieved by adjusting slightly either mirror 1 or mirror 2 up and down and/or sideways until clear fringes are obtained on the screen. Beams must be mutually coherent for fringes to be seen. These fringe patterns was then observed and recorded.

3.6 Lens-Pinhole Spatial Filter

In most laser setups the laser beam passes through optical components such as lenses, prisms, and beam splitters. Imperfections on and within these elements can cause degradation of the beam profile. Also, the air through which the beam passes contains particulates that lead to further beam degradation. (In fact, the scattering of laser light by particulates is an established technique for measuring air cleanliness.) In applications such as holography and interferometry, where two laser beams are combined and compared in order to derive information, it is essential that the nominal beam form be as uniform or at least as smoothly varying as possible. In order to assure this, it is possible to “clean up” a contaminated laser beam by passing it through a spatial filter. The Lens-Pinhole Spatial Filter (LPSF) is designed to provide a very homogeneous Gaussian-profile laser beam. A spatial filter in its simplest form is made up of a well corrected positive lens, usually a microscope objective, and a pinhole placed at the focus of that lens. This arrangement means that all collimated light is focused precisely at the pinhole.

Other light which has originated at points of contamination such as a scratch on a mirror, within the test setup, is focused before or after the pinhole and consequently does not pass through it. That energy is filtered out of the system by the pinhole. In order for a spatial filter to be effective, a proper pinhole and microscope objective lens combination must be obtained for laser in application.

If a lens, in this case a microscope objective, is placed in the path of a light beam, it will focus the beam down to a point, from which it will expand into a wider beam with a Gaussian profile. With a lens with a very short focal length, the beam will rapidly converge and then spread out into a wide beam. By placing a piece of foil with a very small pinhole (ours has a 15 μm diameter) at the focal point of the lens, nearly all the light which is diffracted by dust or other means is removed from the beam. The result is a rapidly diverging, very homogeneous output beam.

Here, spatial filter was made up of a well corrected positive lens, usually a microscope objective, and a pinhole placed at the focus of that lens as shown in Figure 3.2.

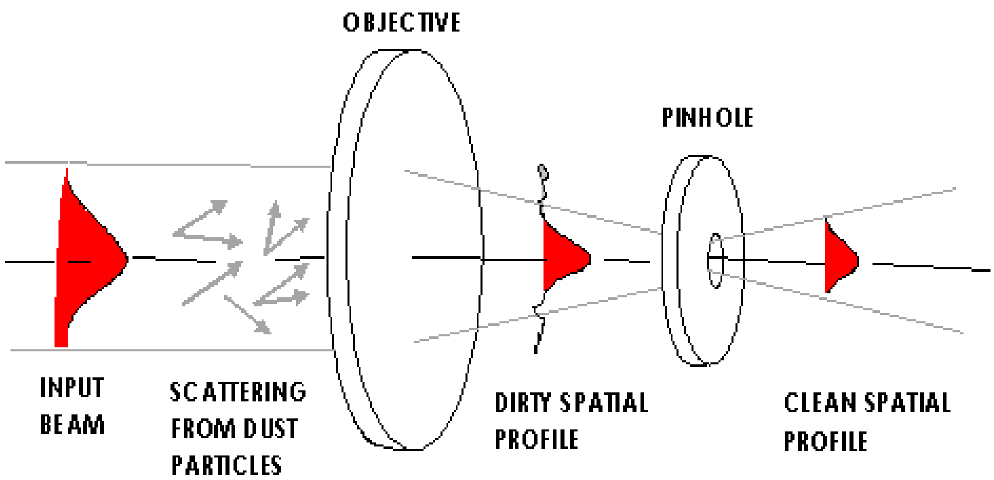


Figure 3.2: Lens-Pinhole Spatial Filter Diagram. The input beam has noise impended on it due to scattering by dust particles or imperfections on the previous optics traversed by the beam.

The Lens-Pinhole Spatial Filter (LPSF) was therefore setup on the optical table as in the following way; a microscope objective was firmly positioned and aligned on the optical table. The focal point of the microscope objective was determined and pinhole placed at this point. Extreme care was observed not to let anything contaminate the foil containing the pinhole. The positioning card was held behind the pinhole of the LPSF and the stand adjusted until the beam hits the center of the pinhole. A large white card was placed at the output so that the output beam of the spatial filter could be observed on it.

Adjustment in the micrometers holding the pinhole was done until the most intense pattern was seen on the card. As one gets closer to the best focus point, the beam become one central disk with faint diffraction rings around it and this was the best focal point where one could see the fewest diffraction rings and the cleanest, brightest central disk.

3.7 Holographic recording

The holographic setup was now arranged as shown in Figure 3.3 below:

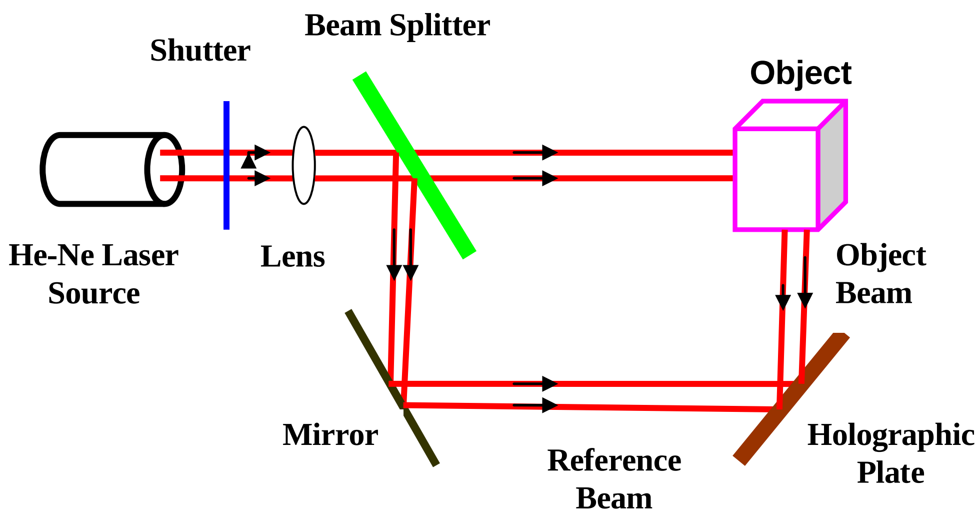
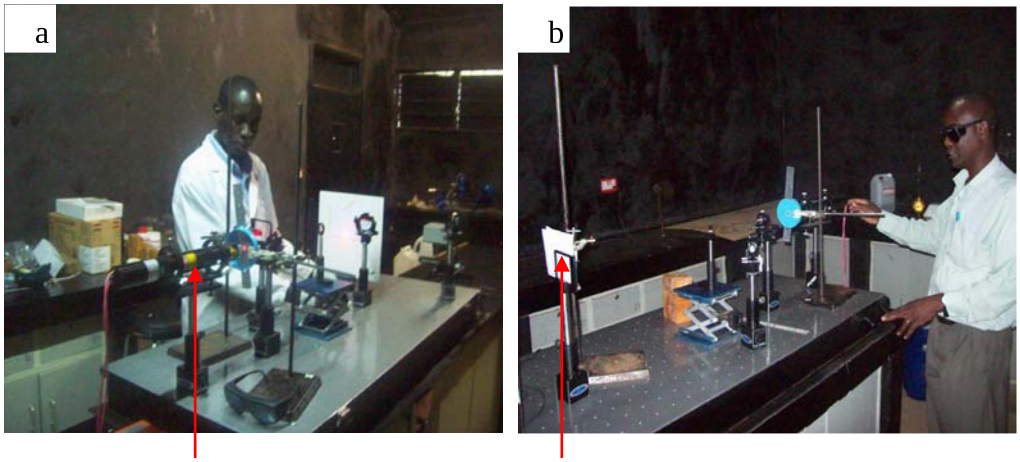


Figure 3.3: Diagram of holographic recording. The beam from the He-Ne laser is splitted by the 50:50 beam splitter to form the illumination beam and the reference beam.

