

Rapid beam shaping using a digital micromirror device



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Declaration

I declare that this Dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.



(Signature of candidate)

_____**1st**____ day of _____**June**____ 20____**20**____ in _____147 rose Avenue, Extension 3,
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Abstract

The ability to structure light into different profiles has many important applications such as materials processing and optical communications. Modern methods of structuring light involve the use of liquid crystal spatial light modulators (LCSLMs), owing to their versatility and robustness in optics and photonics experimentation. However, they have some limitations as they are sensitive to polarisation states of light, have slow refresh rates and are expensive. Traditionally used in digital light processing technologies, digital micromirror devices (DMDs) have been used in many research aspects pertaining to optics and photonics. They are composed of arrays of micromirrors that have binary operational states determined by the angle of tilt of each mirror about an axis. These states make DMDs amplitude-only light modulating devices, insensitive to polarisation states, have faster refresh rates and significantly cheaper compared to traditional liquid crystal spatial light modulators. We employ DMDs to create different structures of monochromatic light, from arbitrary shapes to flat-top beams and spatial modes of light. We test the DMD's refresh rate and demonstrate mode switching at a rate of 3.57 Hz. We show a high quality in the generated beams, with correlation factors of more than 90%, and as such demonstrate a modern alternative to structuring light.

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Publications

Journal papers:

1. Cox M., Maqondo L., **Kara R.**, Milione G., Cheng L., Forbes A. “The resilience of Hermite-and Laguerre-Gaussian modes in turbulence,” *Journal of Lightwave Technology*, vol. 37, no. 16, pp.3911-3917, 2019.
2. Scholes S., **Kara R.**, Pinnel J., Rodriguez Fajardo V., Forbes A. “Structured light with Digital Micro-mirror Devices: A guide to best practice”, *Optical Engineering*, vol. 59, no. 4, p. 041202, 2019.

Conferences:

1. **Kara R.**, Rosales-Guzman C., Forbes A., “Generating high quality spatial modes of light at a high rate”, *61st Annual Conference of the South African Institute of Physics and OSA Network of Students (IONS) South Africa 2*, 2018.
2. **Kara R.**, Scholes S., Forbes A., “Creating structured light with Digital Micro-mirror Devices”, *12th ALC Student Workshop*, 2019.
3. **Kara R.**, Scholes S., Forbes A., “Generating amplitude and phase modulated images using a digital micro-mirror device”, *12th ALC Laser Imaging Workshop*, 2019.
4. **Kara R.**, Scholes S., Forbes A., “An ultra-fast method of shaping light”, *10th Annual Cross Faculty Postgraduate Symposium, University of the Witwatersrand*, 2019.

Chapter 1

Introduction

The on-demand shaping of light's spatial profile, is of great importance with an increasing number of applications in a wide variety of commercial, industrial and scientific areas. In the materials processing industry, laser beams with different irradiance distributions are used. These include beams with a uniform irradiance distribution, or flat-top beams [4] to Gaussian beams for laser drilling processes [5] to Bessel and annular and vortex beams for microdrilling, nanopatterning and photopolymerisation processes [6] and laser annealing processes [7]. Various medical sectors utilise lasers with different irradiance distributions. Surgery [8, 9], laser skin treatment [10, 11], laser hair removal [12, 13] are some examples in which lasers with different irradiance profiles are used. Optical trapping is another field in which microparticles are bounded with the use of a laser beam. Beams with different irradiance distributions such as Gaussian beams, flat-top beams, vortex beams and Bessel beams have been used for optical trapping and micromanipulation [14, 15, 16, 17]. In optical communication, the resilience of spatial modes in turbulence has been investigated [18] and spatial modes of light have also been used for the increase in bandwidth optical communication systems. With an increasing number of applications the optimisation of the techniques of beam shaping is very important. In this chapter we motivate our study of the use of digital micromirrors devices (DMDs) for beam shaping by first briefly reviewing the history of beam shaping and common methods of implementing beam shaping.

Applicable to both incoherent and coherent sources of light, beam shaping involves a given illumination source incident onto an optical system which modulates the intensity or phase (or both simultaneously) to give rise to a desired output beam at some observation plane. The shape of a output beam is defined by the intensity profile and the manner in which it propagates is dependent on its phase profile. A generalised illustration of the beam shaping concept is given in Fig. 1.1. An optical system described by a transmission function T acts upon an incident beam u_{in} to give rise to an output beam u_{out} at some observation plane. The main goal of beam shaping is to design an optical system which performs this transformation.

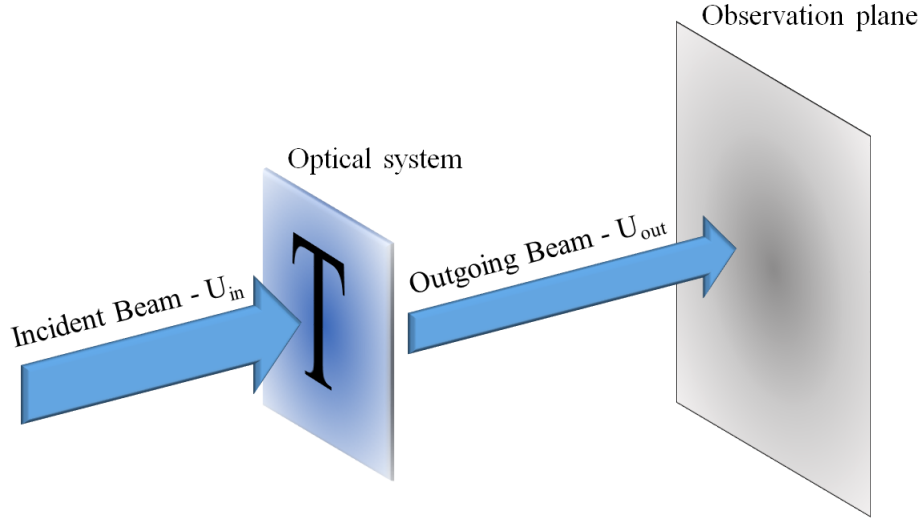


Figure 1.1: Generalised concept of beam shaping.

Custom fabricated physical components such as refractive and diffractive optical elements are examples of beam shaping optical systems. Modern methods of shaping light involve the implementation of digital holographic techniques on computer controlled light modulating devices. Composed of pixelated arrays of micro-structures (cells of liquid crystals, for example), these devices provide more control and robustness in optical experimentation, as the orientation of these micro-structures are computer controlled enabling dynamic beam shaping abilities. The digital micromirror device (DMD) is a product of Digital Light Processing (DLP) technology mainly used in digital projection systems. Composed of pixelated micromirrors, the use of these devices for beam shaping is a topic of great interest.

1.1 History of beam shaping

The earliest reported case, though debatable, of beam shaping was demonstrated by Archimedes between 213 to 211 BC, during which a collection of mirrors was devised using polished pieces of flat metal to break up incident light and focus it onto a single target [19]. During the 1700s, the development of the Fresnel lens by French physicist Augustin-Jean Fresnel was the first physical beam shaping optical element used in lighthouses for the aid in navigation for cruise ships along coastlines [19]. Newer techniques of shaping incoherent light during the 1900s involved non-imaging methods and the use of reflective and refractive optical systems to increase the intensity of solar radiation by concentrating it into a region of interest [20]. The shaping of coherent light occurred after the advent of the laser during the 1980s, with its full development established in the following decades. Initial demonstrations of shaping laser light was performed using reflective, refractive and adaptive optical systems to reshape the amplitude and phase of laser light external and internal to laser resonator cavities. For applications in materials processing and lithography in which the illumination of a specific target with a uniform intensity profile is necessary, the development of lossless beam shaping was established and initially demonstrated by Frieden in 1965 during which an optical system consisting of two optical elements was devised. The first element converted an incident beam with a Gaussian intensity distribution to beam with a uniform intensity distribution and the second corrected for any phase distortions created by the redistribution of the incident light.

1.2 Techniques of beam shaping

As mentioned earlier, the determination of an optical system which acts upon an input beam is the main goal of beam shaping. Most desired beams have an amplitude and a phase. With reference to Fig. 1.1, we consider an input wave with amplitude A_{in} and phase ϕ_{in} acted upon by a beam shaping system described by some transmission function T to give rise to a desired output wave with amplitude A_{out} and phase ϕ_{out} . This may be represented as

$$u_{out} = T \times u_{in}, \quad (1.1)$$

where $u_{in} = A_{in} \exp[i\phi_{in}]$ and $u_{out} = A_{out} \exp[i\phi_{out}]$. The transmission function for complex amplitude modulation is given by [21]:

$$T = \frac{u_{out}}{u_{in}} = \frac{A_{out}}{A_{in}} \exp[i(\phi_{out} - \phi_{in})]. \quad (1.2)$$

Modulation techniques can be amplitude-only, phase-only or amplitude and phase (complex amplitude). The type of modulation technique used has a consequence on the position of the formation of the desired beam. Amplitude-only and complex amplitude modulated beams form at the plane of the beam shaping element, whereas phase-only modulated beams form in the far field of the beam shaping element [21].

Beam shaping may be divided into three categories: apertured beams, field mapping and beam integration [20]. The first class involves the truncation of an input beam by means of an aperture [20, 22, 23], and imparts no phase change on the incident beam. This may be considered as an amplitude-only modulation technique. The desired output beam is dependent on the size of the aperture and may be imaged onto a desired observation plane. This method is trivial and has a main disadvantage of not being lossless (energy is not conserved between the input and the output beam), and efficiency (ratio of the output irradiance distribution to the input) is dependent on the size of the aperture size. In this case, with reference to Fig. 1.1, the transmission function describing the beam shaping optical system is the aperture function. Fig. 1.2 shows an illustration of this category.

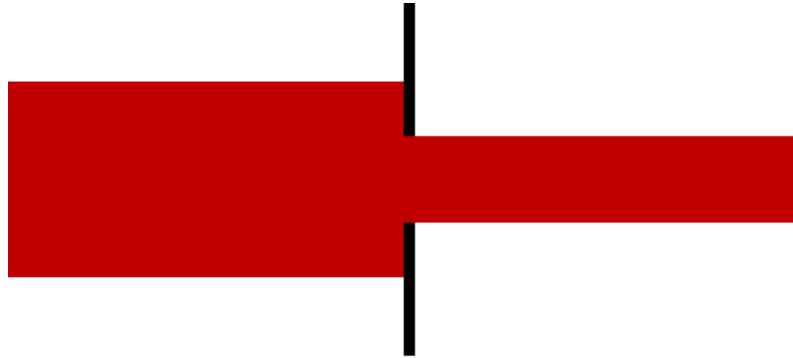


Figure 1.2: Beam shaping by means of aperture truncation.

The next two categories are referred to as “field mapping” and “beam integrators” both of which are phase modulation techniques and have an advantage of being effectively lossless. Field mapping beam shaping elements make use of highly efficient reflective and refractive phase elements with the main objective of introducing spherical aberrations between the beam shaping components in the beam shaping system [20]. Fig. 1.3 shows an illustration of beam shaping using the field mapping concepts. The use of diffractive optical elements in field mapping beam shaping systems leads to a decrease in efficiency as diffraction effects contribute to loss of light [24] and are generally not used. Mainly implemented in telescopes [20] and custom systems for generating laser beams with a uniform irradiance distribution, beam shaping through refractive field mapping was realised with the use of aspheric lenses [24].

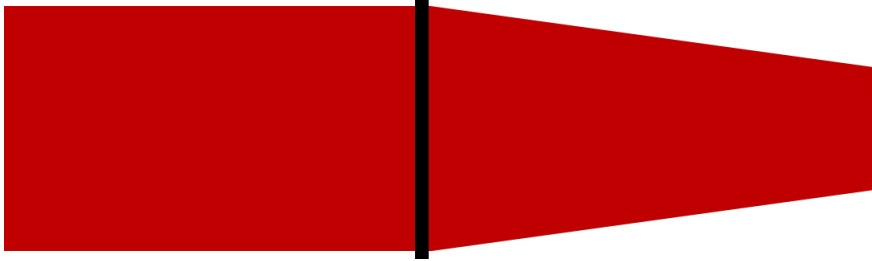


Figure 1.3: Schematic showing the field mapping concept of beam shaping.

Beam integrating systems break up a given input beam onto a number of smaller beams with a phase change applied to each smaller beam by means of an array of small lenses. The desired output beam is formed by the combination of diffraction patterns from each small lens in the array [25]. A basic beam integrator system is composed of two basic optical components: a set of components consisting of an array of small lenses which break up a given input beam into smaller beams and a component that overlaps the smaller beams at a desired observation plane [20]. Beam integration systems may be classified as diffracting or imaging integrators according to the number of lenslet arrays used. The first consists of a single array of lenslets and which the output field is determined by the superposition of the diffraction fields emanating from the beamlets. The second class consists of two lenslet arrays. The output field is a real image of the beamlets emanating from the first lenslet array. Fig. 1.4 shows the two different types of beam integration systems.

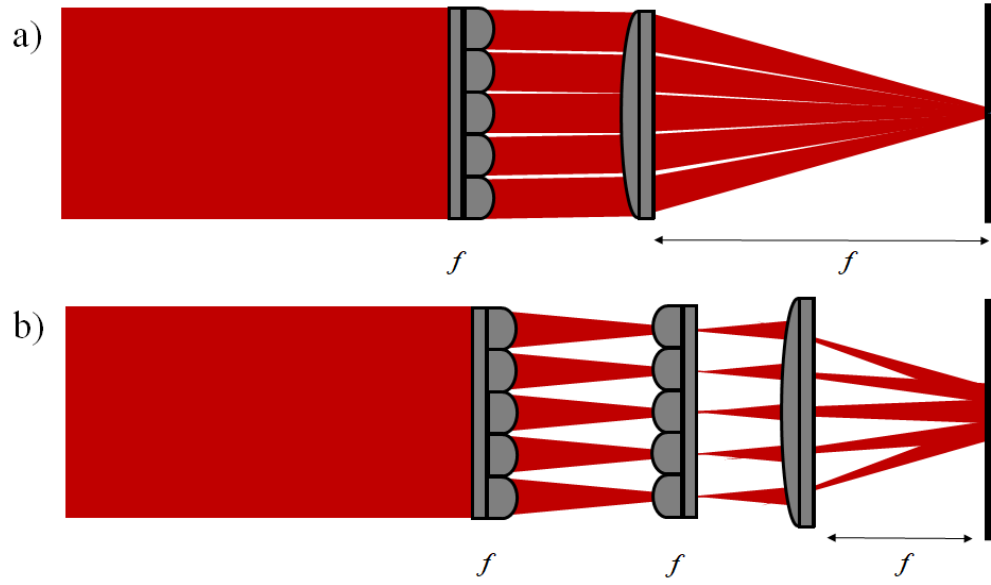


Figure 1.4: Beam integration methods for beam shaping using (a) a single lenslet array and (b) using two lenslet arrays both having a focal length f .

1.3 Tools for beam shaping

1.3.1 Physical beam shaping optical elements

Most optical elements are fabricated from glass, plastic, polymer or crystalline materials and designed according to particular specifications such as the accepted wavelengths and the polarisation states of the incident illumination allowing these elements to function optimally. Beam shaping optical elements may be classified as refractive or diffractive. Refractive beam shaping elements are designed based on the fundamentals of geometrical optics and satisfying imposing conditions of energy conservation and constant optical path length between the input and output beams [20]. Beam shaping through these elements occurs as a result of the change of the dynamic phase (the phase that a beam acquires as it passes through a medium). Established and patented in 1966, this invention shaped a beam with a non-uniform intensity into a beam with a uniform intensity with the use of two aspheric lenses [24]. Beam shaping through refractive optical elements occurs as a result of the thickness, refractive index and surface characteristics of the material used in the fabrication process causing a change in the intensity and phase profile of an input beam [26]. Lenses are examples of refractive beam shaping elements as they transform an incident beam to a new outgoing beam by refraction.

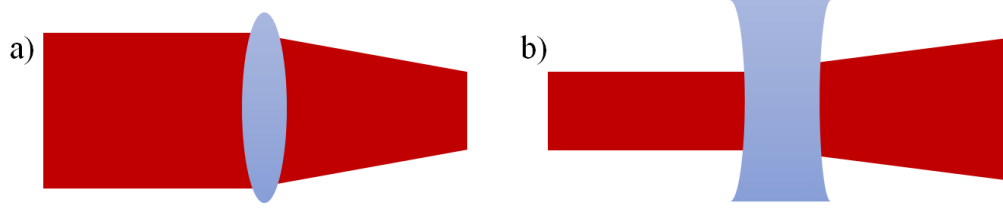


Figure 1.5: Examples of refractive beam shaping elements. (a) A converging lens. (b) A diverging lens.

Spiral phase plates are further examples of refractive optical elements. These are elements with a uniform refractive index and spiral depth d used for the generation of beams carrying orbital angular momentum (OAM). Fig. 1.6 shows an illustration of the generation of OAM through a spiral phase plate. A given input beam with a flat wavefront passing through a spiral phase plate with an azimuthally varying thickness resulting in a beam with a helical wavefront and possessing OAM proportional to the depth of the phase plate. Conversion of Gaussian beams to beams carrying OAM using spiral phase plates have been realised [27, 28, 29].