The incident laser beam was first passed through a diverging lens before being split in two by the beam splitter. The first beam aimed to the mounted holographic film through the reflecting mirror and this we called the reference beam. Every elements and optics involved here are aligned and secured in place so that they do not move after mounting. The object holder was then made and the object raised firmly (in this case we were using a 50 cents coin). All surfaces of holders are required to be dark to prevent any unwanted light from degrading the quality of our hologram. The object is oriented such that, the beam reflecting from its surface falls onto the holographic plate where it is supposed to overlap with the reference beam. The two beams interfere with each other to form an interference pattern. Care was taken while setting up the optics past the beam splitter, so that the path length for both two beams remained almost the same after splitting.

Before loading with holographic film, a "shutter" to stop the beam of laser light from reaching the film holder was improvised. The film was then loaded in the dark with the emulsion side toward the object. The emulsion (sticky) side should always face the object. One can feel the edges for firm seating. A few minutes are allowed for air currents turbulence in the room to calm before taking the hologram.

The shutter was then raised for a short while before closing it back. These was repeated severally for other films each time recording the exposure time till the amount of exposure time that works best was determined. The films were then taken out and developed in the darkroom. The respective development procedure for these films was then followed.



He-Ne Laser source Holographic film mount

Plate 3.11: Complete holographic recording setup photograph: (a) Side elevation of complete holographic recording set up; and (b) Rear view of the holographic recording setup.

3.8 Processing of Holograms

3.8.1 Developer solutions

The following solutions involved in film processing were then processed. Solution A contained 10.0 grams of Pyrogallol per liter of distilled water and this was placed in a volumetric flask. Solution B on the other side contained 60grams of Sodium carbonate per liter of distilled water and this was placed in a different volumetric flask. 50ml of Solution A, 50ml of Solution B and 50ml of distilled water were thus mixed to form the final developer solution which was placed on one tray. To form the bleach, 4.0g of potassium dichromate and 8ml of Sulphuric acid per liter of distilled water were mixed and placed in a different volumetric flask. 100ml of the bleach was then obtained and placed in a separate tray just before development.

Finally, a volatile liquid, isopropanol, was used as a wetting solution to help aid the holographic film in drying.

3.8.2 Processing holographic plate

After exposure the holographic plate was now ready for processing. When the holographic plate is processed, it is exposed to several different chemicals solutions for controlled periods of time as shown on the block diagram below:

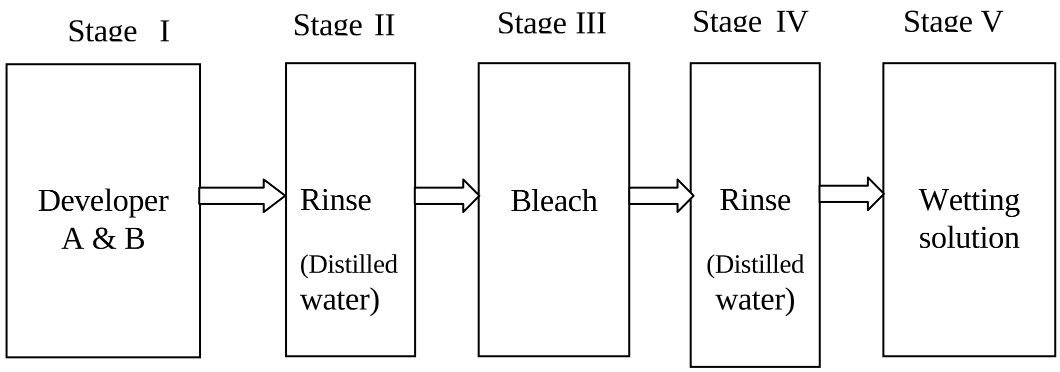


Figure 3.4: Block diagram of holographic Film Development. Stage I. Holographic plate is developed for 2 minutes; stage II. Holographic film is rinsed for 3 minutes; stage III. Holographic plate is bleached for 2 minutes; stage IV. Holographic film is rinsed for 3 minutes and Stage V. Holographic plate is placed in a wetting solution for 30seconds.

The holographic plate was first placed in the developer A and B solution already prepared, the emulsion side being kept up. One end of the tray was then gently lifted every few seconds for agitation. In about 2 minutes or so the exposed surface was observed to be very dark implying the film was ready for the next stage.

Washing - Using plastic disposable gloves, the holographic plate was picked up, held with paper towel with the other hand to catch drips and later placed in a deep container in the sink under running water for about three minutes. This container was narrow enough so that the film or plate was not horizontal inside it.

Bleaching - The developed plate was then placed in the prepared bleach face-up and agitated gently as in the developer. Lights can be turned on at this stage. This was continued until all the darkness (silver coating) was gone, then 30 seconds longer before stopping.

Washing - Using plastic disposable gloves, the holographic plate was picked up, held with paper towel with the other hand catching drips and later placed in a deep container in the sink under running water for about three minutes. This container was also narrow enough so that the film or plate was not horizontal.

Photo-Flow - The plate was now dipped into a photo-flow solution prepared. This was then drained well, by blotting (no wiping or squeezing) with lint-free blotter. Finally this was finished by drying the hologram naturally making sure it remains in vertical position during this process.

To view the finished hologram, the reference beam was reintroduced to the plate. The viewing direction should be approximately the opposite of the direction of the reflected light from the object when the hologram was made. To express it a little differently, the angle between the line of sight towards the image and the line of illumination is the same as the angle between the reference beam and the object beam.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Optical Table

Optical systems comprising from multiple components that must be individually mounted and aligned in a precise and rigid fashion are particularly vulnerable to vibration-induced performance degradation. Holographic experiments are impossible or severely hampered by low vibrations present in the laboratories, for example, the 4-50 Hz vibrations resulting from seismic, acoustic and thermal sources. In this case, the 632.8 nm wavelength of He-Ne laser source was used for holographic application, any vibrations equivalent to half of this wavelength, that is, 316.4 nm would completely wipe out the hologram and inevitably cause an experimental failure. This therefore implies that both holographic and interferometry-based experiments are impossible to perform in the presence of vibrations. These optical experiments therefore require high degree of stability. To be useful, the surface on which an optical system was mounted must satisfy several basic requirements.

1. It has to provide a rigid base on which optics can be mounted and aligned reliably with both long-term stability and no inherent vibrational resonances.
2. The surface must not only successfully damp any vibrations caused by moving parts in the experiment, thereby preventing these vibrations from influencing

critical optical elements, but also isolate the experiment as a whole from ambient background laboratory vibrations.

If these criteria were not met, undesirable effects could often result. An individual component, or the system as a whole, could fail to function properly. Valuable data may have been buried in random noise in essence not having any holograms. Vibration in the laboratory can be classified into three main categories: seismic (ground) vibrations, acoustic vibrations, and forces applied directly to the load on the working surface. Seismic vibrations include all sources that make the floor under the experimental setup vibrate e.g. foot traffic, vehicle traffic to name a few. Acoustic vibrations are a measure of the effects of air pressure variations on the experiment. And finally are forces applied directly to the load on the working surface e.g. vibrations resulting from a moving mirror or lens. Typically, the frequency of the vibrations discussed will range from 4-100 Hz. The primary goal of a well designed optical table is to eliminate relative motion between any two (or more) components on the surface of the optical table. The natural resonances of the table should therefore be as high as possible from this range of vibration frequencies as well as the table should be well damped. Now using the steel compliance curve on Figure 4.1:

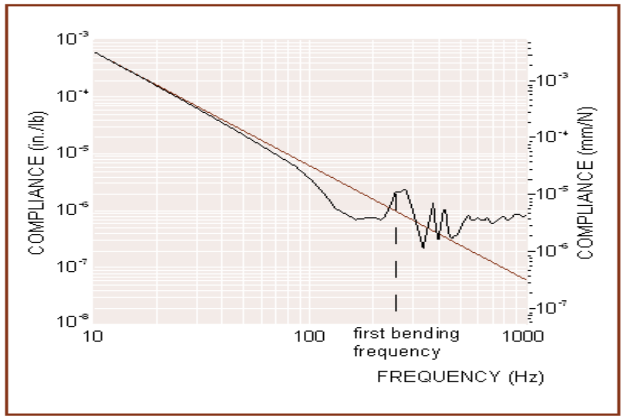


Figure 4.1: Compliance curve of an optical table with the resonance due to the first bending mode of the table labeled (FSL, 2004).

The first resonant frequency of steel occurs far past 100Hz limit discussed in section 2.6.4. This therefore implies steel was the best material to use here for it ideally matches the rigid-body line into high-frequency territory and therefore able to damp all small vibrations.

The optical table was thus made using solid steel plates separated by interior stacked and interlocked structures made from steel. The top and bottom plates provide a stiff, flat working surface while the interior honeycomb structure greatly increases the dynamic rigidity of the optical table without significantly increasing the mass of the optical table. The interlocked structures naturally damp table vibrations as well as resist the long, short, and torsion bending modes. The metal used to construct an optical table ought to have a higher speed of sound than other common materials present in the laboratory that would cause vibrations. Some of this materials are shown on Table 4.1.

Table 4.1: Velocity of Sound in some common solids

MEDIUM	VELOCITY (m/s)
Diamond	12000
Steel	6100
Pyrex	5640
Iron	5130
Aluminium	4877
Brick	4176
Wood	3962
Copper	3901
Concrete	3600
Brass	3475
Cork	518

The speed of sound in steel is 6100ms^{-1} which is second highest to diamond. Steel turns out to be a good compromise because of lower cost than diamond and its availability.

From Table 4.1, steel has the second highest frequency of the first eigenmode (resonant frequency) as compared to the other materials. This implies, any vibration produced on the table below this frequency does not produce a resonant response, thus a setup made of steel is less sensitive to small vibrations present in the laboratories. Diamond would be the best material for optical table setup, unfortunately it is expensive as well as it isn't magnetic and therefore cannot support some of the magnetic optic mounts and bases available.

Compliance characteristics of the optical table can be measured using a dynamic signal analyzer. Another simple and relatively cheap way of analyzing the optical table is the use of the Michelson interferometer experiment discussed below.

4.2 Michelson Interferometer Fringes

The Michelson interferometer produces interference fringes by splitting a beam of monochromatic light so that one beam strikes a fixed mirror and the other a movable mirror. When the reflected beams are brought back together, interference patterns results as observed in section 3.5 above. Precise distance measurements can be made with the Michelson interferometer by moving the mirror and counting the interference fringes which move by a reference point. The distance **d** associated with **m** fringes is given by:

$$d = m\lambda / 2 \quad \text{......} \quad 4.1$$

The Michelson interferometer experiment here is to help detect any vibrations that occur on the table surface or any optical components that are moving. No optical component including the object scene should be moving during the exposure of the hologram.

The following interference fringe patterns were observed using different laser sources as shown by the photographs below (the first plate on both cases being a colored photoraph while the second represents a black and white photograph):

1. The first uncollimated He-Ne laser, continuous wave (CW) source, 632.8nm (1mW) present at the lab gave out circular fringes as shown below:

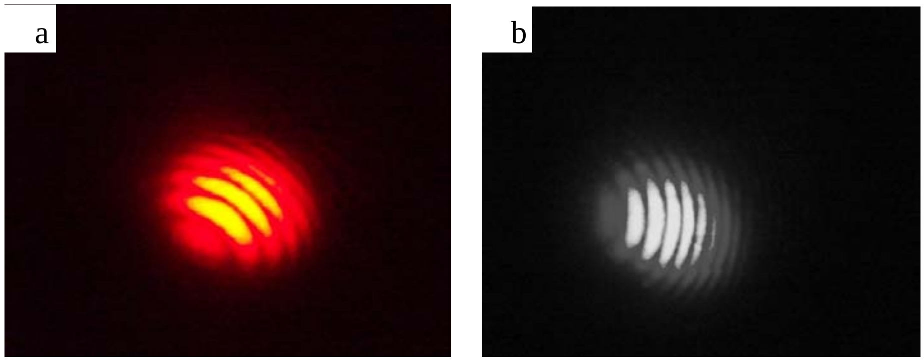


Plate 4.1: He-Ne laser, (1mW) interference fringes: (a) circular interference fringes characteristic of a diverging beam; (b) Shifted circular interference fringes.

2. The second collimated He-Ne laser, a continuous wave source, 632.8nm (10mW) gave out straight line fringes though with spatial noise as shown below:

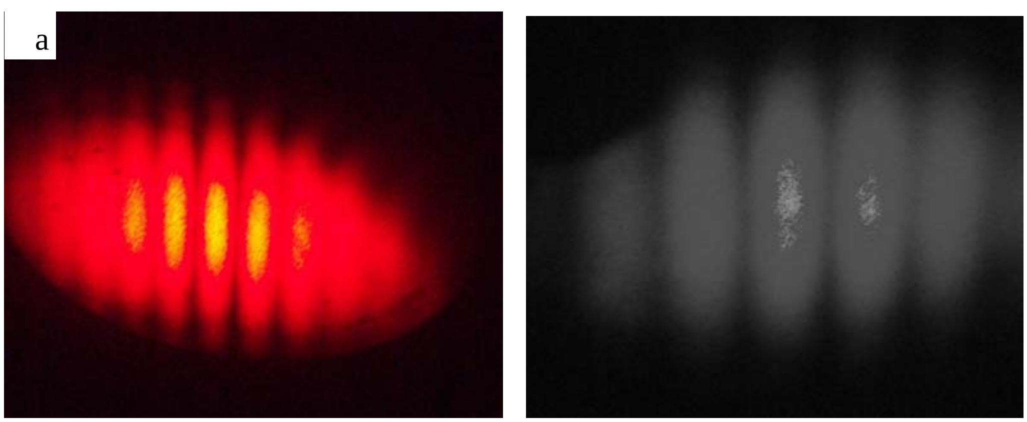
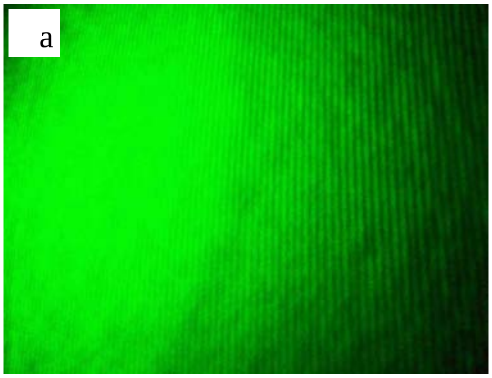