Diffractive beam shaping optical elements use the combination of many diffraction orders to generate a desired shaped output beam. They are designed based on the principles of physical optics in which diffraction and interference effects are taken into account. Consisting of smaller phase apertures, usually less than ten wavelengths, these elements relay a spatial frequency distribution to the phase of a given input beam, resulting in the beam interfering with itself. The advantages of using these elements include a wider variety

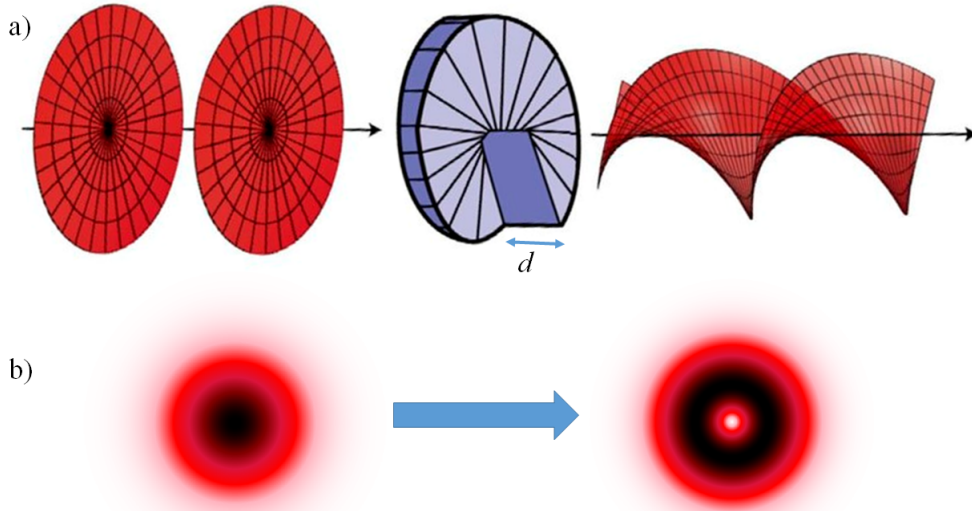


Figure 1.6: OAM generation via a spiral phase plate. a) Wavefront transformation from flat to helical. b) Transverse intensity profile change from Gaussian to doughnut-shaped.

of beam shaping abilities than refractive elements as many complex optical elements with different functions may be combined into a single element to modulate light which may not be accomplished by refractive beam shaping optical elements; they are tolerable to input beam conditions such that they are relatively insensitive to alignment and size of the input beam [25]; they are highly efficient, simple and customisable structures that offer a wide degree of flexibility and effective for high power laser applications [25]. The main disadvantage of using these elements is the presence of speckle [25, 20]. Gratings, diffractive lenses and far-field diffractive diffusers are examples of beam shaping diffractive optical elements. A diffractive lens is composed of a series of annular concentric regions, making the surface of the element having stepwise discontinuities. Fig. 1.7 shows examples of diffractive optical elements.

Despite the advantages provided by the use of custom fabricated physical optical elements for beam shaping, these elements have many drawbacks. In addition to the costly and technical challenges in the manufacturing of these elements, they are dependent on the incident illumination source size and wavelength and as such provide very little control in optics and photonics experiments. Custom fabricated optical elements is not ideal for use in experimentation in which a range of modulated light is needed. For example, mode division multiplexing uses the spatial degree of freedom of a given laser source to increase the information bandwidth in optical communication systems [30]. Such implications together with the ever increasing commercial, industrial and research applications of structured light imposes a need for the more versatile methods creating structured light.

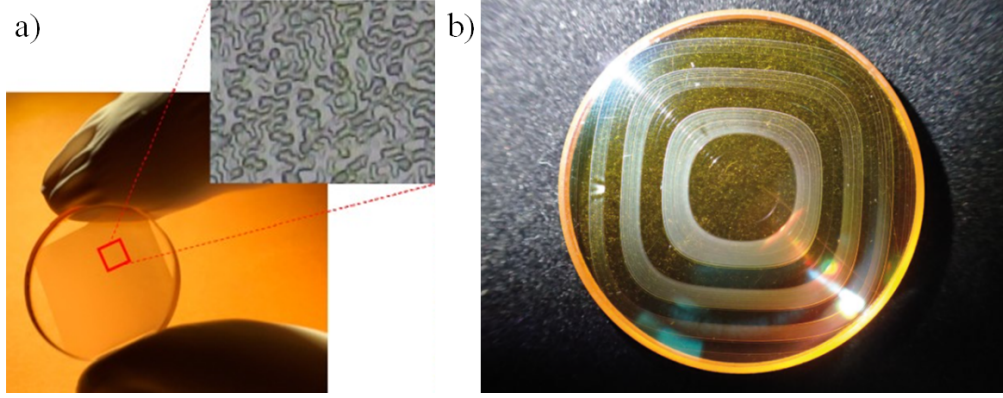


Figure 1.7: Examples of diffractive optical elements. The insert in (a) shows a microscopic view of the smaller structures within the element [1]. (b) A diffractive lens manufactured on zinc selenide lens [2].

Modern methods of shaping light implement digital holographic methods on computer controlled light modulating devices. These are composed of pixelated arrays of micro-structures (cells of liquid crystals, for example), of which may be individually controlled by means of an applied voltage addressed across electrodes which enables a change of the orientation of the micro-structures. Implementing digital holography on these devices involves the generation of an array of numbers, or a matrix, of dimensions equal to that of the device. This forms of one-to-one mapping between the matrix and each pixel of the device. The magnitude of each element in the matrix determines the orientation of the corresponding pixel. These devices provide more control and robustness in optics experimentation, as the orientation of the micro-structures are computer controlled enabling the dynamic beam shaping abilities.

1.3.2 Liquid crystal spatial light modulators (LCSLMs)

The most common light modulating devices are liquid crystal spatial light modulators (LCSLMs). These electro-optical devices are phase-only reflective or transmissive light modulating devices. The general structure of these devices are composed of birefringent uniaxial layers of nematic elongated liquid crystals (molecules arranged in random positions but with the same orientation) arranged according to a particular optical axis [21, 31]. The properties of the liquid crystals, mainly chirality and binding forces, make the LCSLM screen birefringent. Birefringent materials have a refractive index dependent on the polarisation state of light. The orientation of the crystals are controlled by the magnitude of an externally applied voltage. The angle $\theta(V)$ at which these molecules rotate is calibrated such that when the voltage is at a maximum, the angle of rotation is at a maximum and a minimum for a minimum applied voltage. The birefringence of the molecules allow for the modulation of linearly polarised light. Fig. 1.8 shows an example of a LCSLM screen together with a schematic of the internal structure.

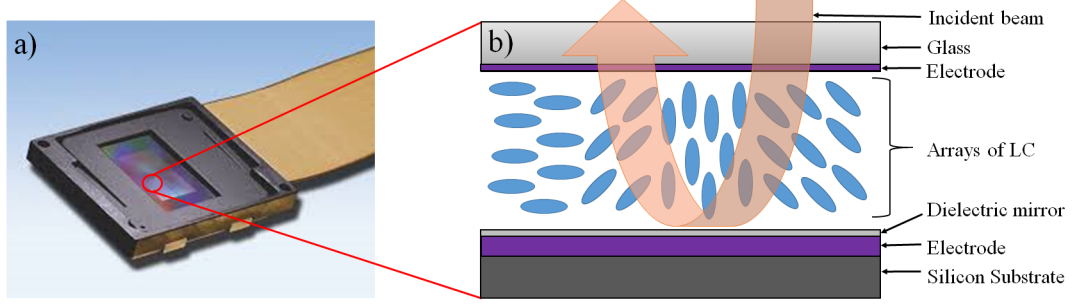


Figure 1.8: (a) A LCSLM screen with (b) a schematic of the internal structure.

Dynamic phase modulation occurs as a result of the path length and propagation time of light through a material of varying thickness or refractive index. Light rays parallel to the optical axis (with its polarisation perpendicular to the optical axis) are classified as ordinary rays and characterised by an ordinary refractive index n_o and light rays with the polarisation component perpendicular to the ordinary rays are classified as extraordinary rays and characterised by an extraordinary index of refraction n_e . With regards to LCSLMs, dynamic phase change occurs as a result of varying refractive index. We consider linearly polarised light with electric and magnetic field components aligned perpendicular and parallel to the axis of the molecules [32] incident at an angle θ_i and give a brief overview of the relation of the refractive indices of the ordinary and extraordinary rays. Due to anisotropy (property of a material having different physical properties along different axes of the molecules), a dielectric diagonal tensor ϵ is used as a dielectric function in Maxwell's equations.

$$\epsilon = \begin{pmatrix} \epsilon_x & 0 & 0 \\ 0 & \epsilon_y & 0 \\ 0 & 0 & \epsilon_z \end{pmatrix}, \quad (1.3)$$

where ϵ_x , ϵ_y and ϵ_z are the Cartesian components. For uniaxial materials $\epsilon_o = \epsilon_x = \epsilon_y$ and $\epsilon_e = \epsilon_z \neq n_o$. An analysis of Maxwell's equations leads to the following relation which shows how $n_e(\theta_r)$, with $\theta_r = \theta_r(V)$ being the angle of refraction changes according to the applied voltage [21, 32, 31]

$$n_o^2 = \frac{n_o^2 n_e^2}{n_o^2 \sin^2(\theta_i) + n_e^2 \cos^2(\theta_i)}. \quad (1.4)$$

The phase difference between the ordinary and extraordinary rays over a distance equal to that of a liquid crystal d is given by [31]

$$\delta = \frac{2\pi d}{\lambda} (n_e - n_o). \quad (1.5)$$

The induced phase shift is proportional to the applied voltage

$$\delta_d \propto l \frac{2\pi V}{\lambda}, \quad (1.6)$$

where l , V and λ is the pixel length, applied voltage and wavelength of light respectively. Digital holography is implemented on an SLM by means of

computer generated holograms, through appropriate encoding schemes which maps each pixel of the SLM onto a coordinate of a matrix with dimensions equal to that of the SLM. A computer generated hologram (or digital hologram) is a digital display of the transmission function that acts on an input beam. It is displayed on the SLM as a grey scale image with 256 colours ranging from black (0) to white (255). The grey scale level is related to the phase change of the device which the range may be calibrated from 0 radians for grey scale level 0 to 2π radians for grey scale level 255. Due to the arrangement of the pixels, a two dimensional amplitude grating is formed. This results in the desired shaped light to be formed on-axis with the zeroth order of diffraction of which has no interaction with an applied hologram. The desired modulated light is formed in the first order of diffraction. In order to separate the diffraction orders, a diffraction grating (sinusoidal or blazed for example) is incorporated into the encoding scheme of the computer generated hologram.

Depending on the model, these devices generally have an $8\text{ }\mu\text{m}$ pixel size, fill factors (ratio of the area of the active pixels to the total area of the screen) of more than 90%, reflectivity of more than 65%, input frame rates (rate at which pixels change orientation for the display of different holograms) between 50 Hz and 180 Hz, and a first order diffraction efficiency of more than 80%, depending on the wavelength used and incident angle of illumination [33]. Another advantage is that these devices do not require any software. They are addressed by high definition media interface (HDMI) cables which provides versatility and dynamic control in optics experimentation.

Despite the versatility and robustness of these devices there are some disadvantages. They are sensitive to polarisation states of light and as such there is one less degree of freedom and thus may require additional optical equipment, such as waveplates to compensate for this shortage in experimentation where beams of different polarisation states are required. They have very slow frame rates, which limits the dynamic control in optics experimental set-ups, as well as being very expensive.

1.3.3 Digital micromirror devices (DMDs)

Micro-electro-mechanical-systems (MEMS), which may be referred to as micro-machines incorporate mechanical and electrical components for the engineering of small scale devices ranging from micrometres to millimetres. The Digital Micromirror Device (DMD) is one of the most successful MEMS devices and are fundamental components of all Digital Light Processing (DLP) technologies. Invented by Dr Larry Hornbeck, a Fellow at Texas Instruments (TI), the development of the DMD started with the objective of developing reflective spatial light modulators (SLMs) in 1977, which composed of a deformable mirror, a metallised polymer membrane and charged-coupled-device (CCD, a device for the conversion of an electric charge into a digital signal) manufactured using n-type metal oxide semiconductor (nMOS) transistors. Pixel-level analogue deformation of the mirror was achieved by means of an applied voltage and electrostatically controlling the deformation of the mirror [34, 35].

An improvement in the way modulation of light was achieved when overcoming the inability of the deformable mirrors to meet printing and display applications standards during 1986 [35]. A transition from analogue mirror deformation to the use of micromirrors to digitally modulate light was established [36]. Each mirror was mounted on torsion hinges, on which electrodes on a silicon chip are located. These mirrors were able to tilt about the torsion hinges and restricted to either one of two operational states, the “On” and “Off” state. Using these mirrors as binary switches to create pulses of light enabled the implementation of pulse width modulation (PWM) techniques to digitally modulate light [37]. This increased the performance, lowered the operational voltages and made it compatible with CMOS transistors.

The first digital micromirror device was successfully built in 1987, which composed of a two dimensional array of 512-by-512 micromirrors, and was combined with an illumination source and projection optics [34]. This technology was patented - U.S. Patent Number 5,061,049 “Spatial Light Modulator and Method”, and named the Digital Micromirror Device [38]. The first commercial application of a DMD was in a high-speed airline ticket printer in 1992 [39]. A larger DMD with two million micromirrors led to an application in high-definition television (HDTV) [40, 41, 36]. Thereafter interest in the use of DMDs was seen by the motion picture and entertainment industry. Developing large-screen, high-brightness projectors brought about non-degradable quality which were key components for digital cinema applications [42, 43]. Focusing more on digital video display applications and digital signal processing, the application of DMDs steered towards developing commercial projection systems for office rooms, which led to the first ultra portable projector in 1996 [43].

All modern DMDs are fabricated by means of surface micromachining (technique of fabrication of micro-mechanical structures by etching layers onto a substrate) upon a CMOS circuit. They are composed of an array of square mirrors of dimension of the order of a micrometre which tilt at fixed angles (either positive or negative relative to the device's screen) about an axis caused by an electrostatic force between the mirrors and associated underlying electrodes. This causes the mirrors to reflect incident light in two different directions, one which is of interest and the other which is disregarded, thus making the device a binary amplitude spatial light modulator. Due to its pixelated structure and functionality, they have very fast operational speeds, are insensitive to the polarisation state of light, and are significantly cheaper than commonly LCSLMs and as such provide an alternative to LCSLMs.

Applications of DMDs are present in a number of research, commercial and industrial areas. Texas Instruments offers a range of products which include a variety of additional components such as circuit boards and projection systems which are designed to work with DMDs for specific applications ranging from small scale portable pico-projectors, smart home displays, virtual and augmented reality systems, smartphones and tablet to industrial large scale display systems, automotive head-up display (HUD) and headlight systems and spectroscopic applications.

New emerging display and illumination applications sees the development of many patented products based upon the DMDs. An ultra-violet (UV) light emitting diode (LED) digital micromirror device illuminator has been invented [44]. This invention uses a high irradiance LED UV sources of illumination instead of conventional arc lamps together with a DMD, projection optics and incorporates "Chip-on-Boards" (COB), high thermal conductivity heat components and high efficiency imaging optics to provide high performance, more reliable and cost effective systems for the use in photocuring of materials for printing and lithographic applications.

The application of DMDs has also been present in the automotive industry. Some modern vehicles have head-up-displays (HUDs) as opposed to conventional speedometers, tachometers and navigation systems. They may also include many driver assist options such as parking assistance guidelines, lane departure warning systems (which displays the width of the road and detects stray from it) and vehicle tracking and detection [45]. Such information may be displayed on a sheet of glass separate or onto the driver's windscreen of the vehicle, contributing to safer driving. The key components in traditional HUD systems are a thin film transistor (TFT) liquid crystal (LCD) projection display and a lens system to display a virtual image in the line of sight of the driver. The implementation of a DMD replaces TFT LCD technologies and provides sharper and brighter images. Implementing DMDs in the headlights of vehicles is another automotive application. With the use of dynamic image sensor processing systems, a DMD may be controlled to modulate light depen-

dent on the signal obtained from the image sensors and change the outgoing illumination thus optimising the view ahead of the driver and the effects of glare on oncoming cars [46].

Digital photofinishing was the next application of DMDs to be patented, [47]. The invention stems from digital printing systems and the demand for photographic quality image printers for high speed and cost effective production of photographic quality images. With the implementation of DMDs to replace traditional photofinishing transport mechanisms, a modulated light source and a photosensitive medium, a digital alternative method to traditional photographic printing has been established with a high number of prints and higher resolution.

DMDs have been significant components in spectroscopic instrumentation. The first implementation of a DMD for use in a spectrometer was investigated by Eugene P. Wagner [48]. The absorption spectra of potassium dichromate (K_2CrO_4) and a potassium permanganate (KMnO_4) were recorded and background scatter was accounted for, and as such validated the possibility of a DMD-based spectrometer. The use of DMDs in spectrometers that use echelle gratings has been patented [49]. The concept involves the use of DMDs as match-filters to correlate with the spectrogram of a substance to be detected and to steer light towards a detector. A characterisation of a DMD for the use as spatial light modulator for applications in spectroscopy has been carried out in which multi-object spectrographs are designed for object selection and an optical and diffraction analysis was carried out [50]. The use of DMDs for applications in ground- and space-based multi-object spectrometers has been investigated in which the performance of DMDs were tested under associated space deployment conditions [51].

The use of DMDs for display applications has enabled the implementation of these devices in a range of imaging and illumination systems. A spectral imaging system based on a DMD has been developed for the improvement of scanning processes in conventional spectral systems by means of using the ability of DMDs to realise single and multiple static photomasks for compressive sensing measurement patterns [52]. An implementation of a DMD in a programmable array microscope (PAM) and using quantitative phase imaging have been investigated with different optical sectioning methods and the use of structured light for biological sample observation [53, 54]. By exploiting the DMDs' ability to rapidly display binary computer generated holograms, variable illumination patterns are incident onto biological samples and the resultant complex fields are reconstructed by interferometric methods. Aspect vision and colour research requires the need to control the colour spectrum for improvements in prediction and perception of colour vision models. The use of a DMD has been implemented for fast and precise shaping of the spectrum of stimuli [55]. The dynamic range of a digital microscope has been improved up to five times that of a digital camera with the application of a DMD by

means of an illumination controlled by varying the bit levels of the DMD [56]. More imaging and illumination applications may be found in [57, 58, 59].