Plate 4.2: He-Ne laser, (10mW) interference fringes: (a) Straight line interference fringes characteristic of well collimated beam from source and (b) Straight line intereference fringes with noise characteristic of unfiltered beam.

3. The third source, Nd:YAG laser source, continuous wave, 532nm (30mW) gave a straight line fringes as shown below:



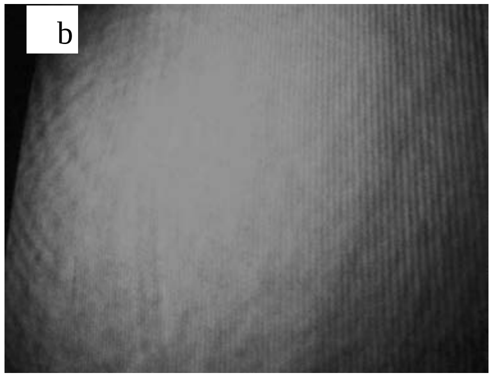


Plate 4.3: Nd:YAG laser, (30mW) interference fringes: (a) Straight line intereference fringes characteristic of well collimated green laser; (b) Straight line intereference fringes though Camera resolution too low to give clear contrast.

Circular fringes as in the first case, Plate 4.1; implies a diverging beam getting off from the source, while straight line fringes imply a well collimated beam is in the output. A collimated beam is one that is nearly parallel, and therefore will spread slowly as it propagates. The word collimation is related to "collinear" and implies a beam that does not disperse with distance (ideally), or that will disperse minimally (in reality). A perfectly collimated beam with no divergence cannot be created due to diffraction, but a beam can be approximately collimated by a number of processes for instance by means of a collimator. Collimated light is sometimes said to be focused at infinity. Thus as the distance from a point source increases, the spherical wave fronts become flatter and closer to plane waves, which are perfectly collimated. When a Michelson interferometer accepts divergent light rays (so that it has a non null field of view), a spatial interference pattern appears at the output port. This pattern looks like concentric circles and is commonly called the bull's eye as observed on the Plate 4.1. These are Haidinger equal inclination fringes and are due to the fact that off-axis rays do not experience the same optical path difference as on-axis rays. For holographic applications, a well collimated laser beam is required. Using the results above, it was observed that the later two laser sources would be useful to us and not the first continuous wave He-Ne lasers source (1mW) from the physics lab for it gave circular fringes implying that it wasn't well collimated.

The Michelson interferometer interference fringe patterns were also used to analyze the table surface for any vibrations occurring or any movement of the optical components. For a fringe pattern that moves rapidly before settling down, this would imply the table was receiving ground vibrations. These types of vibrations may be caused by moving vehicles, people walking in an adjacent room, moving equipments etc. It was observed best to run this setup in the evenings or in the early mornings when the surrounding environment is quieter. This was also the best time to make holographic exposures.

Suppose the fringe pattern moved slowly back and forth, this was a result of air currents in the room. It was made sure all air conditioning units were turned off. Here most of the input vents to the room were blocked i.e. windows and doors. This type of pattern movement may also have been caused by optical components that were not locked tightly into position. All thumb screws on the optical mounts and posts were carefully tightened onto the optical table.

A fringe pattern that moves slowly in one direction is a result of thermal expansion or contraction caused by adjusting the optical components (usually the mirrors) or transferring heat from the body to the components. Most thermal effects usually dissipate rapidly (within 30 seconds). The above movement can also be caused by mechanical creeping of the mounting clamps or optical holders. These components are once again confirmed to be tightened.

It was convenient to have the Michelson interferometer set up during a hologram exposure so confirm whether or not any movement occurred during an exposure. If there is no movement in the interference pattern during testing, there will probably not be any movement during the exposure as long as the above precautions have been taken. The bottom line is that the quieter the table, the brighter the hologram.

4.3 Lens-Pinhole Spatial Filter

There is evident degradation of the beam profile, because the laser beam passed through several optical components. However, a uniform beam was required for holographic applications. This therefore called for a clean up of the contaminated beam using a Lens-Pinhole Spatial Filter (LPSF) as indicated on Figure 3.2. This arrangement mean’s that all collimated light is focused precisely at the pinhole. All other diffracted light is focused before or after the pinhole and consequently does not pass through it. That energy is filtered out of the system by the pinhole. In order to have an effective spatial filter, a proper pinhole and microscope objective lens combination for the laser must be choose.

Placing a lens, in this case a microscope objective, in the path of the laser beam, focuses the beam down to a point (focal point of microscope objective), from which it will expand into a wider beam with a Gaussian profile. With a lens with a very short focal length, the beam will rapidly converge and then spread out into a wide beam. By placing a very small pinhole (we used a 15 μm diameter) at the focal point of the lens, nearly all the light which is diffracted by dust or other means is removed from the beam. The result is a rapidly diverging, very homogeneous output beam as observed on the Figure 3.2. The wave fronts of the beam are circular and passes most of the lasers energy.

4.3.1 Determining the Pinhole Size

For good beams with maximum power, the pinhole size is obtained from:

$$D = \frac{2\lambda f'}{a} \quad \text{……………………………………………………………………. 4.2}$$

Where, D – Pinhole diameter, λ – Wavelength, f ' – lens focal length and

a – input beam diameter.

For example, using the continuous wave (10mW) He-Ne laser used here, the required appropriate pinhole size can be calculated for as follows:

The He-Ne input beam diameter was obtained to be 1.099 mm from the spectrum analyzer, the wavelength of the laser beam was 632.8 nm, and the lens focal length was 30mm. Replacing these values into equation 4.2 above gives the value of the pinhole diameter, D, as 34.55 µm. The required pinhole size therefore should be 34.55 µm. Unfortunately the only available pinhole size in the laboratory was the 15µm pinhole. Using this pinhole in the setup therefore gave out a very dim (less intense) output beam which also had a distorted profile. The less intense output beam was a result of using a smaller pinhole size than the required. The cause of the distortion on the output beam was to be investigated.

4.3.2 Troubleshooting of the pinhole

The distorted output beam called for troubleshooting of the pinhole to determine the cause. Note that 15µm pinhole size is an extremely very small diameter to observe with the normal human eye. This therefore called for a higher resolution microscope to aid us in this investigation.