Structured light research involving the use of DMDs has been investigated with the implementation of different methods. Initial attempts at experimentally generating Laguerre-Gaussian beams through the diffraction of forklike gratings computationally calculated from the interference of a plane wave and a simulated vortex phase term [60]. The results in this work implemented phase-only modulation with the beams observed in the far field and have only considered specific cases (a set of l , or modes with different azimuthal index) of Laguerre-Gaussian beams. Further research implemented amplitude and phase modulation on a DMD for the generation of l- and p-modes of Laguerre Gaussian beams with high purity [61], vortex beams carrying orbital angular momentum, angular modes and demonstrated the high speed capabilities of a DMD with mode switching in the kilohertz range [62]. Perfect optical vortex (POV) beams have been generated with implementation of amplitude and phase modulation on a DMD [63]. A summary of three of the techniques for implementing digital holography on a DMD, with experimental demonstrations of Laguerre-Gaussian beams, non-diffracting Bessel beams, Airy beams, flat-top beams and vector-vortex beams has been demonstrated [64]. The first method, the superpixel method, combines a collection of pixels into a “superpixel”, and the field in a target plane is given by the sum of the responses of all the individual pixels within a superpixel [65]. The second method involves the generation binary computer holograms proposed by Wai-Hon Lee [66]. The last method outlined is an iterative method for generating computer generated holograms, by means of the Gerchberg-Saxton algorithm. An error diffusion algorithm together with iterative methods for optimising holograms and the uniformity of the resulting shaped beams [67]. Utilising the high speed refresh rate of a DMD, an ultra-fast DMD-based binary pulse shaper has been developed [68].

DMDs have also been used in the development of more cost effective, versatile and robust sensory equipment. Implementing a DMD as a wavefront sensor has been investigated and demonstrated an alternative to traditional wavefront sensing devices, the most popular being the Shack-Hartmann wavefront sensor [69]. Developing technologies, particularly in the field of compressive sensing, replaces the conventional CCD and CMOS cameras with DMDs to use as single-pixel detectors [70]. Among many, these include the investigation of a polarimetric imaging sensor [71], adaptive compressed sensing based on a DMD has been implemented for the development of high resolution single-pixel camera [72], a photon-counting laser detection and ranging (LiDAR) system for three dimensional imaging [73, 74].

Chapter 2

DMD characterisation

In this chapter we examine the physical and optical characteristics of DMDs with attention paid towards a specific chipset, *DLP 3000* DMD. We develop a model for its diffraction properties which may also be applied to different chipsets with the adjustment of certain parameters.

2.1 Structure, operation and calibration

The number of micromirrors within a DMD chipset and hence the resolution, varies according to the model. For example the *DLP 3000* DMD has a resolution of 684×608 pixels where as the *DLP 6500* DMD has a resolution of 1920×1080 pixels. Fig. 2.1 shows the *DLP 3000* DMD showing a microscopic view of a section of the two dimensional array and a close up view of a single pixel.

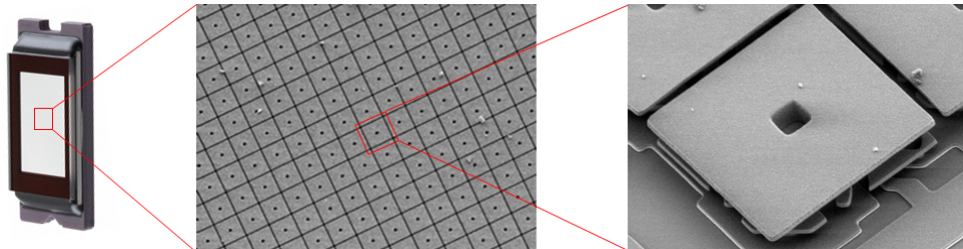


Figure 2.1: Example of a DMD chipset with a microscopic structure of the two dimensional array and a close-up view of a single pixel [3].

The general structure of a DMD may be characterised by two fundamental sections. The first consists of a set of three-layered metal components and the second contains a layer of CMOS circuits on a silicon substrate. Fig. 2.2 gives an exploded schematic of the structure of a single DMD pixel. The micromirror forms the first layer which is mounted onto the second layer composed of a harnessing unit for the torsion hinges. The micromirror rotates about the torsion hinges. The spring tips limit the angle of rotation of the micromirror. The third layer is composed of electrodes that address the second layer and a bias bus for allowing voltages to be addressed to the mirror.

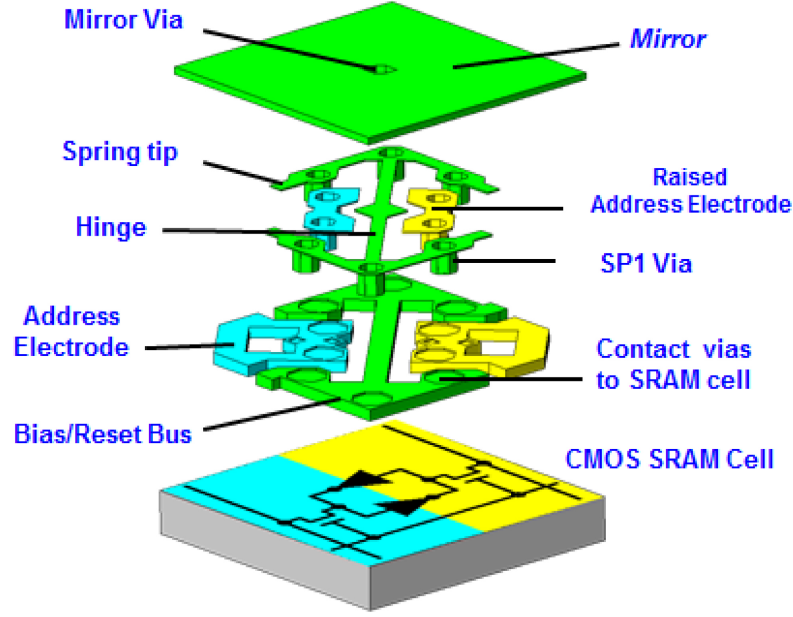


Figure 2.2: Exploded view of a single DMD pixel showing the underlying components [3].

The functionality of the DMD is based on the ability of each micromirror to tilt about the torsion hinges. This ability is due to an electrostatic force created by an electric field generated between each mirror and corresponding electrodes in the second layer of the structure of each pixel. With no external power supplied to the DMD, there is no electrostatic interaction between the mirrors and the electrodes, and hence no tilt of the mirrors. This makes the mirrors exist in the “flat-state”. All of the micromirrors in the array are restricted to tilt at either a positive or a negative angle relative to the “flat”-state of the mirrors. These angles correspond to two operational states of the mirrors. Positive angles refer to the “On” state and negative angle refer to the “Off” state. These states correspond to the direction at which incident illumination is reflected. Mirrors in the “On” state reflect light to a region that is of interest, which is then directed through to a projection lens system. The resulting image has a corresponding bright pixel. Mirrors in the “Off” state reflect light to a region that is disregarded, typically towards an absorber with the resulting projected image having a corresponding dark pixel [75]. Fig. 2.3 gives an illustration of the states (operational and non-operational) of the device.

The magnitude of the tilt angle of the mirrors, dimensions of each micromirror, resolution and layout is set by the manufacturer (Texas Instruments), and also varies with different chipset models. For example the mirrors in the *DLP3010* model has a $\pm 17^\circ$ tilt angle, $5.4 \mu\text{m}$ pitch, and an orthogonal layout where as the *DLPC3000* has a $\pm 12^\circ$ tilt angle, $7.6 \mu\text{m}$ pitch and a diamond layout. These devices are accompanied by the necessary electronics and auxiliary equipment. Consisting of advanced light control, display and projection applications and automotive solutions, there are two main sets of components

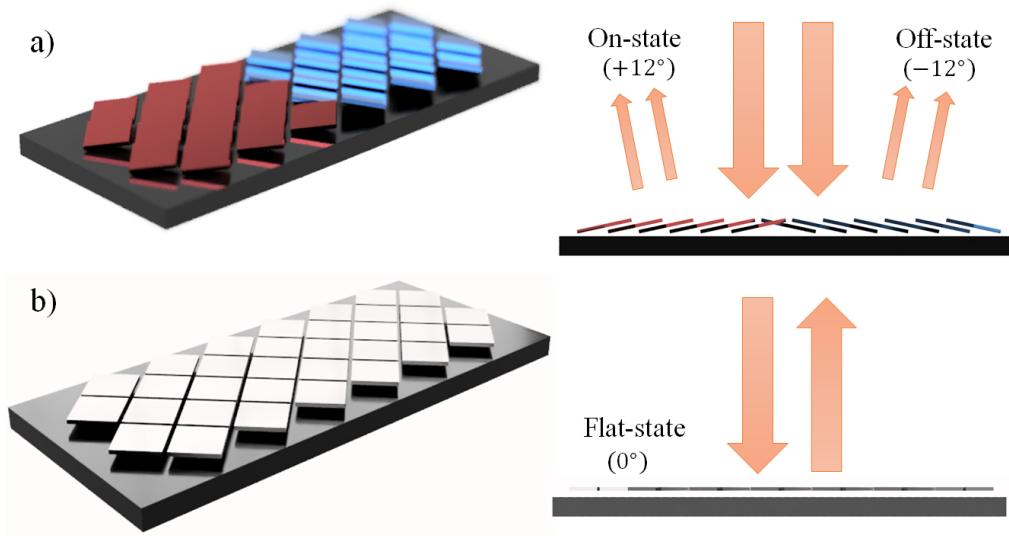


Figure 2.3: A scaled three dimensional diagram of the micromirror array in the (a) binary operational states and (b) non-operational flat-state.

underlying each DMD-based product: The DMD chipset and the set of associated controller and driver boards which provides power management and an interface between the DMD, and other electronics and many other functions of which are also application-dependent. For example, advanced light control includes spectroscopic applications and these products are accompanied by an optical engine which collects “chemical fingerprints” from samples in the form of near infra-red light reflected off a sample and along with a spectrometer engine comprising of a different set of optical components. The display and projection applications comprises of “Pico-products” which are small projection display systems, and hence are only accompanied by an optical engine.

These devices may also be grouped into “Evaluation Modules” and “Development Kits”. The Evaluation Modules are platforms that provide users with easy but limited access to the DMD chipset. The Development kits offers users more freedom in accessing the DMD chipset, allowing for development of many different possible user-desirable applications. In this research two DLP DMD products were considered: The *DLP LightCrafter Evaluation Module* and the *DLP 6500 Development kit*, with more emphasis on the former.

2.2 The DLP LightCrafter Evaluation Module

The DLP LightCrafter Evaluation Module used in this research holds the *DLP 3000* Digital Micromirror Device and accompanied by three subsystems: a light engine which consists of the DMD chipset and a set of red, blue and green light LEDs with projection optics; A driver board which holds the *DLPC3000* DMD controller, microcontroller and power management circuits; and a system board which contains the DaVinci Digital Media Processor, a field-programmable gate array (FPGA) and an integrated circuit and external input connectors.

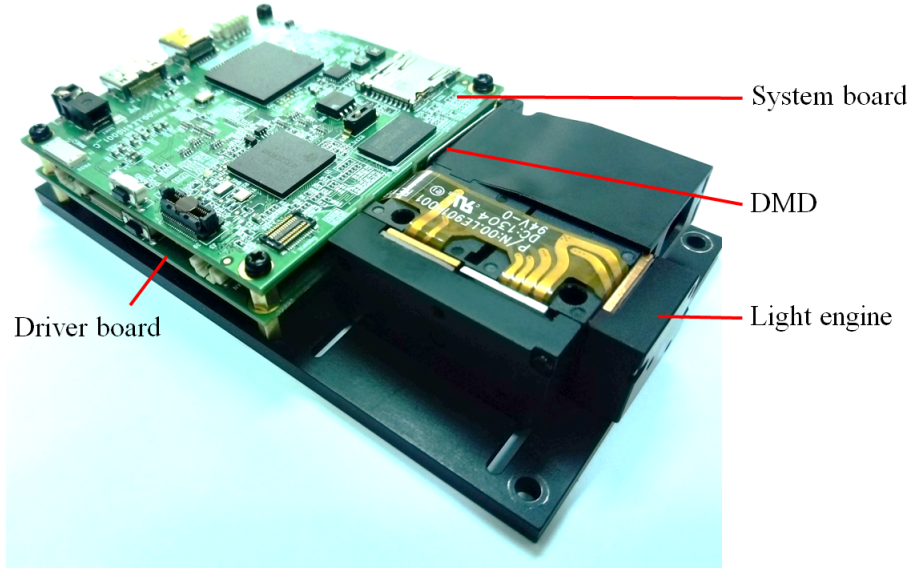


Figure 2.4: The DLP LightCrafter Evaluation Module.

As seen in Fig. 2.4, the system board sits on top of the driver board. Although the DMD chipset is part of the light engine, it is vertically sandwiched between the projection optics, the system and driver boards.

2.2.1 Removal of the light engine

For the purposes of this research, it is essential that the projection optics of the light engine are removed. It is worth noting that once this has been done, the warranty is then void. A detailed step-wise process is given on how to successfully complete this process.

1. Removal of the system board

The system board is attached to the driver board by means of four screws (circled in Fig. 2.5(a)). The system and the driver boards are connected by means of a board connector. The removal of the four screws enables the disconnection of the system board from the driver board. Fig. 2.5(b) shows the module with the driver board and the reverse side of the system board with the board connection enclosed in the red box, together with the projection light engine attached to the thermal base plate.

connected to the system board via a system interface connector as seen in Fig. 2.6. The PCB is attached to the projection system housing by 2 screws circled in Fig. 2.7(a). The removal of the PCB exposes a metal plate, which serves as an alignment aid during installation and may also serve as a heat sink and is also attached to the projection system housing by two screws circled in Fig. 2.7(b). Once the metal plate is removed, the DMD chipset is easily removed, and hence isolated from the light engine. The DMD chipset is comprised of DMD test pads, a system interface connector and a ceramic substrate, as seen in Fig. 2.8.

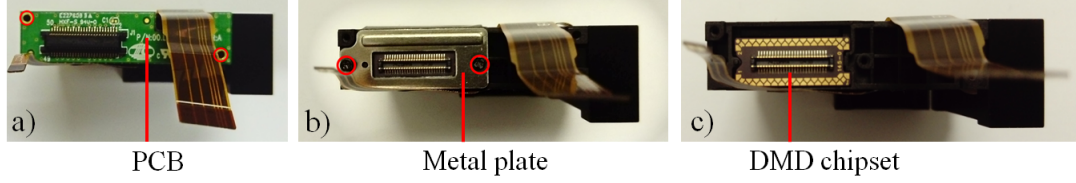


Figure 2.7: The DLP LightCrafter EVM light engine. (a) shows the two screws mounting the PCB to the housing. (b) shows the metal clamp and the two screws that mount into the housing. (c) shows the connector side of the DMD chipset.

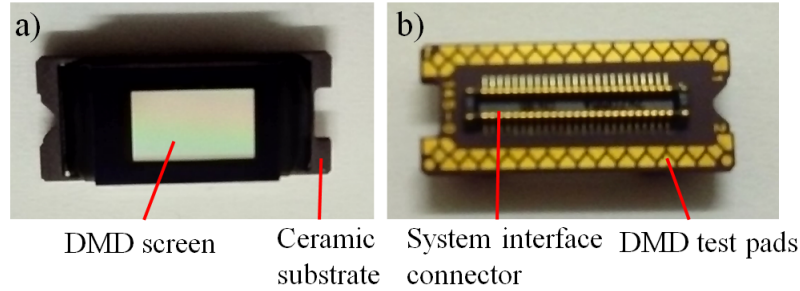


Figure 2.8: The isolated DMD chipset. (a) The front side and (b) the connector side.

4. Re-assembly

The first step in the assembly involved the attachment of the DMD chipset to the connector PCB together with the metal clamp. The metal clamp was mounted on its reverse side as it was stable in this position without the projection optics.

The next step involved a 180° rotation of the driver and system boards about the thermal base plate, such that reconnection of the DMD chipset led to its position being on the edge of the thermal base plate. This was to optimise exposure of the DMD chipset to incident light. Thereafter, the DMD chipset along with the metal clamp and the connector PCB is connected to the driver board, after which the system board may be re-connected to the driver board and screwed in with the corresponding screws removed from step 1.

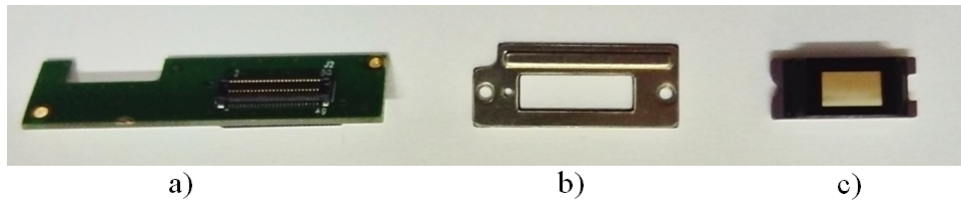


Figure 2.9: The components needed to attach the DMD chipset to the driver board. (a) The PCB, (b) The metal plate and (c) the DMD chipset.

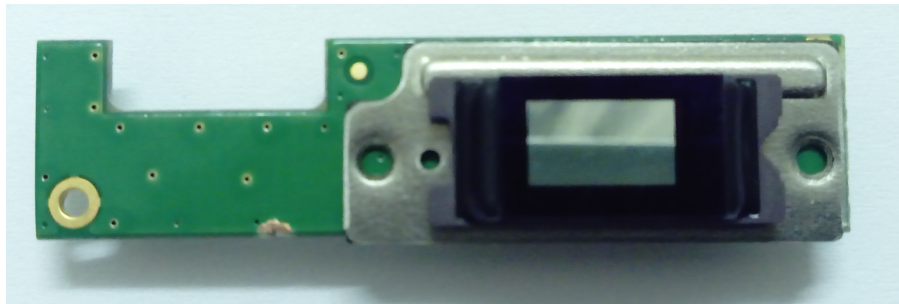


Figure 2.10: The DMD chipset mounted onto the metal plate and the PCB.



Figure 2.11: The DLP LightCrafter EVM with the projection optics system removed.

2.2.2 Specifications of the DMD chipset

For purposes of this research selected characteristics and specifications from official documentation of the DMD chipset are provided. Details regarding other components (driver and system boards and light engine) may be found in [76].