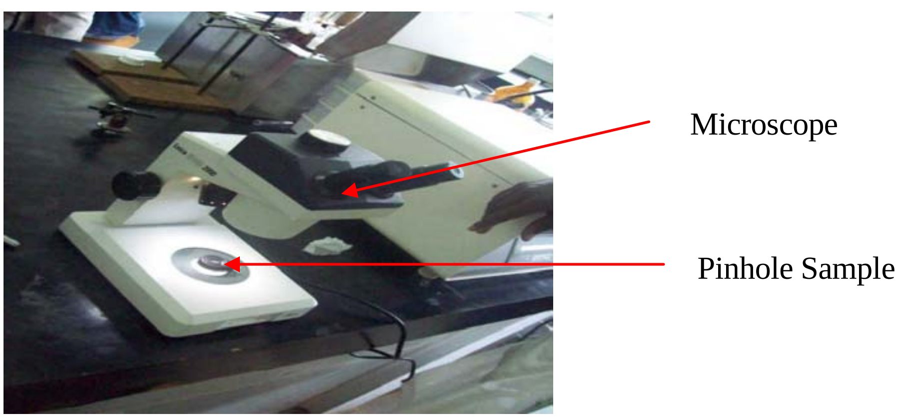


Plate 4.4: Pinhole troubleshooting using a dissecting microscope: The photograph also indicates the sample which is a pinhole.

A dissecting microscope was therefore used to magnify the pinhole surface as shown on plate 4.4. It was then observed that the pinhole did not have one clear aperture, but rather the surface next to the aperture had been scratched and therefore the pinhole had several uneven slits that once a beam was incident on it, it would give out several output beams instead of the single beam required from the output. This was the cause of the resultant distorted beam viewed. The solution to this is to get the right pinhole size with a very clean and clear aperture away from any scratches or dust particles which may cause distortions or block the pinhole.

4.4 Laser Beam Analysis.

A single mode coherent laser source is required. To check this out, a spectrum analyzer was used.

Plate 4.5: Photograph of spectrum analyzer attached onto a computer.

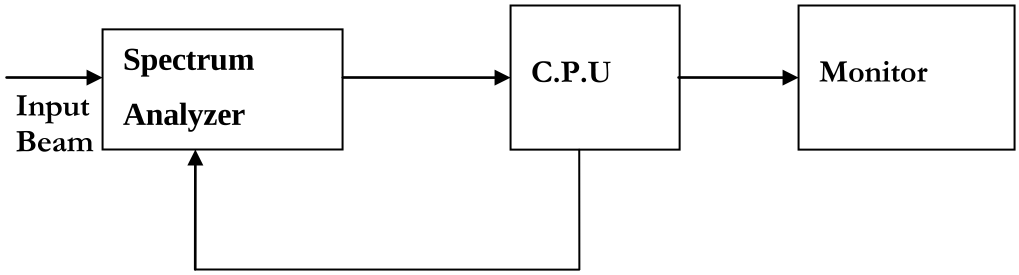


Figure 4.2: Block diagram of Spectrum Analyzer, Computer network.

The optical fiber transmits the beam from the laser to the spectrum analyzer. The spectrum analyzer is interfaced with the computer for beam analysis as indicated on Figure 4.2. A spectrum analyzer examines the spectral composition of some electrical, acoustic or optical waveform. It also measures the power spectrum over a given frequency range.

The following are the outputs obtained from the spectrum analyzer:

Table 4.2: Intensity - wavelength relations of 10mW He-Ne laser beam

Wavelength (nm)	**Intensity (W/m^2)**
620	-0.0006
621	9.74E-05
622	-0.01079
623	0.001276
624	0.001385
625	0.00251
626	0.000787
627	0.001965
628	0.001919
629	0.001791
630	1.4182
631	1.3817
632	0.59603
633	0.2015
634	0.04251
635	0.001281
636	0.001352
637	0.002741
638	-0.00169
639	-0.00038
640	-0.00288

The data on the table shows the intensity of the beam at different wavelength location of the spectrum analyzer. Plotting these values on a graph gives the following curve;

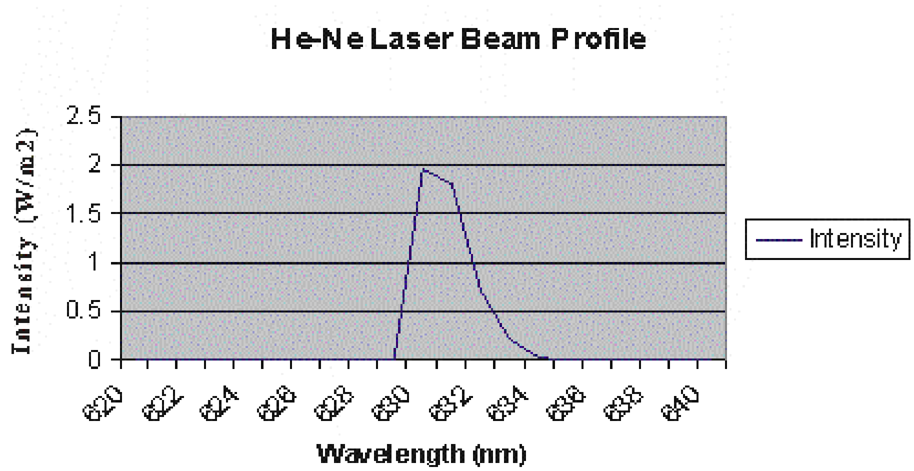


Figure 4.3: He-Ne Laser Beam Profile:

The curve is not symmetrical because of another small mode present. This mode is very close to the dominant that the spectrum analyzer can not resolve. As observed on Figure 4.2, the curve on the right side of the beam is not the same as that on the left side. The optical spectrum analyzer resolution was set to the smallest step size of 1nm while investigating these. This deviation on the beam curve is as a result of another small mode present on the right side of the curve but can not be resolved by this analyzer resolution. This mode is very close to the dominant wavelength though it was observed that this mode almost disappears after the He-Ne laser source has been heated for about 3 hours. The spectrum analyzer gives out almost a single mode curve after that long. Here, irradiance was obtained to be 84.856 W/m^2. Small negative values obtained on the tables are a result of spectrum analyzer instability resulting to poor resolution as well as transmission of beam errors specifically because of foreign interaction between laser beam and other particles from source up to the spectrum analyzers optical fiber.