Physical specifications

The *DLP3000 0.3 WVGA Series 220 DMD* within the DLP LightCrafter Evaluation Module has physical dimensions of 6.5718 mm in length and 3.699 mm in breadth, with 608 active micromirror rows and 684 micromirror columns with a gap of approximately $0.8 \mu\text{m}$ between adjacent micromirrors. Surrounding the active array is a border of inactive pixels that cannot be addressed. The arrangement of the pixels on the DMD is such that, in view of the DMD, the top left is the position of row and column zero and the bottom right is the position of row 683 and column 607, respectively. The pixels are square with a side length of approximately $7.6 \mu\text{m}$. Each mirror has a diagonal pitch of $7.637 \mu\text{m}$, a horizontal and a vertical pitch of $10.8 \mu\text{m}$. Each pixel is orientated in a diamond configuration resulting in an offset of half a pixel between each odd row from each even row of pixels in the array. The mirrors tilt about their vertical pitch with a tilt angle of $\pm 12^\circ$, with a variation of $\pm 1^\circ$. Fig. 2.12 gives an illustration of the physical characteristics of the micromirror array.

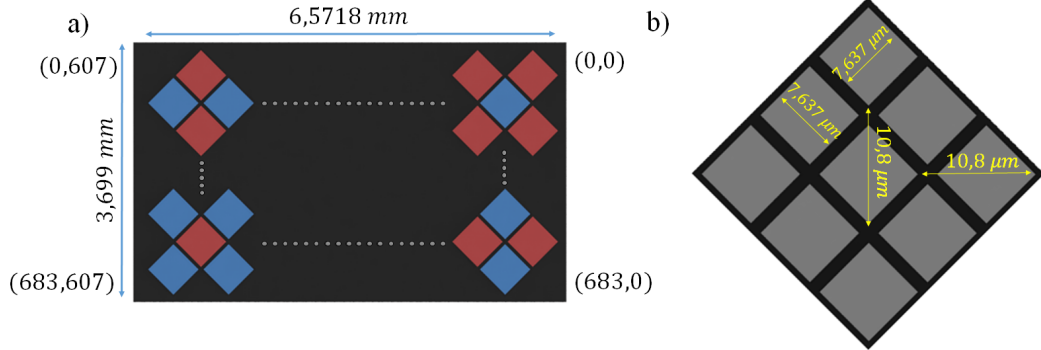


Figure 2.12: (a) Schematic showing the dimensions, row and column numbers, pitch and diamond arrangement of the micromirrors of the active micromirror array. (b) A selected region of pixels showing the mirror vertical and horizontal pitch and side length.

Optical Characteristics

DMD chipsets contain different window materials and coating layers to account for type of incident light used. The *DLP3000 0.3 WVGA Series 220 DMD* has a Corning Eagle XG window designed for optimal transmission in the visible (400 nm - 700 nm) region of light. Table 2.1 shows extracted information from official documentation from Texas instruments regarding the optical characteristics of the DMD chipset.

Table 2.1: Optical characteristics of the DMD.

Parameter	Value (%)
Window Transmission	97
Mirror Reflectivity	88
Array diffraction efficiency	86
Array fill factor	92
Micromirror array optical efficiency	68*
Metal specular reflectivity	89.4
Window refractive index	1.5119 **
Window transmittance ***	97 %

* All mirrors in the “On” state

** At wavelength 546.1 nm

*** single pass

2.2.3 DMD surface characterisation

An interferometric analysis was performed on the DMD chipset to obtain a more detailed structure of the surface of the DMD in the “Flat” and the “On” state. A laser Zygo interferometer was used for this analysis.

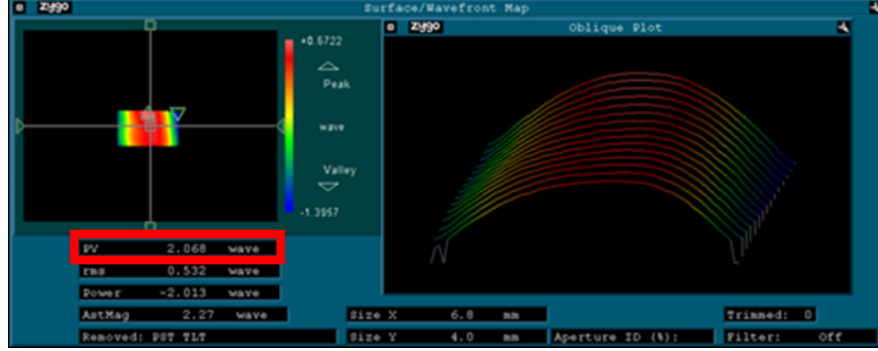


Figure 2.13: Interferogram of the DMD in the Flat state.

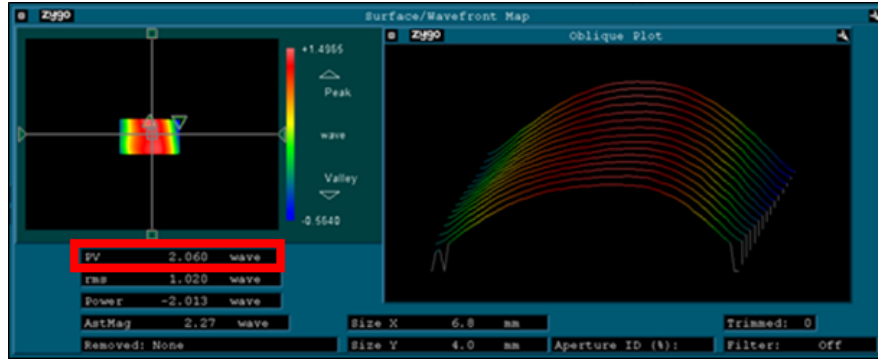


Figure 2.14: Interferogram of the DMD in the On state.

Fig. 2.13 and Fig. 2.14 are interferograms of the micromirror array in the “Flat” and “On” state respectively, which contain a heat map and an oblique plot of the surface of the micromirror array in the respective states. From the interferograms, it is seen that the surface of the micromirror array is curved and cylindrical. In order to quantify the surface flatness of the DMD, we look at the “PV” (peak-to-valley) value, which is the value from the highest to the lowest point of the micromirror array, given in wavelengths. Using this value, we can calculate the Sagittal depth (SAG). The SAG of the micromirror array is related to the PV value and radius of curvature of the surface by

$$\frac{PV}{2} \equiv SAG = R - \sqrt{R^2 - \left(\frac{D}{2}\right)^2}, \quad (2.1)$$

where R and D are the radius of curvature and the width of the micromirror array, respectively. From the interferograms and the dimensions of the DMD chipset, we find the SAG to be twice the PV value, that is, the SAG

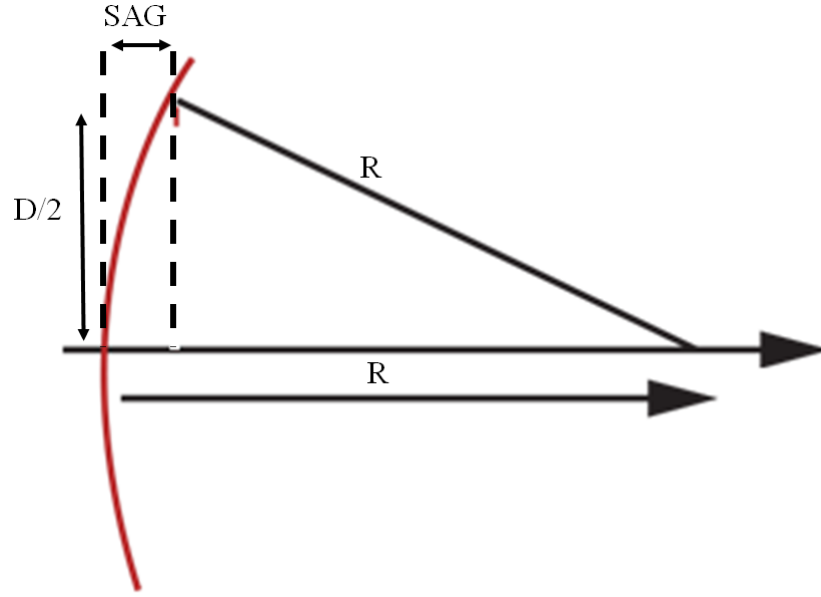


Figure 2.15: Schematic showing the geometry of the SAG calculation.

for the “flat” and “On” states are 4.136 and 4.120 wavelengths respectively. Numerically solving for the radius of curvature in Eq. (2.1), we find that the surface of the DMD in the “Flat” and “On” state has a radius of curvature of 2.07 m and 2.1 m respectively.

2.2.4 Experimental diffraction analysis

The two dimensional arrangement of the micromirrors makes the device act as a two dimensional reflective diffraction grating. We examine the resulting diffraction patterns of the DMD chipset and report on three of the optical characteristics of the device: the optical efficiency, the specular reflectivity and the first-order holographic diffraction efficiency under different alignment configurations. A similar experimental set-up was used for the testing of both characteristics.

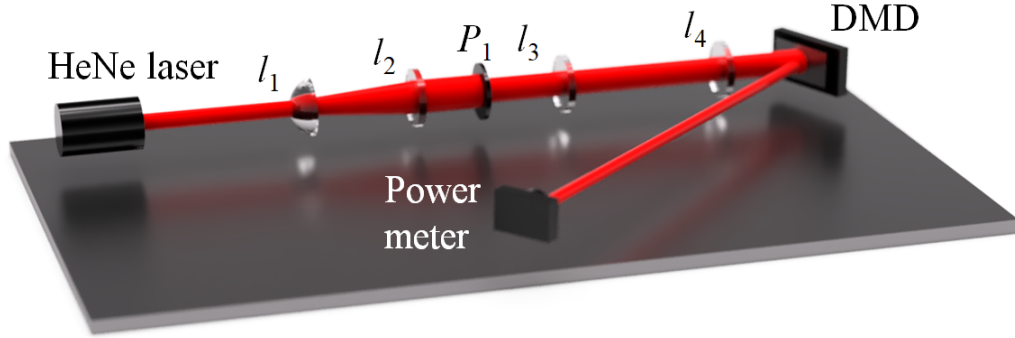


Figure 2.16: General configuration of the experimental setup used for the measurements of the optical characteristics of the DMD chipset.

Fig. 2.16 shows the general arrangement of the experimental set-up used. The source was expanded and collimated by lenses l_1 and l_2 , of focal length 25 mm and 200 mm, respectively. The plane from pinhole P_1 was imaged onto the DMD by a 4-f system created by lenses l_3 and l_4 both of focal length 200 mm. The beam reflected off the DMD was then imaged onto a photodiode power sensor (Thorlabs S120C - Standard Photodiode Power Sensor) together with an aperture to block out higher orders of diffraction and ambient light for the optimisation of the signal-to-noise ratio.

Measurement of micromirror array optical efficiency

The micromirror array optical efficiency is defined as the ratio of the incident light onto the DMD to the light sent to the zero-order of diffraction when all the mirrors are set to the “On” state. We consider two cases of alignment of the device. The first involves the screen of the DMD chipset aligned perpendicular to the incident beam, and the second case uses the manufacturer’s recommendation for alignment. These cases of alignment will be referred to as “perpendicular alignment” and “manufacturer’s alignment” respectively. The manufacturer’s recommendation [77] involves setting all the mirrors in the Off-state and then rotating the device such that the specular reflection is back-reflected towards the incident beam. Thereafter the mirrors are switched to the On-state for which measurements can be taken.

Fig. 2.17 shows the resulting diffraction patterns with corresponding alignments of the device. Incident beams of power of $857 \mu W$ and $321 \mu W$ was used for the perpendicular and manufacturer's alignment, respectively. Different beam sizes were used to make the diffraction patterns more visually distinguishable. The diffraction pattern obtained with the device aligned according to the manufacturers recommendation is symmetric about the zero-order, whereas the diffraction pattern obtained from the device aligned in the perpendicular configuration is not. One has to look more closely to locate the zero-order when the device is aligned perpendicular to the incident beam. Upon visual inspection, the zero-order of both alignment configurations was isolated, and the power in this order was measured.

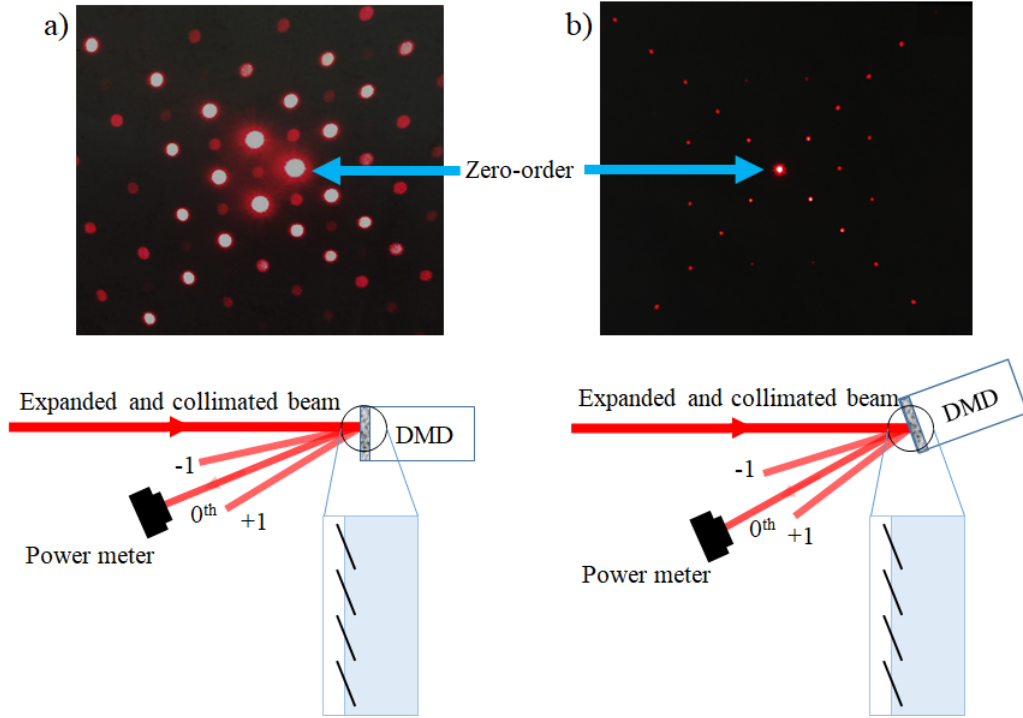


Figure 2.17: Diffraction patterns observed with all the micromirrors in the on-state according to the (a) perpendicular alignment and (b) manufacturers alignment specifications given below, respectively.

Table 2.2: Micro-mirror array Optical efficiency measurements

Alignment configuration	Incident beam power (μW)	Zero-order power (μW)	Efficiency
Perpendicular	857 ± 1	180 ± 1	21 %
Manufacturer	321 ± 1	158 ± 1	49 %

Observing the results from table 2.2, it is seen that the micromirror array optical efficiency was 21% and 49% for the perpendicular and manufactures configurations and a difference of 30% in the efficiency between the two configurations.

Measurement of specular reflectivity

The specular reflectivity of the DMD chipset is defined as the amount of light sent to the brightest order when all the micromirrors are in the “Flat” state. Measurement of the specular reflectivity required a change in the alignment device. With the device aligned according to the manufacturer’s recommendation, the device was then rotated until the zero-order of the diffraction pattern was back-reflected towards the incident beam. This arrangement makes the device with all the micromirrors perpendicular to the incident beam. The device was then switched off, after which all the micromirrors returned to the flat-state. The diffraction pattern was then observed and the specular reflection was isolated and measured. Fig. 2.18 shows the experimental set-up along with the observed diffraction pattern.

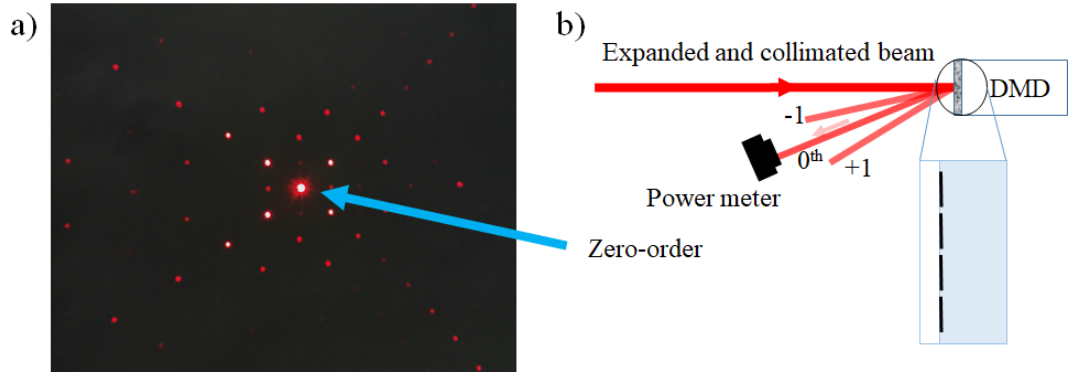


Figure 2.18: (a) The observed diffraction pattern when all the mirrors are in the “Flat” state. (b) Simplified experimental set-up used for the measurement of the specular reflectivity of the micro-mirror array.

The diffraction observed in Fig. 2.18 is similar to that obtained when measuring the micromirror array optical efficiency using the manufacturer’s alignment configuration. There exists a bright zero-order specular reflection and two main diagonals long which the intensities decrease with increasing diffraction order. There are also higher off-diagonal diffraction orders of which have intensities significantly lower than the diffraction orders along the two main diagonals. The following results were obtained with an incident beam power of $857 \mu\text{W}$ and diameter of 2.43 mm .

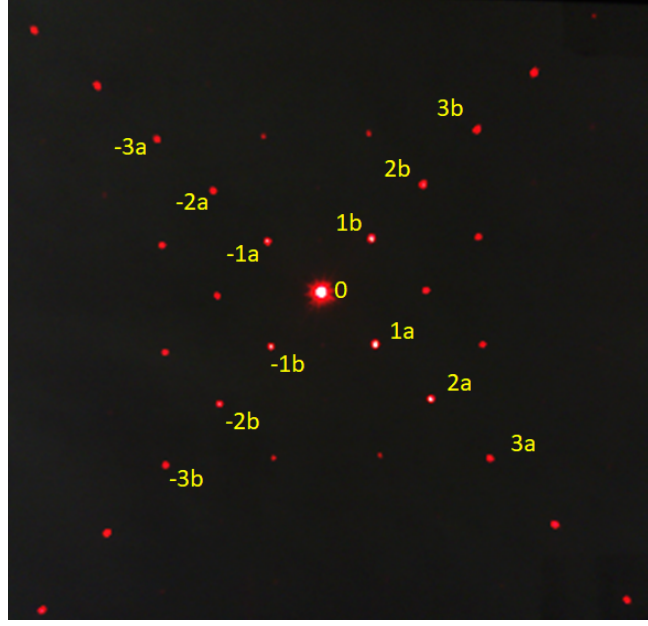


Figure 2.19: Diffraction pattern of all the mirrors in the flat-state with the higher diffraction orders in the two main diagonals labelled.

Table 2.3: Measurements of reflectivity in other orders.

Order	Reflected beam Power (μW)	Efficiency
0	503 ± 1	57%
1a	5 ± 1	0.6%
1b	4 ± 1	0.5%
1c	3 ± 1	0.3%
-1a	7 ± 1	0.8%
-1b	4 ± 1	0.5%
-1c	3 ± 1	0.4%
2a	5 ± 1	0.6%
2b	4 ± 1	0.4%
2c	3 ± 1	0.3%
-2a	7 ± 1	0.8%
-2b	5 ± 1	0.5%
-2c	3 ± 1	0.4%

It is seen that more than 50% of the incident light is sent in the specular direction. The light sent into the higher diffraction orders is insignificant compared to that of the zeroth order. As such higher orders of diffraction will not be of interest.

First-order holographic diffraction efficiency

The first-order holographic diffraction efficiency is defined as the amount of light in the first-order when an additional diffraction grating is computationally generated and displayed on the device as a hologram. Fig. 2.20 shows a schematic of the experimental used with the corresponding diffraction pattern. A HeNe laser source is expanded and collimated by lenses l_1 and l_2 of focal length 20 mm and 200 mm , respectively. The beam from pinhole P_1 is imaged onto the DMD by a 4-f imaging system created by lenses l_3 and l_4 of focal length 100 mm . The first order is isolated by pinhole P_2 and imaged onto the power meter by a 4-f imaging system created by lenses l_5 and l_6 of focal length 100 mm , respectively.

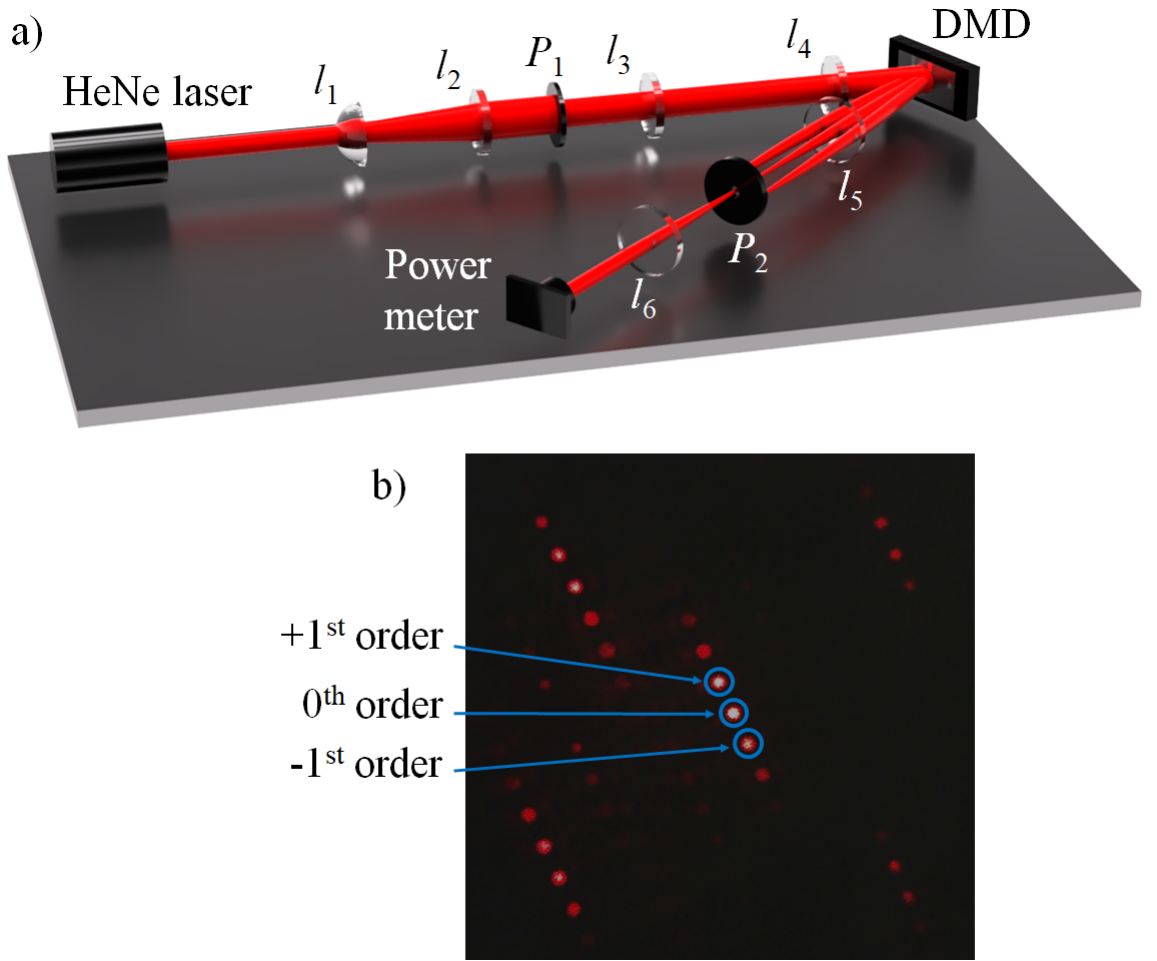


Figure 2.20: Experimental setup used for measuring the first-order holographic efficiency.

We isolate and measure the efficiency of the +1st order to be 4.5%.

2.2.5 Theoretical diffraction analysis

Considering the tilt of the micromirrors, it is intuitive to regard the DMD chipset as a reflective blazed diffraction grating. It is also reported in [78], that a diffraction analysis was performed using a blazed grating configuration. A blazed diffraction grating maximises incident light into a single diffraction order. From the diffraction pattern in figures Fig. 2.18 and Fig. 2.19 it is clear that this is not the case. By looking at two characteristics, the blaze angle and the blaze wavelength, of a one dimensional case of the DMD chipset as a blaze grating configuration of the DMD is not sufficient to describe its diffraction properties.

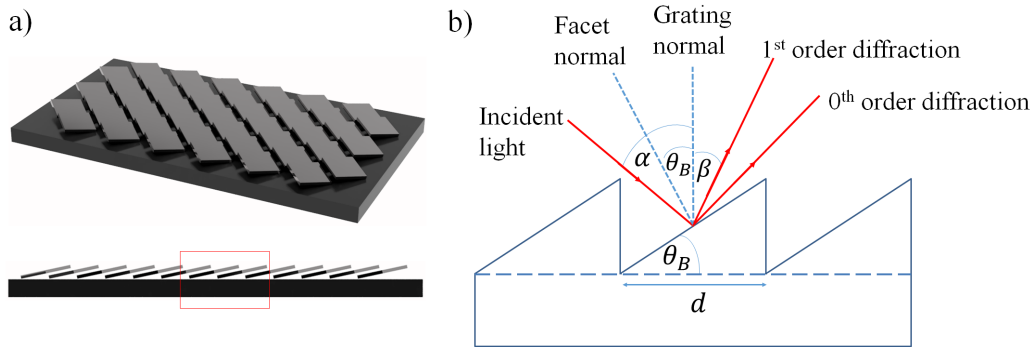


Figure 2.21: (a) The micro-mirror array with all the mirrors in the on-state with a side-view given below. (b) A schematic showing a reflective blaze grating configuration related to the side view of (a).

The tilt angle of the micromirrors was 12° . Taking into account the blazed diffraction grating, the tilt angle of the mirrors corresponds to the blaze angle. Given the blaze angle and wavelength, the feasibility of the DMD chipset behaving as a blazed grating was investigated by determining the angle of incidence. The blaze wavelength λ_B is related to the blaze angle θ_B , diffraction order m , incident angle α and grating period N by the following equation:

$$\lambda_B = \frac{2}{Nm} \sin \theta_B \cos (\alpha - \theta_B), \quad (2.2)$$

where θ_B is 12° for the DMD under investigation. We examine the blaze wavelength as a function of the incident angle. We scan through the feasible domain of incident angles, from -90° to the blaze angle of the DMD θ_B , and extrapolate the incident angle in this domain which would enable the DMD to behave as a blazed grating with the use of a laser in the visible wavelength regime. A plot of the blaze wavelength λ_B against the incident angle α is given in Fig. 2.21. It is seen that for a Helium-Neon source of wavelength 633 nm, the blaze angle extrapolated is more than -75° with an angular separation of less than 9 milli-degrees. An implementation of using the blaze grating configuration is not a feasible solution in optical experimentation, and as such a different model for a diffraction analysis of the DMD is needed.

For a more detailed diffraction analysis, we consider the reflective nature of the micro-mirror array and develop a reflective transmission function for

Blaze wavelength as a function of Incident angle

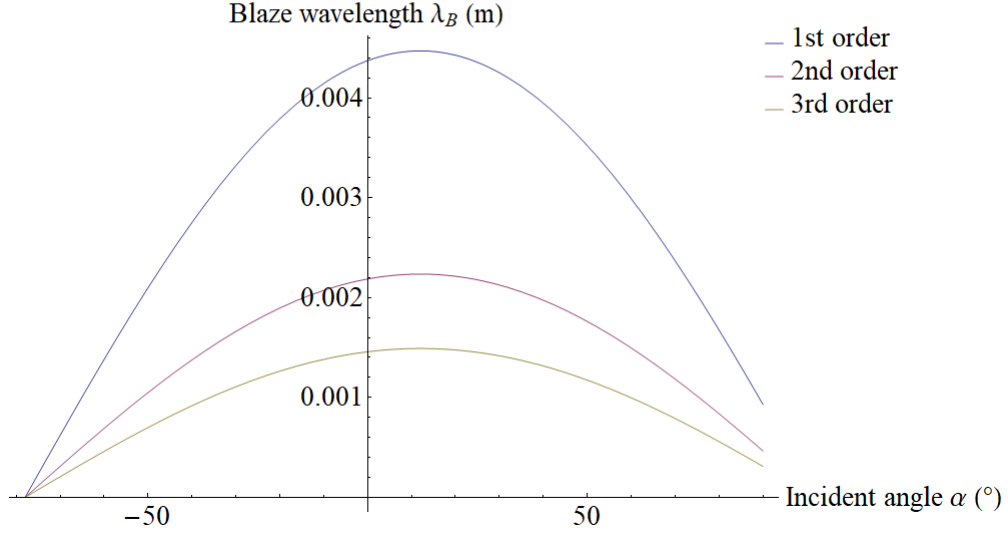


Figure 2.22: Graph of the Blaze wavelength against the incident angle of illumination onto the micro-mirror array.

the micro-mirror array in order to evaluate the performance of the device. We investigate the behaviour of the device with the mirrors in the “Flat” state, the “On” state and not from the “Off” state. From the diffraction patterns of the device in the “On” state with the device aligned according to the manufacturer’s alignment configuration and the flat-state in Fig. 2.18 and Fig. 2.19, it is seen that there exists a similarity in the diffraction patterns, and hence a similarity in the behaviour of the micro-mirrors in these respective states. To determine the type of diffraction analysis that will be used, we look at the Fresnel number

$$F = \frac{A}{\lambda z}, \quad (2.3)$$

where A is the area of the aperture (which in our analysis corresponds to the area of a single micro-mirror), λ is the wavelength of the light used and z is the distance from the aperture to the plane of observation. For Fraunhofer diffraction analysis, it is required that $F < 0.01$. In this analysis, a HeNe laser (wavelength of 632.8 nm) was used. The diffraction patterns were observed at a distance of 15 cm and the side length of a single micro-mirror is 7.6 μm . With these parameters, the Fresnel number is calculated to be 0.0006 (rounded to 4 decimal places).

It is clear that the the Fresnel number is much less than 0.001, and hence a Fraunhofer diffraction analysis may be performed. From Eq. (1.2), a transmission function of an aperture distribution may be defined as the ratio of the amplitudes of the transmitted output field U_{out} to the incident field U_{in} , from which the desired output field may be determined, given the transmission

function and the input field.

$$T(x, y) = \frac{U_{out}(x, y)}{U_{in}(x, y)} \Rightarrow U_{out}(x, y) = T(x, y) U_{in}(x, y). \quad (2.4)$$

In rectangular coordinates, the output field under Fraunhofer diffraction is proportional to the Fourier transform of the input field and the transmission function [19]

$$U_{out}(x, y) = \frac{\exp(ikz)\exp(i\frac{k}{2z})}{i\lambda z} \iint_{-\infty}^{\infty} U_{in}(X, Y) \exp\left(-i\frac{2\pi}{\lambda z}(xX + yY)\right) dXdY, \quad (2.5)$$

$$U_{out}(x, y) = \frac{\exp(ikz)\exp(i\frac{k}{2z})}{i\lambda z} \mathcal{F}\{U_{in}(X, Y) T(X, Y)\}, \quad (2.6)$$

where X and Y are the spatial frequencies. For a monochromatic wave with planar wavefronts and unit amplitude, the output field is proportional to the Fourier transform of the the transmission function of the aperture distribution

$$U_{out}(x, y) = \mathcal{F}\{T(X, Y)\}. \quad (2.7)$$

The intensity is defined as the squared magnitude of the complex phasor representation of the field, and it is also proportional to the power density. To calculate the diffraction pattern, we look at the intensity

$$I(x, y) = |U_{out}(x, y)|^2 = |\mathcal{F}\{T(X, Y)\}|^2. \quad (2.8)$$

In the Fraunhofer analysis, we consider incident illumination of plane waves of unit amplitude. The micromirrors are arranged in a non-orthogonal diamond arrangement with a spacing of $0.8 \mu m$ between adjacent mirrors. For simplicity, we consider a square region of interest consisting of N micromirror rows and columns that aligns with the diamond configuration and define a new coordinate system for this region as seen in Fig. 2.23. Let the width of each mirror be a and the spacing between adjacent mirrors be w .

We first consider reflective transmission function of a single micromirror in the “Flat” state which may may be described by a two dimensional rectangular function

$$T_i(x', y') = \text{rect}\left(\frac{x'}{a}, \frac{y'}{a}\right), \quad (2.9)$$

where

$$\text{rect}\left(\frac{x'}{a}\right) = \begin{cases} 0, & \frac{x'}{a} < \frac{1}{2} \\ 1, & \frac{x'}{a} > \frac{1}{2} \end{cases}. \quad (2.10)$$

Given the reflective transmission of a single micromirror, we may regard the active micromirror array (with all the mirrors in the On state) as square pulse trains in the x' and y' directions. A pulse train may be created by the convolution of a rectangular function with a Comb function [19]. In the case

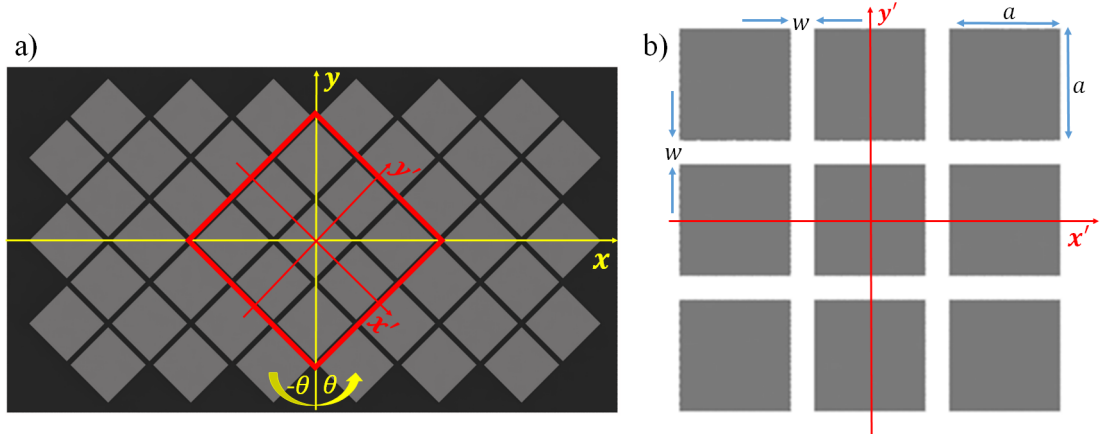


Figure 2.23: (a) A scaled top-view of the two dimensional array of micromirrors showing the two coordinate systems (x, y) and (x', y') and a square selected region of interest boxed in red. (b) An enlarged view of the region of interest.

of the array of the micromirror array, the transmission function may be given by:

$$T(x', y') = \text{rect}\left(\frac{x'}{a}, \frac{y'}{a}\right) \otimes \text{comb}\left(\frac{x'}{w}, \frac{y'}{w}\right), \quad (2.11)$$

where

$$\text{comb}\left(\frac{x'}{w}\right) = \sum_{m=-\infty}^{m=\infty} \delta\left(x' - \frac{m}{w}\right) = \begin{cases} \infty, & x' = \frac{m}{w} \\ 0, & \text{otherwise} \end{cases}. \quad (2.12)$$