In the case of the Nd:YAG laser beam, the following are the outputs obtained from the spectrum analyzer:

Table 4.3: Intensity – wavelength relations of 30mW Nd:YAG laser beam

Wavelength (nm)	**Intensity (W/m^2)**
528	-26493
529	27522
530	13712
531	26421
532	1.45E+08
533	-12438
534	-270370
535	24569
536	87965
537	8215.8
538	-23846

Plotting these values on a graph gives the following curve:

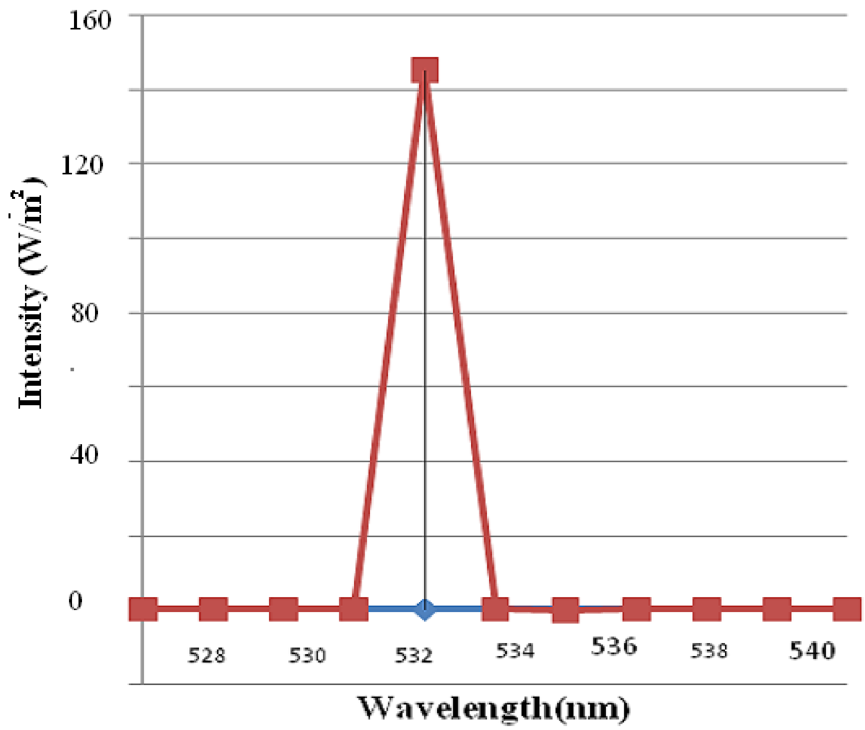


Figure 4.4: Nd:YAG Laser Beam Profile

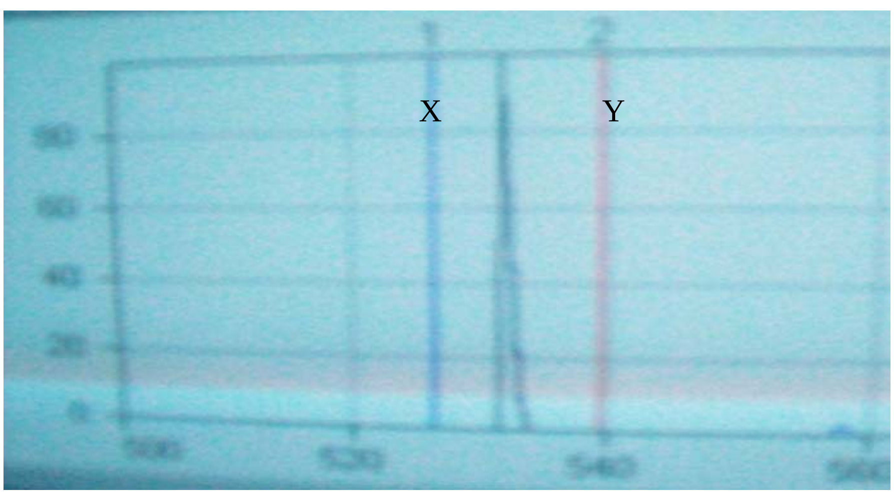


Plate 4.6: Nd:YAG Laser Beam Profile photograph: X and Y are the markers specifying the portion of the signal to be analysed.

The curve on Figure 4.3 and Plate 4.6 is symmetrical implying that the output beam from the laser source is of single mode; note that, the curve on the right side of the beam is almost the same as that on the left side. Here, the Nd:YAG laser Irradiance was obtained to be 347.9524 KW/m^2

4.5 Holographic Recording

Silver halide emulsions have a typical spatial frequency (resolving power) around 3000 - 5000 lines/mm, depending on sensitivity region. This is a very high resolution as compared that of photographic films which has a maximum of 200 lines/mm. The holographic films used here are from Slavich i.e. ultra-fine grain and has more than 5000 lines/mm at spectral sensitivity range 600-680nm. The He-Ne laser source used here had 632.8nm wavelength and therefore within the sensitive spectral range. Silver halide films are produced both in selected sensitivity ranges and as per chromatic plates (full visible spectrum).

During recording, a silver halide crystal was exposed to light, here, photons cause electrons to be promoted to a conduction band thus a sensitivity speck on the surface of the crystal was turned into a small speck of metallic silver. Areas of the emulsion receiving larger amounts of light undergo the greatest development and therefore results in the highest optical density. A larger silver speck of two or more atoms is stable, but to make a latent image it has to be a speck of at least three or four atoms. These silver specks are often referred to as the latent image, because they can be converted into a hologram by wet processing as described in the methodology. No vibrations are to be present during this process else no hologram will be observed after film development.

4.6 Processing holographic plate

After exposure the holographic plate was ready for processing. When the plate is processed, it is exposed to several different chemicals solutions for controlled periods of time. Processing film basically involved the following five steps.

1. Development - The developing agent gives up electrons to convert the silver halide grains to metallic silver. Grains that have been exposed to the radiation develop more rapidly, but given enough time the developer will convert all the silver ions into silver metal. Proper temperature control is needed to convert exposed grains only to pure silver while keeping unexposed grains as silver halide crystals.

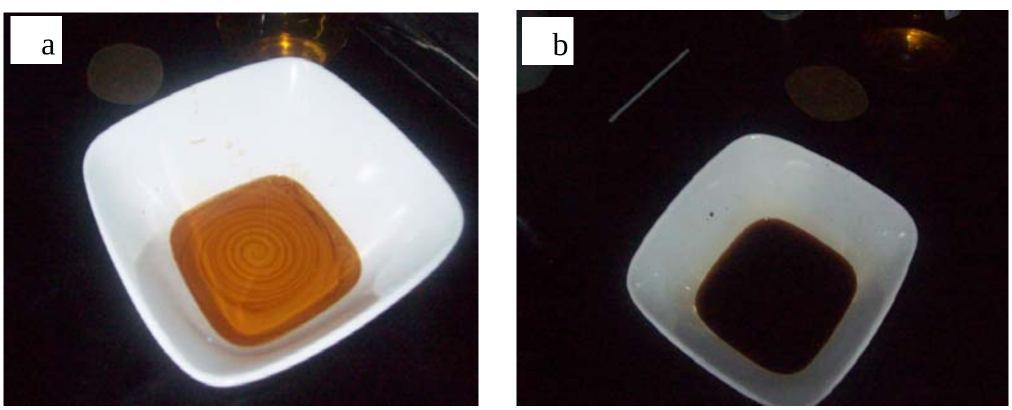


Plate 4.7: Developer solutions: (a) before exposure; (b) after exposure with film

2. Stopping the development (Rinse) - The stop bath simply stops the development process by diluting and washing the developer away with distilled water.

Distilled water is used instead of tap water for tap water has traces of impurities and extra foreign particles which might leave residual chemicals onto the developed film.

3. Fixing (Bleach) – Here, unexposed silver halide crystals are removed by the fixing bath. The fixer dissolves only silver halide crystals, leaving the silver metal behind.

Plate 4.8: Photograph of the bleach (Fixer) solution

4. Washing - The film is washed with water to remove all the processing chemicals.
5. Drying - The film is passed through a wetting agent to help it dry evenly before it's dried for viewing.

Plate 4.9: Photograph of the wetting solution

Processing film is a strict science governed by rigid rules of chemical concentration, temperature, time, and physical movement. Excellent holograms require a high degree of consistency and quality control. Below find a time series for a few of the processed holograms. The painted rows gave out positive results.

Table 4.4: Table depicting the time series of Film Development

Exposure time (s)	Developing time (s)	Washing time (s)	Bleaching time (s)	Washing time (s)	Wetting time (s)
8	180	120	180	180	60
20	120	150	120	180	30
80	180	180	120	120	60
45	120	180	120	180	40
30	90	120	110	120	30
15	90	120	100	120	20

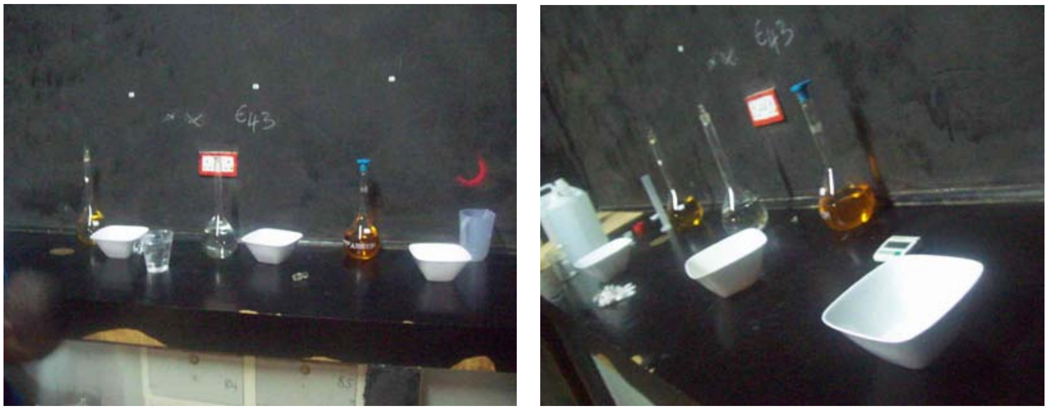


Plate 4.10: Photographs of the complete holographic films developing solutions

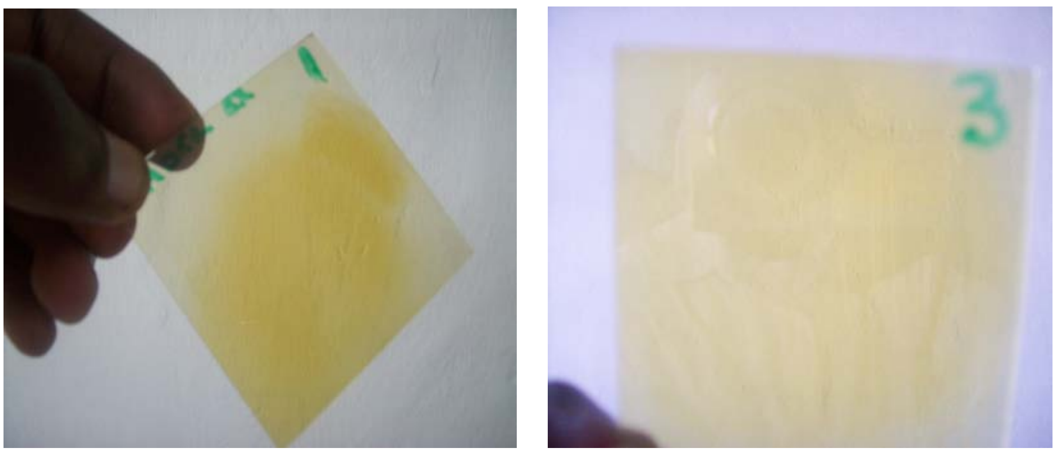
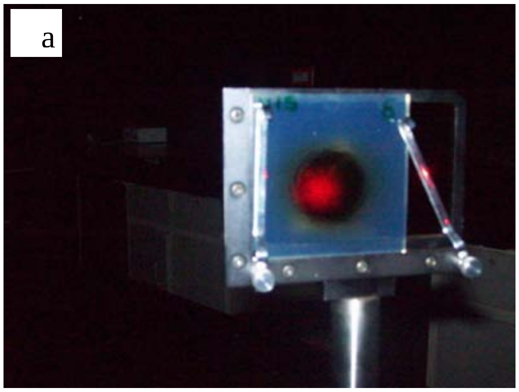


Plate 4.11: Sample photographs of completely developed holograms from the laboratory

To view the finished hologram, the original reference beam was reintroduced to the holographic plate in the dark room. The viewing direction should be approximately the opposite of the direction of the reflected light from the object when the hologram was made, that is, the angle between the line of sight towards the image and the line of illumination is the same as the angle between the reference beam and the object beam.

The following photographs are an illustration of the holograms viewed from the completely developed films from the setup assembled in the laboratory. The object used here was a 50 cents coin. The coin was preferred for its small surface area to fit in the spread beam. The coins surface is also shiny and rough thus able to scatter incident light into several different direction. From the photographs of the holographic films demonstrated below, different dimensions of the coin are observed relative to the orientation of the incident reference beam striking the film. Photographs presenting the coin front surface, rear view and depth are shown on the plates below:



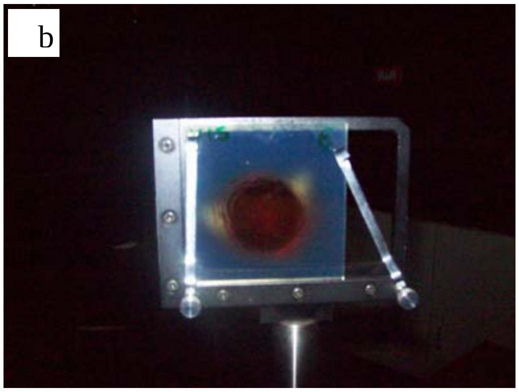


Plate 4.12: Hologram photographs presenting the front surface of a 50 cents coin

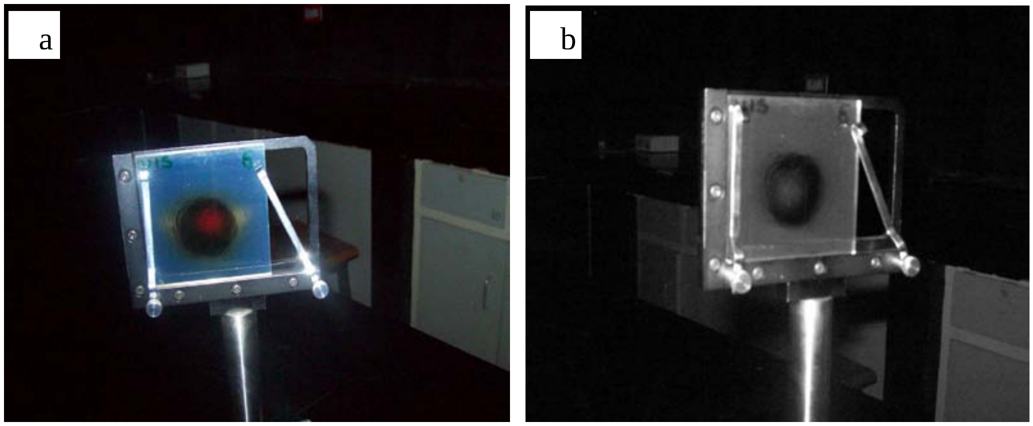


Plate 4.13: Hologram photographs presenting slightly tilted front surface of a coin: (a) Slight rear view of the coin; (b) Further rear view of the coin hologram.