As the micromirror has finite dimensions and we consider a square region of interest, the above series needs to be bounded such that the transmission function will be within the region of interest. In order to achieve this, the above series is multiplied by another rectangular function in the x' and y' direction. As such, the transmission function becomes

$$T(x', y') = \left[\text{rect}\left(\frac{x'}{a}, \frac{y'}{a}\right) \otimes \text{comb}\left(\frac{x'}{w}, \frac{y'}{w}\right) \right] \times \text{rect}\left(\frac{x'}{Na}, \frac{y'}{Na}\right), \quad (2.13)$$

which may be expressed in a separable form

$$T(x', y') = T(x')T(y'), \quad (2.14)$$

where

$$T(x') = \left[\text{rect}\left(\frac{x'}{a}\right) \otimes \text{comb}\left(\frac{x'}{w}\right) \right] \text{rect}\left(\frac{x'}{Na}\right), \quad (2.15)$$

$$T(y') = \left[\text{rect}\left(\frac{y'}{a}\right) \otimes \text{comb}\left(\frac{y'}{w}\right) \right] \text{rect}\left(\frac{y'}{Na}\right). \quad (2.16)$$

Using the separable form of the transmission function in Eq. (2.15) and Eq. (2.16) and properties of the Fourier transform, we calculate the diffraction pattern and hence the intensity. The Fourier transform of the x' and y' components are

$$\mathcal{F}\{T(x')\} = \left(a \operatorname{sinc}(af_{x'}) \sum_{m=-\infty}^{\infty} \delta\left(x' - \frac{m}{w}\right) \right) \otimes (Na) \operatorname{sinc}(Naf_{x'}), \quad (2.17)$$

$$\mathcal{F}\{T(y')\} = \left(a \operatorname{sinc}(af_{y'}) \sum_{m=-\infty}^{\infty} \delta\left(y' - \frac{m}{w}\right) \right) \otimes (Na) \operatorname{sinc}(Naf_{y'}), \quad (2.18)$$

respectively. The transmission function derived and its Fourier transform are defined in our region of interest of the micromirror array of finite dimensions and hence may be regarded as a bandwidth-limited function. The mirrors may be regarded as sampled data, with the distance between adjacent mirrors sufficiently large, such that we may apply sampling theory [19]. Using the *Whitter Shannon Sampling theory*, which implies that the reconstruction of a bandwidth limited function can be achieved with the use of relevantly spaced rectangular arrays of it's sampled values, a further simplification of the Fourier transform of the x' and y' components are given by

$$\mathcal{F}\{T(x')\} = \sum_{m=-\infty}^{\infty} a \operatorname{sinc}\left(a \frac{m}{w}\right) Na \operatorname{sinc}\left[Na\left(f_{x'} - \frac{a}{w}\right)\right], \quad (2.19)$$

$$\mathcal{F}\{T(y')\} = \sum_{m=-\infty}^{\infty} a \operatorname{sinc}\left(a \frac{m}{w}\right) Na \operatorname{sinc}\left[Na\left(f_{y'} - \frac{a}{w}\right)\right]. \quad (2.20)$$

The Fraunhofer diffraction pattern intensity with the micromirrors in the “flat” state, within our region of interest is given by:

$$I(x', y') = \left(\frac{a^2 N^2 w^2}{\lambda z} \right) \left(\sum_{m=-\infty}^{\infty} \operatorname{sinc}\left(a \frac{m}{w}\right) \operatorname{sinc}\left[Na\left(\frac{x'}{\lambda z} - \frac{a}{w}\right)\right] \right)^2 \times \left(\sum_{m=-\infty}^{\infty} \operatorname{sinc}\left(a \frac{m}{w}\right) \operatorname{sinc}\left[Na\left(\frac{y'}{\lambda z} - \frac{a}{w}\right)\right] \right)^2, \quad (2.21)$$

where

$$x' = \frac{x - y}{\sqrt{2}}, \quad (2.22)$$

$$y' = \frac{x + y}{\sqrt{2}}. \quad (2.23)$$

With the correct parameters, we simulate the diffraction pattern within our region of interest from Eq. (2.21). Fig. 2.24. shows a simulation of the theoretical diffraction pattern with the experimental diffraction pattern.

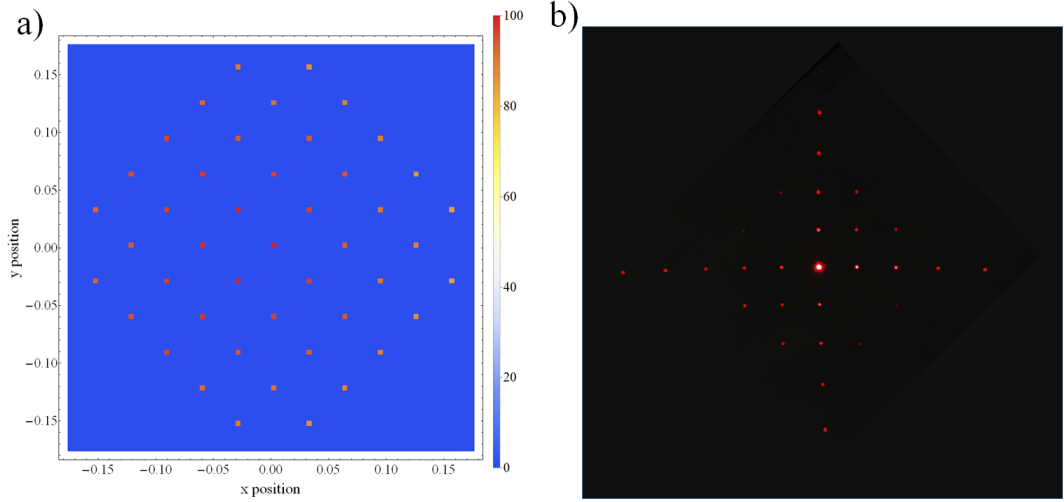


Figure 2.24: DMD diffraction patterns. (a) Simulated as per Eq. (2.21). (b) Experimental diffraction pattern.

The diffraction efficiency of gratings may be defined as the ratio of the power of light in a particular diffraction order to that of the power of incident light [19]. This may analytically calculated by the Fourier expansion of the transmission function and the fraction of power present in different diffraction orders are related to the coefficients in the expansion

$$Eff_n \propto \frac{A_n^2}{\sum_m A_m^2}, \quad (2.24)$$

where A_n are the coefficients in the Fourier expansion corresponding to the n_{th} order. With regards to the DMD, this is given by [79].

$$Eff_n = \frac{\text{sinc}^4\left(a\frac{n}{w}\right)}{\left[\sum_m \text{sinc}\left(a\frac{m}{w}\right)\right]^4}. \quad (2.25)$$

Taking into account the width of the mirrors a to be $7.6 \mu m$ and the spacing between them w to be given as $0.8 \mu m$, we obtain a 61% efficiency, which is in agreement with manufacturer specifications.

Next we look the behaviour of the device with mirrors in the “On” state. The tilt angle of the DMD θ_B , and the angle of incidence α are taken into account. Performing a similar analysis to the case of the mirrors in the “flat” state, we have that the Fraunhofer diffraction pattern intensity becomes

$$I(x', y') = A \left(\sum_{m=-\infty}^{\infty} \text{sinc}\left(a\frac{m+A}{w}\right) \text{sinc}\left[Na\left(\frac{x'}{\lambda z} - \frac{a}{w}\right)\right] \right)^2 \times \left(\sum_{m=-\infty}^{\infty} \text{sinc}\left(a\frac{m+A}{w}\right) \text{sinc}\left[Na\left(\frac{y'}{\lambda z} - \frac{a}{w}\right)\right] \right)^2, \quad (2.26)$$

where $A = \frac{a^2 N^2 w^2}{\lambda z}$ and $B = \sin(2\theta_B) + \sin(\alpha)$. The efficiency is given by [79]

$$Eff'_n = \frac{\text{sinc}^4\left(a \frac{n+A}{w}\right)}{\left[\sum_m \text{sinc}\left(a \frac{m+A}{w}\right)\right]^4}. \quad (2.27)$$

Next we look at the behaviour of the device with an additional diffraction grating computationally generated and displayed on the device as a hologram. The applied grating may be regarded as a binary amplitude grating of which the first-order efficiency $\nu_{\pm 1}$ is given by [19]

$$\eta_{\pm 1} = \frac{1}{4} \text{sinc}^2\left(\frac{n}{2}\right). \quad (2.28)$$

Taking into account the micromirror array structure of the device and the effect of an encoded diffraction grating, the first-order efficiency may be expressed as [79]

$$Eff''_n = Eff'_n \times \eta_{\pm 1}, \quad (2.29)$$

where Eff'_n is given in Eq. (2.27). We calculate the diffraction efficiency of the device in two different alignment configurations with all the mirrors in the “On” state, with the mirrors in the “flat” state and with an additional diffraction grating applied as a hologram. In all calculations we set the incident beam normal to the device. The first alignment configuration sets the device aligned at 0° with the mirrors in the “flat” state, and hence $\theta_B = 0$, perpendicular to the incident beam. The second alignment configuration sets the device aligned at 12° with the mirrors in the “On” state [79]. Table 2.4 shows the results of the calculated zeroth order efficiencies and Fig. 2.25, Fig. 2.26 and Fig. 2.27 show schematics of the different alignment configurations. The first two rows of table 2.4 are in agreement with the measurements of the micromirror array optical efficiency with a deviation of 4.7% and 1.4% from the calculated values for the “perpendicular” and “manufacturer” alignment configurations, respectively. The last row is in agreement with the specular reflectivity measurements, with a deviation of 4.9% from the calculated values. We calculate a diffraction efficiency of the device with a diffraction grating encoded of 6% which is significantly close to experimentally measured 4.5% [79].

Table 2.4: DMD diffraction efficiency.

Optical characteristic	Mirror state	Device alignment ($^\circ$)	Calculated efficiency (%)	Measured efficiency (%)
Micromirror array optical efficiency	On	0	25.7	21
	On	12	50.4	49
Specular reflectivity	Flat	0	61.9	57
1st order holographic	On	12	6	4.5

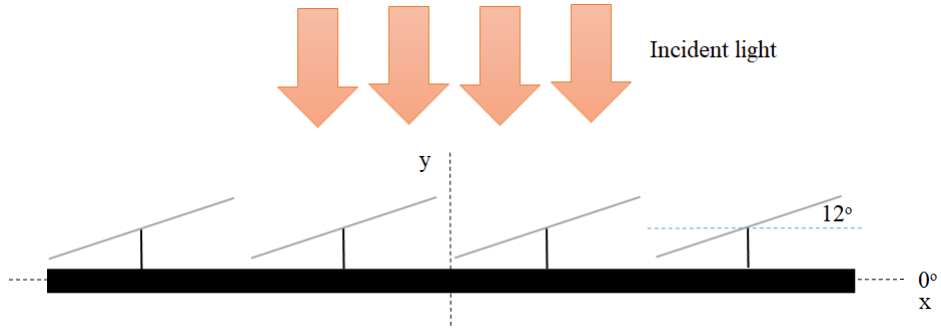


Figure 2.25: Schematic showing the alignment configuration with the device aligned at 0° and the mirrors in the “On” state.

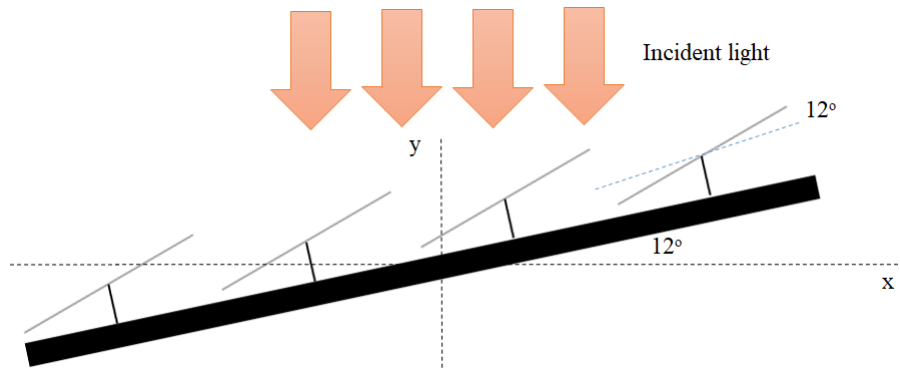


Figure 2.26: Schematic showing the alignment configuration with the device aligned at 12° and the mirrors in the “On” state.

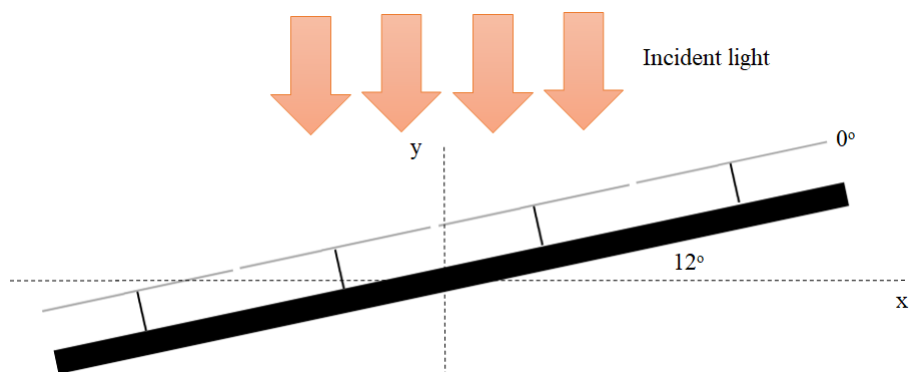


Figure 2.27: Schematic showing the alignment configuration with the device aligned at 0° and the mirrors in the “Flat” state.

2.2.6 Mirror cross-over rate

The time for which the mirrors change from the “On” state to the “Off” state is referred to as the mirror cross-over rate and limited by the manufacturer and vary for different chipsets. In this section, the DLP Light Crafter Evaluation model with the DLP 3000 chipset and DLP 300C controller board is focused upon. The mirror cross-over rate is dependent on the bit-depth of the image (or hologram) displayed on the DMD chipset. The bit-depth of an image is the amount of information in the form of bits stored in an image, and corresponds to the number of colour components of the image. The number of colours within an image are related by 2^N , where N is the number of bits. For example, a 5-bit image has $2^5 = 32$ colours. The model of interest allows for images of bit-depths ranging from 1 to 8 to be displayed. In this section, we make use of the graphical user interface (GUI) obtained from TI to store a series of holograms and display them in a sequential manner referred to as the pattern rate [76]. The number of holograms that may be uploaded onto the device is determined by their bit-depth, and limited to a maximum of 96 holograms. The ratio of the maximum number of holograms and the bit-depth determines the number of holograms that may be uploaded. For example, for holograms with bit-depth 8, the number of holograms that may be uploaded is $96/8 = 12$. The bit-depth of the uploaded holograms also determines the pattern rate, as per manufacturer specifications.

Table 2.5: Bit-depth of holograms and Pattern rate.

Bit-depth	Number of holograms	Pattern rate (Hz)
1	96	4000
2	48	1600
3	32	480
4	24	360
5	19	240
6	16	240
7	13	180
8	12	120

For the purpose of investigating the mirror cross-over rate, holograms with 1 bit-depth were uploaded, and programmed all the mirrors to lie on the in the on- and off-state corresponding to a full-white and full-black hologram, respectively. Typical CCD or CMOS cameras have maximum frame rates of up to a few hundred hertz and are not sufficient for testing the mirror cross-over rate of DMDs. In order to detect changes in the intensity of a beam reflected off the DMD at the rate specified by the manufacturer, a light detector with a response time shorter than the DMD is required. These may be photo-diodes. As shown in Fig. 2.28 a simple, easy to construct and cost effective light detector photo-diode circuit was built, consisting of an operational amplifier, potentiometer, voltage regulator, LED, and a photo-diode for the measurement of the mirror cross-over rate of the DMD used in this research.

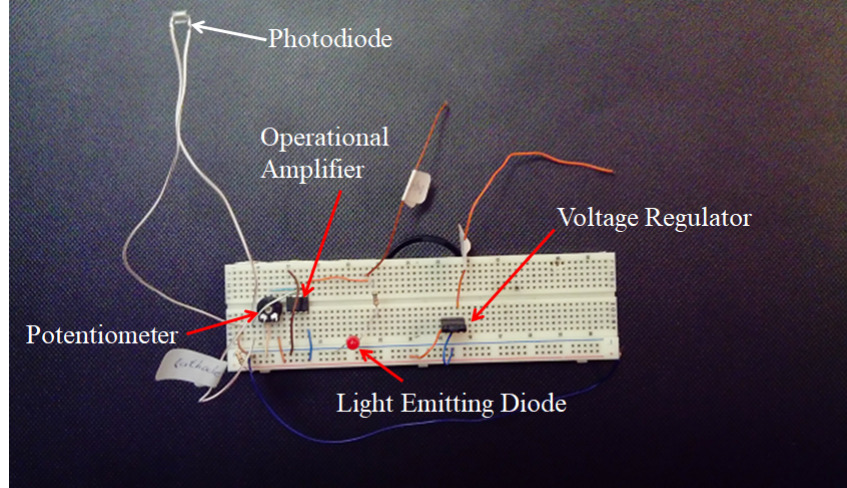


Figure 2.28: Photograph of the custom built photo-diode circuit.

The photo-diode circuit was placed in the path of the beam reflected off the DMD, with the photo-diode placed in a well enclosed tube system for the prevention of ambient light hitting the photo-diode. The circuit was powered by an external power supply and an oscilloscope was used for the observation of the resulting signal. Fig. 2.29 shows a schematic of the experimental setup used for this measurement.

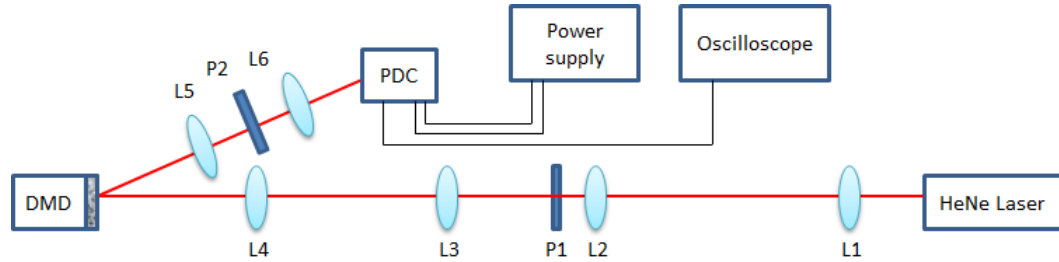


Figure 2.29: Diagram showing the experimental set-up used for the measurement of the DMD Pattern rate. A HeNe laser was expanded and collimated by lenses L1 and L2 of focal length 25 mm and 300 mm , receptively. Pinhole P1 controls the size of the expanded beam and imaged onto the DMD via a 4-f imagine system created by lenses L3 and L4 of focal length 100 mm . The zero-order was then imaged onto the photodiode circuit by another 4-f system created by lenses L5 and L6 of focal length 100 mm . The photodiode circuit is connected to a power supply and an oscilloscope and the resulting signal is registered on the oscilloscope.