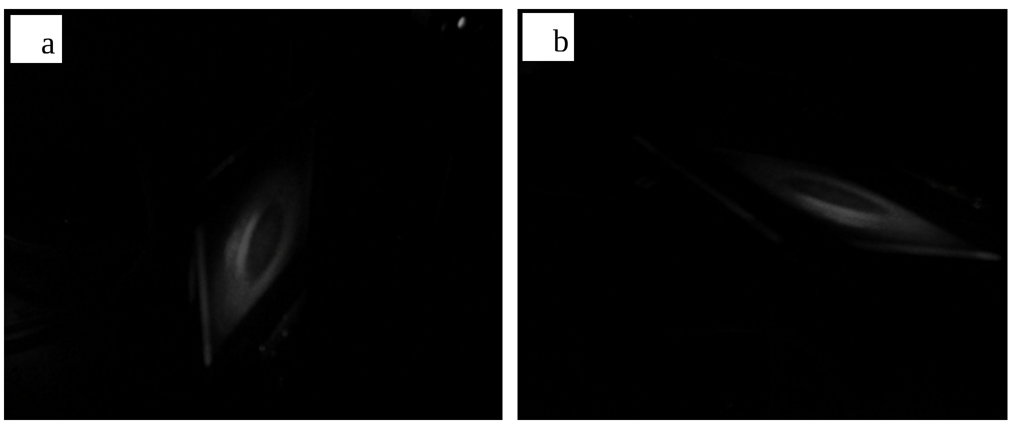


Plate 4.14: Hologram photographs presenting the depth of the tilted 50 cents coin: (a) Viewing from the extreme rear; (b) Viewing from the extreme top. Note that, the small angles of viewing relative to the plane of the holographic plate accounts for the oval shape of the coin. However the aspect of depth is evident in both photographs. The contrast between the dark and bright regions was not very good mainly because of the low resolution of the camera used.

As observed from the holographic plates above, different dimensions of the coin's hologram are viewed relative to different orientation of reference beam striking the holographic film. As the film is gradually tilted relative to the incident reference beam, the front surface of the coin is clearly observed before gradually proceeding to the depth. These holograms were photographed using a 7.0 mega pixel Kodak digital camera. This camera did not give out the best quality contrast for clear holograms as observed using the naked eye in the laboratory. A higher resolution camera in the order of 14 mega pixel and printer would give out better clearer print results equivalent to that observed with the ordinary eyes in the laboratory.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

A stable Optical table was designed and fabricated. This table purely made from steel weighs about 325 Kg and is specially designed with good static rigidity thus implying excellent stiffness. It has a well damped structure which means no low frequency (<100 Hz) resonances are present. The interior design of this table is made of honeycomb structures to resist the long, short, and torsional bending modes in essence having a sensitive system for demonstrating holography, interferometry amongst other sensitive experiments.

Stability of fabricated optical table was analyzed using a Michelson interferometer experiment. Still straight line interference fringes were obtained with no movement back or forth. This implies that the fabricated table was able to resolve both the seismic, acoustic and thermal vibration and none of these vibrations was present during the holographic recording period.

Laser analysis using spectrum analyzer was done. It was observed that the He-Ne laser had another mode very close to the dominant wavelength when switched on. This mode was studied and observed to almost disappear after the He-Ne laser source had been heated for about 3 hours thus giving out a single mode curve. This was observed to be the best time to record clear holograms.

Optimal conditions for the hologram processing were determined. The concentrations of reagents used in holographic film processing were thus formulated. A strict study of chemical concentration, temperature and time was done. Excellent holograms were obtained after a high degree of consistency and quality control on exposure time, chemical concentration and time was done.

A successful experimental set-up to implement holography was therefore designed and fabricated. This is such a step forward for local companies and institutions for a custom made local setup is now available that can be applied in research and training as well as for commercial use within the region of Africa.

Successful samples of holograms were generated and observed using this setup. This implies that we have demonstrated the feasibility of holography in this region of Africa.

5.2 Recommendations and future work

To improve on the setup and make it more effective, the correct and efficient size of pinhole should be used for this setup to help in filtering the beam. Better results can also be obtained if a complete dark room is obtained for currently there are lots of openings that allow stray light into the current partial dark room while the experiments are in progress in effect reducing the quality of the holograms.

Future further work can be done especially on holographic interferometry and processing of embossed holograms. Using this preliminary setup already generated, more improvement and development can be made to have an advanced holography laboratory. This set-up will be modified for the purpose of making embossed holograms. This can be used as security holograms that are very difficult to forge which can be impended on quality merchandise locally, for example on Currency notes, Title deeds, University certificates, Car Log books amongst many others. These holograms can then be easily replicated from a master hologram carrying special 3-dimensional emblem of a company and attached onto documents. These holograms will then be used by any client to verify the authenticity of products or documents and make it impossible to counterfeit in essence curbing this underlying problem

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APPENDICES

APPENDIX 1: HE-NE LASER SPECIFICATIONS

10mW HE-NE LASER SPECIFICATIONS	
Mode Structure	TEM_{00}>99%
Beam Drift After 20 min Warm-up	<0.20 mrad
Long Term Beam Drift	<0.05 mrad
Starting Voltage	<10,000 VDC
Power 3 s After Turn On	>75%
Shock	15 g for 11 ms
Operating Temperature	-20 to 70 °C
Storage Temperature	-40 to 80 °C
Operating Humidity	≤80%
Storage Humidity	≤95%
Operating Altitude	0 to 3,000 m
Storage Altitude	0 to 6,000 m
Power	10.0 mW
$1/e^2$ Beam Diameter	0.88 mm
Divergence	0.92 mrad
Polarization Ratio	Linear > 500:1
LMS**	316 MHz

Noise (RMS)[†]	<1%
Operating Voltage	3000 VDC
Operating Current	6.50 mA

APPENDIX 2: Nd:YAG LASER SPECIFICATIONS

Wavelength	532nm (Green)
Output Power Class (IIIb)	>20 mW
Beam Size (1 / e^2)	Diameter <1.0mm
Beam Divergence (full angle)	<1.2 mrad
Mode	TEM_{00}
Mode Purity (TEM_{00})	>95%
Mode Quality	$M^2 < 1.4$
Spectral Linewidth	<0.1nm
Polarization	Linear 50:1
Power Stability (over 2 hours)	±10%
Warm-up Time (maximum.)	15 minutes
Operating Temperature	0°C to 40°C (32°F to 104°F)
Power Consumption	<40 watts
Expected Operating Lifetime	10,000 hrs.
Dimensions	
Laser Head	30mm H x 30mm W x 66mm L
Power Supply	55mm H x 105mm W x 125mm L