The patterns were programmed to stay exposed for a certain period of time in order to obtain a clear signal on the oscilloscope. As seen in Fig. 2.30, there is a distinct rise on the signal, indicating that light has reached the photo-diode and hence a change in the pattern and a state in the micromirrors, from the “On” state to the “Off” state. Using the in-built functions of the oscilloscope, the time for which device changes patterns can be read, as shown in the boxed region of Fig. 2.30. The interval as measured by the two blue vertical lines gives a value of 3.57 kHz.

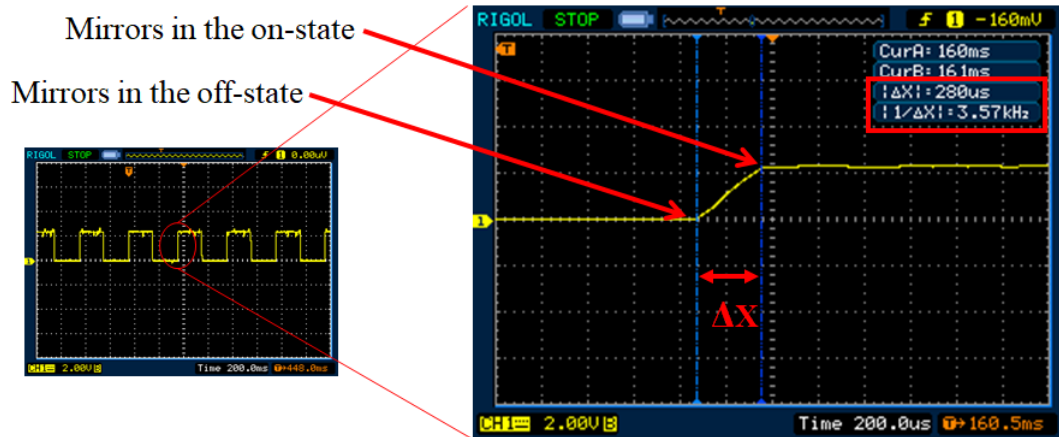


Figure 2.30: Screen shot of the oscilloscope measuring the rise and fall in the signal detected by the photo-diode.

Chapter 3

Implementing beam shaping on a DMD

In this section we use the information from chapter 2 and implement beam shaping on the DMD. Taking into account the recommendations of alignment configurations which optimises diffraction efficiency, we demonstrate amplitude and phase control of light on a binary pixelated SLM and investigate the effects of alignment configurations and determine the optimal pixel encoding schemes on the quality of the generated beams.

3.1 Theoretical framework for amplitude and phase modulation

The periodic two-dimensional array of micro-mirrors may be modelled as square wave pulse-trains with period x_0 and y_0 , with the pulse width and position controlled by grating-dependent parameters ω_x and ω_y and p_x and p_y in the horizontal and vertical direction, respectively. The transmission function may be given by [62]

$$T(x, y) = \sum_{m_1=-\infty}^{\infty} \sum_{m_2=-\infty}^{\infty} \text{rect} \left[\frac{x - (m_1 + p_x)x_0}{\omega_x x_0} \right] \text{rect} \left[\frac{y - (m_2 + p_y)y_0}{\omega_y y_0} \right], \quad (3.1)$$

where

$$\text{rect}[X] = \begin{cases} 0, & |X| < \frac{1}{2} \\ 1, & |X| > \frac{1}{2} \end{cases}. \quad (3.2)$$

The periodicity of the transmission function enables a Fourier series expansion.

$$T(x, y) = \sum_{K=-\infty}^{\infty} C_K(x, y) \exp \left[i2\pi k \left(\frac{x}{x_0} \right) \right] \exp \left[i2\pi k \left(\frac{y}{y_0} \right) \right], \quad (3.3)$$

where $C_K(x, y)$ are the Fourier coefficients. We consider a phase filter $\Phi(\nu)$ of length L with N partitions, phase modulation $\phi(\nu)$ and a high carrier frequency $\beta(\nu)$ with amplitude $h(\nu)$ [80, 81]

$$\Phi(\nu) = \exp [\phi(\nu) + h(\nu)\beta(\nu)]. \quad (3.4)$$

After a series representation of this filter, the Fourier coefficients A_j may be given by [81]

$$A_j = \frac{L}{N} \sum_{n=0}^{N-1} S_n \left(\frac{j}{N} \right) \exp \left[\phi_n - \frac{2\pi j n}{N} \right], \quad (3.5)$$

with

$$S_n = \frac{1}{2\pi} \int_{-\pi}^{\pi} \exp [h_n(s)\beta(s) - us] ds. \quad (3.6)$$

As β increases, N increases indefinitely. Following a Taylor series expansion of S_n about $u = 0$, it is found that

$$S_n = \frac{1}{2\pi} (-i)^p \int_{-\pi}^{\pi} \exp [ih_n(s)\beta(s)] ds. \quad (3.7)$$

With the above method, we find that the Fourier coefficients $C_K(x, y)$ are given by

$$C_K(x, y) = \frac{\sin(m\pi\omega(x, y))}{m\pi} \exp [im\pi p(x, y)], \quad (3.8)$$

where ω and p are implicit functions of x and y , respectively. As reconstructed waves are formed in the first order, $m = 1$, we have that

$$C_1(x, y) = \frac{\sin(\pi\omega(x, y))}{\pi} \exp [ip(x, y)]. \quad (3.9)$$

The transmission function may be found using the method of interfering a desired wave with a reference [66] wave as previously discussed.

$$T(x, y) = \cos \left(\pi p(x, y) + 2\pi \left(\frac{x}{x_0} + \frac{y}{y_0} \right) \right) - \cos(\pi\omega(x, y)). \quad (3.10)$$

Taking into account the binary operational states of a DMD, the transmission function in Eq. (3.10) is binarised, setting the amplitude to either 0 or 1 which corresponds to the “On” and “Off” states of the DMD, respectively. The transmission becomes:

$$T(x, y) = \frac{1}{2} + \frac{1}{2} \text{sign} \left[\cos \left(\pi p(x, y) + 2\pi \left(\frac{x}{x_0} + \frac{y}{y_0} \right) \right) - \cos(\pi\omega(x, y)) \right], \quad (3.11)$$

where the $\text{sign}(x, y)$ function has been scaled and the transmission function has been shifted so that it is binarised with values of 0 or 1

$$T(x, y) = \frac{1}{2} + \frac{1}{2} \text{sign} [\text{Arg}(x, y)] = \begin{cases} 0, & \text{Arg}(x, y) > 0 \\ 1, & \text{else} \end{cases}, \quad (3.12)$$

where $\text{Arg}(x, y) = \cos \left(\pi p(x, y) + 2\pi \left(\frac{x}{x_0} + \frac{y}{y_0} \right) \right) - \cos(\pi \omega(x, y))$. The functions $p(x, y)$ and $w(x, y)$ may be found by considering a scalar complex input field $u_0 = A(x, y) \exp[i\phi(x, y)]$ which is acted upon by T_1 to give rise to a desired output field u_1 . With reference to Fig. 1.1 and using the transmission function T_1 , we have that

$$\begin{aligned} u_1 &= T_1 u_0 \\ &= \frac{\sin(\pi \omega(x, y))}{\pi} \exp[i\pi p(x, y)] A(x, y) \exp[i\phi(x, y)] \\ &= A(x, y) \frac{\sin(\pi \omega(x, y))}{\pi} [\cos(2\pi p(x, y) + \phi(x, y)) + i \sin(2\pi p(x, y) + \phi(x, y))]. \end{aligned} \quad (3.13)$$

It follows that

$$\frac{\pi}{A(x, y) \sin(\pi \omega(x, y))} = \cos(2\pi p(x, y) + \phi(x, y)) + i \sin(2\pi p(x, y) + \phi(x, y)). \quad (3.14)$$

Equating the real and imaginary parts, we find that

$$\frac{\pi}{A(x, y) \sin(\pi \omega(x, y))} = \cos(2\pi p(x, y) + \phi(x, y)), \quad (3.15)$$

$$0 = i \sin(2\pi p(x, y) + \phi(x, y)), \quad (3.16)$$

respectively. Solving for $\omega(x, y)$ and $p(x, y)$ from the above, we find that

$$\omega(x, y) = \frac{1}{\pi} \arcsin(A(x, y)), \quad (3.17)$$

$$p(x, y) = \frac{1}{\pi} \phi(x, y). \quad (3.18)$$

The amplitude and phase modulating terms are given by Eq. (3.17) and Eq. (3.18), respectively with $\phi(x, y)$ and $A(x, y)$ being the phase angle and amplitude of the desired beam, respectively. Given the expression for a desired field, we implement Eq. (3.10), Eq. (3.17) and Eq. (3.18) to the desired field, and with manipulations of Eq. (3.10), we show amplitude- and phase-only modulation as well as complex amplitude modulation.

3.1.1 Amplitude-only Modulation

With the control of each pixel of the DMD chipset, it is possible to generate arbitrary shapes of light and hence demonstrate amplitude modulation of light by means of a digital aperture. Such a transmission function with no phase modulation, may be given by:

$$T(x, y) = |A(x, y)| \exp[i(0)] = |A(x, y)|, \quad (3.19)$$

where $|A(x, y)| \leq 1$ is the amplitude distribution of the aperture function. The desired output at the plane of the DMD is given by:

$$U_{out} = U_{in} T(x, y) = U_{in} A(x, y). \quad (3.20)$$

The generation of binary computer holograms for the implementation of amplitude modulation on a DMD is purely dependent on the function $A(x, y)$ digitally encoded, which controls regions of pixels within the micro-mirror array to reflect light in either the “On” state or the “Off” state. With reference to the pulse-train model, there is no control of the position of the pulses $p(x, y)$ and no diffraction grating encoded. As a result the transmission function reduces to

$$T(x, y) = \frac{1}{2} + \frac{1}{2} \text{sign} [\cos(2\pi) - \cos(\pi\omega(x, y))]. \quad (3.21)$$

The width of the pulse $w(x, y)$ dominates the structure of the hologram and the desired shaped beam is formed in the zero-order. Fig. 3.1 shows an example of an amplitude only hologram for the generation of a beam with a square transverse profile, together with a cross-sectional analysis. We use a square hologram of side length 4.6 mm which maps onto 600 pixels on the DMD. Optimal encoding schemes for ensuring optimal generation of holograms are discussed in the next section.

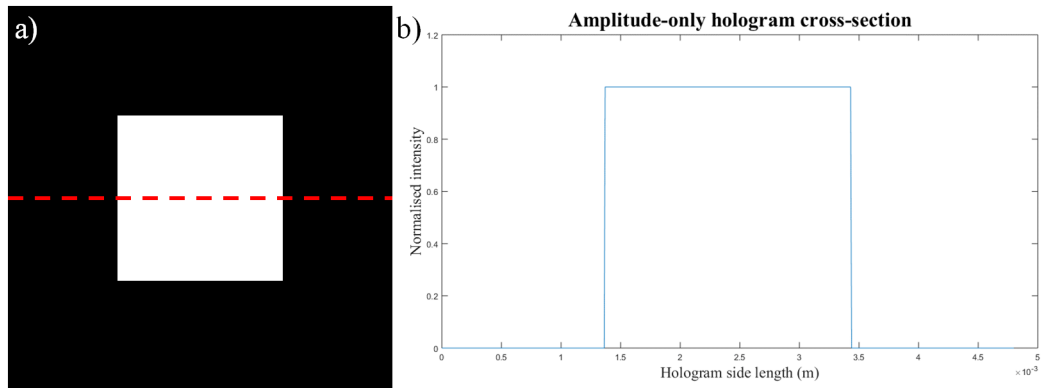


Figure 3.1: Example of an (a) amplitude-only modulating hologram and corresponding (b) cross-section.

3.1.2 Phase-only modulation

The transmission function of a phase-only modulating element may be given by

$$T(x, y) = \exp[i\phi(x, y)], \quad (3.22)$$

where $\phi(x, y)$ is the phase to be imparted onto an incident beam. Phase modulation is demonstrated by encoding a diffraction grating onto the DMD. With reference to the pulse-train with no amplitude modulation, there is no control of width of the pulses $\omega(x, y)$, but incorporates a diffraction grating into the hologram. The transmission function for the DMD reduces to

$$T(x, y) = \frac{1}{2} + \frac{1}{2} \text{sign} \left[\cos \left(\pi p(x, y) + 2\pi \left(\frac{x}{x_0} + \frac{y}{y_0} \right) \right) \right]. \quad (3.23)$$

A diffraction grating dominates the structure of the hologram with the desired shaped beam formed in the first order and in the far field. Fig. 3.2 shows an example of an phase-only hologram for the generation of a beam with a square transverse profile, together with a cross-sectional analysis. As with the amplitude-only case, we consider a square hologram of side length 4.6 mm which maps onto 600 pixels on the DMD with a diffraction grating encoded as 76 and 110 lines per millimetre in the horizontal and vertical direction, respectively.

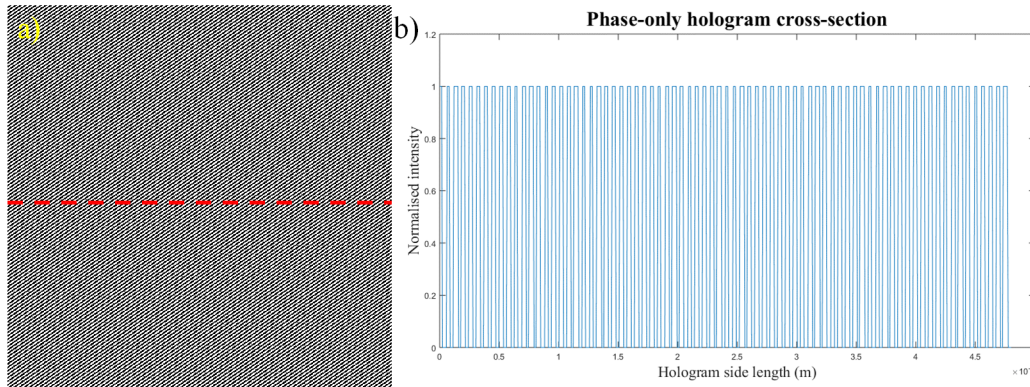


Figure 3.2: Example of an (a) phase-only modulating hologram and corresponding (b) cross-section.

A complex amplitude hologram for the generation of a beam with a square transverse profile is given in Fig. 3.3.

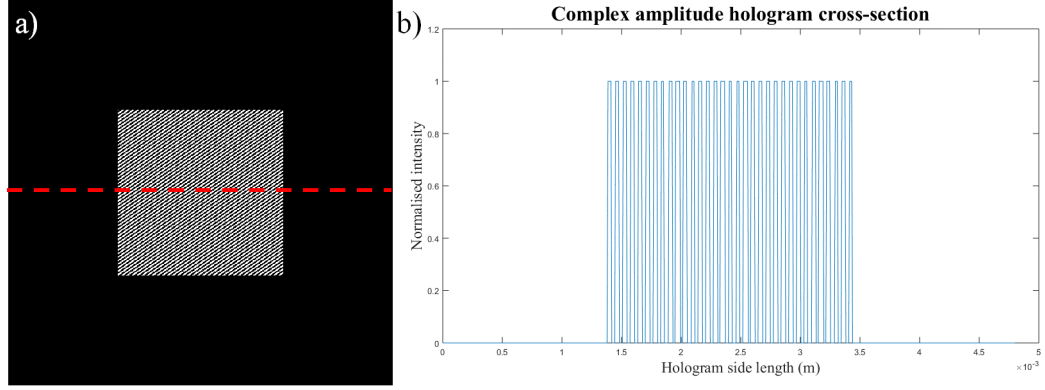


Figure 3.3: Example of an (a) complex amplitude modulating hologram and (b) cross-section.

3.2 Pixel encoding scheme

As mentioned in chapter 1, implementing digital holography on computer controlled pixelated light modulating devices involves computation of a two dimensional matrix of dimensions which match the screen of the device, has a one-to-one mapping of each element in the matrix to each pixel with the correct pixel dimensions of the device. The DMD used (DLP 3000 series) has square mirrors of side length $7.6 \mu\text{m}$ with a horizontal and vertical pitch of $10.8 \mu\text{m}$, placed in a diagonal arrangement. Due to this arrangement, the computation of the matrix is performed using the mirror pitch as the pixels' dimension in the encoding scheme. Initial encoding schemes uses a vertical pitch equal to half of that of the diagonal. Incorporating this into the encoding scheme results in an inaccurate mapping of the programmed matrix from a conventional Cartesian-coordinate based matrix onto a diamond arrangement of the pixels on the DMD, with ellipticity in the generated output beams. Fig. 3.5 shows the holograms for the generation of of beam with circular transverse profile as generated in software, displayed on the screen of the DMD, and the resulting experimentally generated beam. It is clear that there exist ellipticity in the beam and hence the initial pixel encoding scheme is not sufficient.

The ellipticity was corrected by means of iteratively optimising the scale of the horizontal dimension in the encoding scheme [79]. As seen in Fig. 3.5 shows selected circular amplitude-only modulation holograms and corresponding generated output beams with different pixel encoding schemes. The yellow circle indicates the ideal case of a beam with a circular transverse profile.

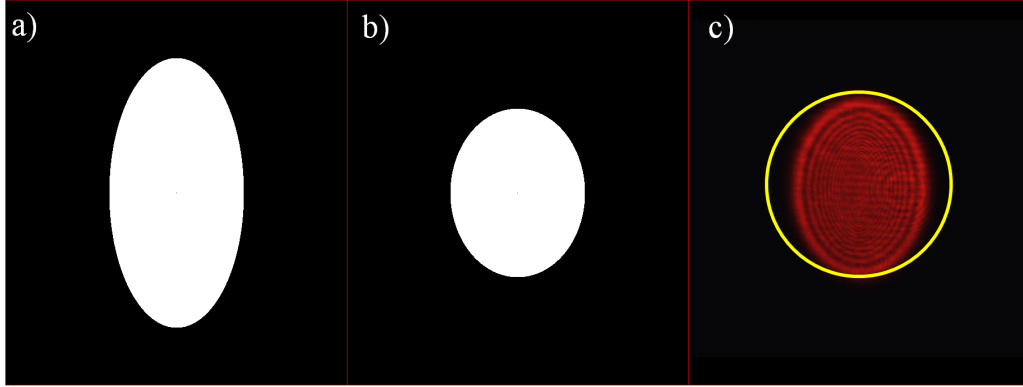


Figure 3.4: Initial pixel encoding scheme. a) Hologram generated in software. (b) Hologram displayed on the DMD screen. (c) The resulting experimentally generated beam.

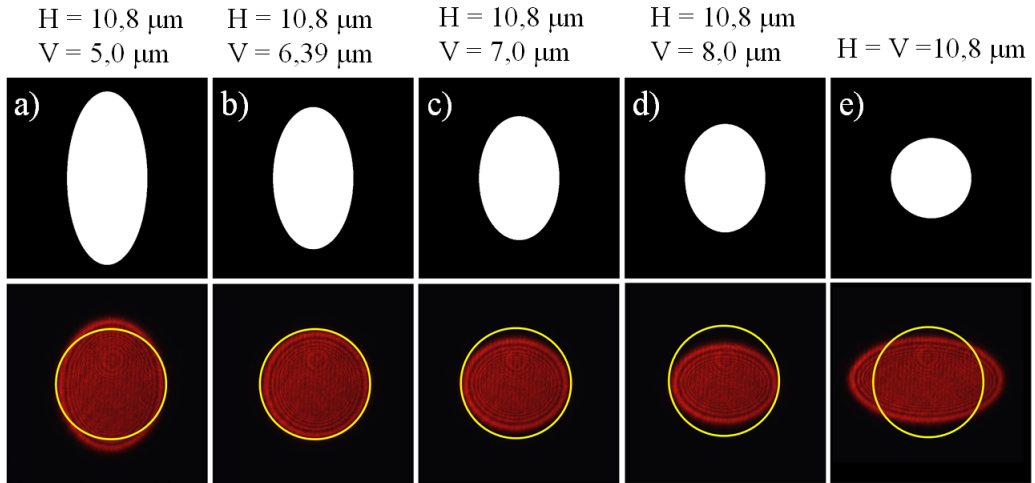


Figure 3.5: Holograms and associated generated output beams for different pixel encoding schemes. H and V refer to the horizontal and vertical dimensions used in the encoding scheme.

Observing Fig. 3.5(e), it is seen that when an equal pixel pitch in the horizontal and vertical direction of $10.8 \mu\text{m}$ is used in the encoding scheme the resulting beam is horizontally elongated. Decreasing the horizontal pixel pitch corrects the elongation in the beam. It was found that the optimal ratio between the vertical and horizontal encoded pixel size was 1.6889, as shown in Fig. 3.5(b).

3.3 Amplitude modulation

Implementation of the transmission function for amplitude-only modulation discussed in section 3.1.1 allows for a dynamic method of beam truncation by means of binary computer generated holograms. A diffraction pattern observed is a result of the structure of the micromirror array. The observed shaped beam is formed at the plane of the DMD and occurs in the zeroth order. Fig. 3.6 shows the experimental setup, similar to that used in section 2.2.4 used for amplitude modulation with the DMD. Pinhole P_2 isolates the zeroth-order.

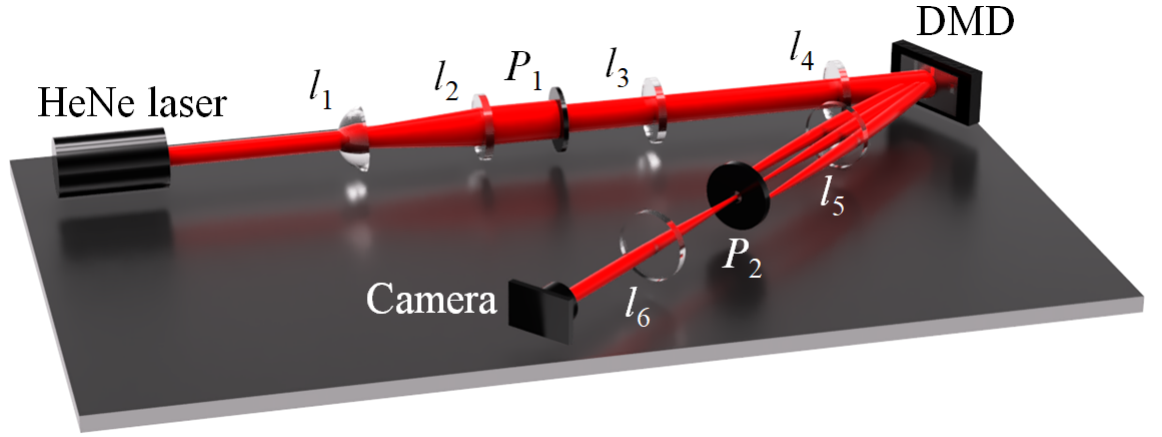


Figure 3.6: Experimental setup used for amplitude modulation. A HeNe source expanded and collimated by lenses l_1 and l_2 . Aperture P_1 controls the size of the incident beam and is imaged onto the DMD by lenses l_3 and l_4 . The zeroth order of diffraction emanating from the DMD is then imaged onto the camera by lenses l_5 and l_6 .

Fig. 3.7 shows examples of amplitude-only modulating holograms as displayed on the DMD with the correct encoding scheme implemented. At first glance the aspect ratio of the holograms appear incorrect as the shapes are elongated. This is due to the optimal pixel encoding scheme implemented, as discussed in section 3.2.

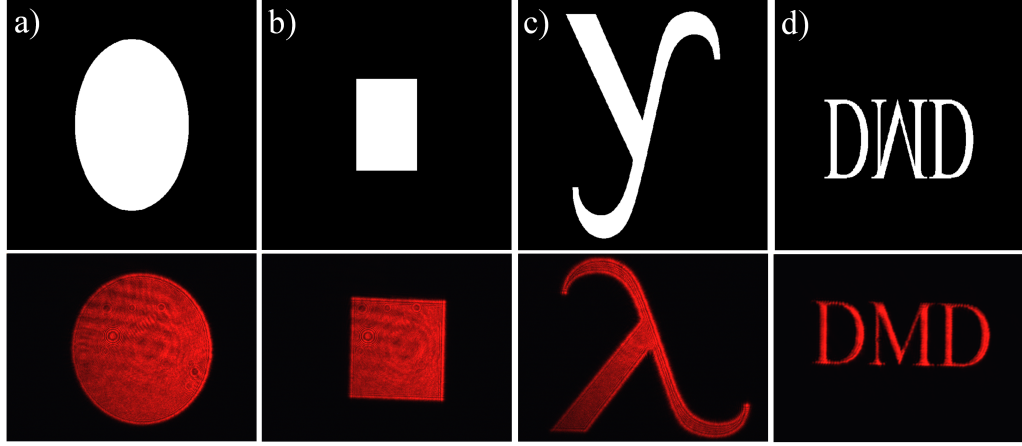


Figure 3.7: Amplitude-only modulating holograms and the correspond experimental results for (a) circular, (b) square (c) Greek symbol Lambda and (d) DMD abbreviation apertures.

Uniformity analysis

An investigation of the uniformity of the shaped beams through amplitude modulation was conducted. Fig. 3.8 shows the hologram used, a simulated and an experimentally generated square beam and a horizontal cross-section analysis. The ideal profile of a square has a uniformly normalised intensity of 1. The profile of the experimentally generated beam fluctuates very rapidly, with a maximum value of 1 and a minimum value of 0.4. The mean intensity of the experimentally generated beam (in normalised units) is 0.5 with a standard deviation of 0.3. With this analysis and from the graph in Fig. 3.8(c), beam shaping through amplitude modulation with a DMD produces beam profiles with non-uniform intensities. A method of generating beams with uniform intensity distributions is discussed in the nest section.

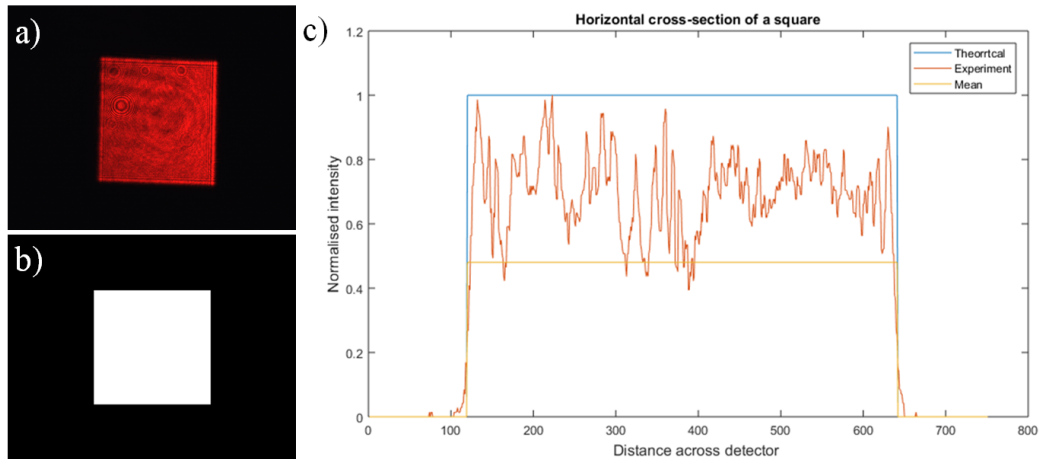


Figure 3.8: Uniformity analysis of an experientially generated square beam by amplitude-only modulation. (a) Experimental beam. (b) Simulated beam. (c) Horizontal cross-sectional analysis.

3.4 Phase Modulation

In this section we implement the technique described in section 3.1.2. We demonstrate lossless laser beam shaping with the generation of flat-top beam (beams with a uniform transverse irradiance distribution) [82, 83].

3.4.1 Lossless beam shaping

Developed by F. M. Dickey and L. A. Romero, the method of lossless beam shaping relies on the conservation of energy of the process in converting a given source into a desired shaped beam. Fig. 3.9 shows a diagram of the method. A beam of coherent light passes through some beam shaping element which imparts a phase change on the incident light and the desired shaped beam is observed in the far field.

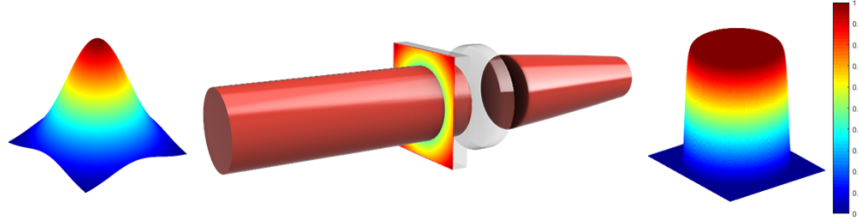


Figure 3.9: Schematic of the conversion of a Gaussian beam into a flat-top beam using the lossless beam shaping method.

Scaling properties of the incident and outgoing beam during the conversion process during lossless beam shaping plays an important role. A dimensionless scaling parameter β is defined which is dependent on the wavelength λ of light, the focal length f of the Fourier transforming lens, and characteristic lengths or scaling factors R and D of the incident and outgoing irradiance distributions, respectively.

$$\beta = \frac{2\pi RD}{\lambda f}. \quad (3.24)$$

The method involves three steps with an ultimate goal of determining a phase function for the beam shaping element. The first step involves the calculation of a scaling constant A for the conservation of energy, defined as the ratio of the desired output beam to the input beam.

$$A = \frac{E_{in}}{E_{out}}, \quad (3.25)$$

where E_{in} and E_{out} is the energy of the input and the output beam, respectively. The next step involves the determination of a function $\alpha(x, y)$ that maps regions of the input beam to regions of the output beam. The last step determines a function $\alpha(x)$ which performs a spatial mapping of the incident beam to a position of the desired shaped output beam. This is determined by considering a light field passing through an element with phase ϕ and a lens

with focal length f and phase $\phi_{lens} = \frac{2\pi}{\lambda f}$ where λ and f are the wavelength and lens focal length, respectively. The field at the focal plane of the lens, up to a proportionality constant C in one dimension is given by [82, 83]

$$U_{out}(f_x) \rightarrow U_{out}(\alpha(x)) = C \int_{-\infty}^{\infty} U_{in}(x) \exp[i\beta(\Phi(x) - \alpha(x)x)] dx, \quad (3.26)$$

where $\Phi(x) = \frac{\lambda f}{2\pi} \phi(x)$ and $\beta = \frac{2\pi}{\lambda f}$. Using the method of stationary phase, we the following is obtained [82, 83, 20]

$$U_{out}(f_x) \rightarrow U_{out}(\alpha(x)) = C \exp\left[i\beta\left(\Phi(x) - \alpha(x)x + \frac{\pi}{4}\right)\right] \sqrt{\frac{\pi}{\beta\Phi''(x)}}, \quad (3.27)$$

with $\frac{d}{dx}[\Phi(x) - \alpha(x)x] = 0$. The scaling function is then given by the solution to

$$\frac{d}{dx}(\alpha(x)) = \frac{1}{C} \frac{|U_{in}|^2}{U_{out}(\alpha(x))}. \quad (3.28)$$

The last step uses $\alpha(x)$ for the determination of the phase function $\phi(x)$. This is found from the solution to

$$\frac{d}{dx}\phi(x) = \beta\alpha(x). \quad (3.29)$$

Gaussian to Circular flat-top

The incident and outgoing irradiance distributions are given by

$$I_{in}(r) = \exp[-r^2], \quad (3.30)$$

$$I_{out}(r) = \begin{cases} 0, & r < 1 \\ 1, & r > 1. \end{cases} \quad (3.31)$$

Solving for the scaling constant, we find that

$$A = \frac{1}{2\pi}.$$

The spatial mapping function and the resultant phase function is given by

$$\alpha(\xi) = \sqrt{2\pi} \sqrt{1 - \exp[-\xi^2]} d\xi, \quad (3.32)$$

$$\phi(\xi) = \sqrt{2\pi} \int_0^\xi \sqrt{1 - \exp[-r^2]} dr, \quad (3.33)$$

respectively. The solution for the phase function for the conversion of a Gaussian beam into a circular flat-top beam is given by:

$$\phi(\xi) = \beta \frac{\sqrt{\pi}}{2} \int_0^\xi \sqrt{1 - \exp(-\rho^2)} d\rho, \quad (3.34)$$

where

$$\xi = \frac{\sqrt{2}r}{r_0},$$

$$\beta = \frac{2\sqrt{2}r_0 y_0}{f\lambda},$$

with r being the radial coordinate, r_0 is $1/e^2$ of the radius of the incoming Gaussian beam and y_0 is the radius of the desired spot.

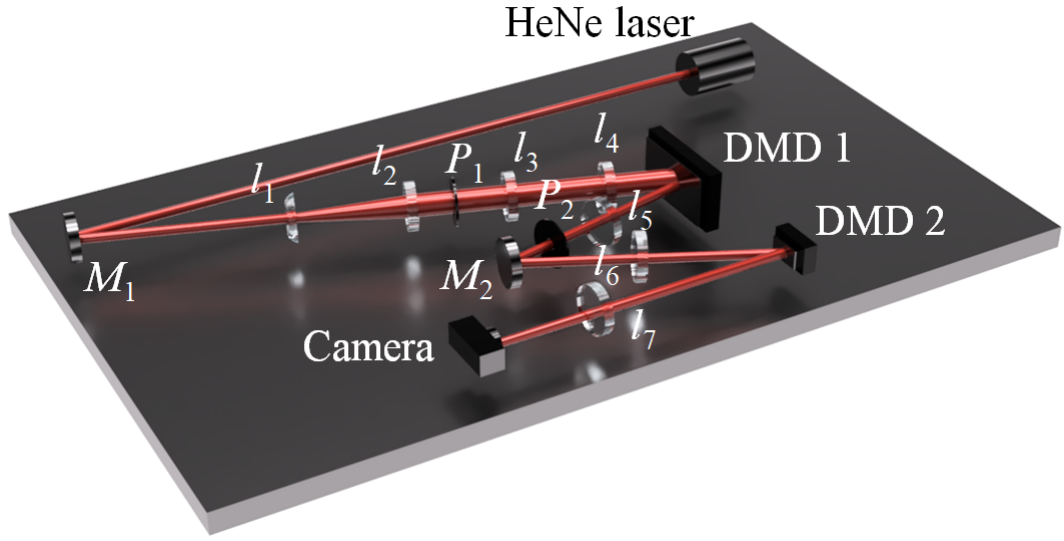


Figure 3.10: Experimental set-up used for the generation of Flat-top beams.

Fig. 3.10 is a schematic of the experimental set-up used for the implementation of lossless beam shaping using DMDs. A HeNe (wavelength of 632 nm) was expanded and collimated by lenses l_1 and l_2 of focal length 50 mm and 300 mm respectively. Aperture P_1 controls the size of the expanded and collimated beam and is imaged onto DMD 1 by a 4-f system created by lenses l_3 and l_4 of focal length 100 mm. DMD 1 generates a Gaussian beam through complex amplitude modulation of which the first order is spatially filtered and imaged onto DMD 2 by a 4-f system created by lenses l_5 and l_6 of focal length 150 mm. DMD 2 performs the conversion of the Gaussian beam to a circular flat-top beam through phase modulation. The far field observation of the flat-top beam is observed in the Fourier plane of lens l_7 of focal length 300 mm by the camera. The use of two DMDs provided versatility and control of the experiment as the size of the Gaussian beam and the generated flat-top beam could be controlled.

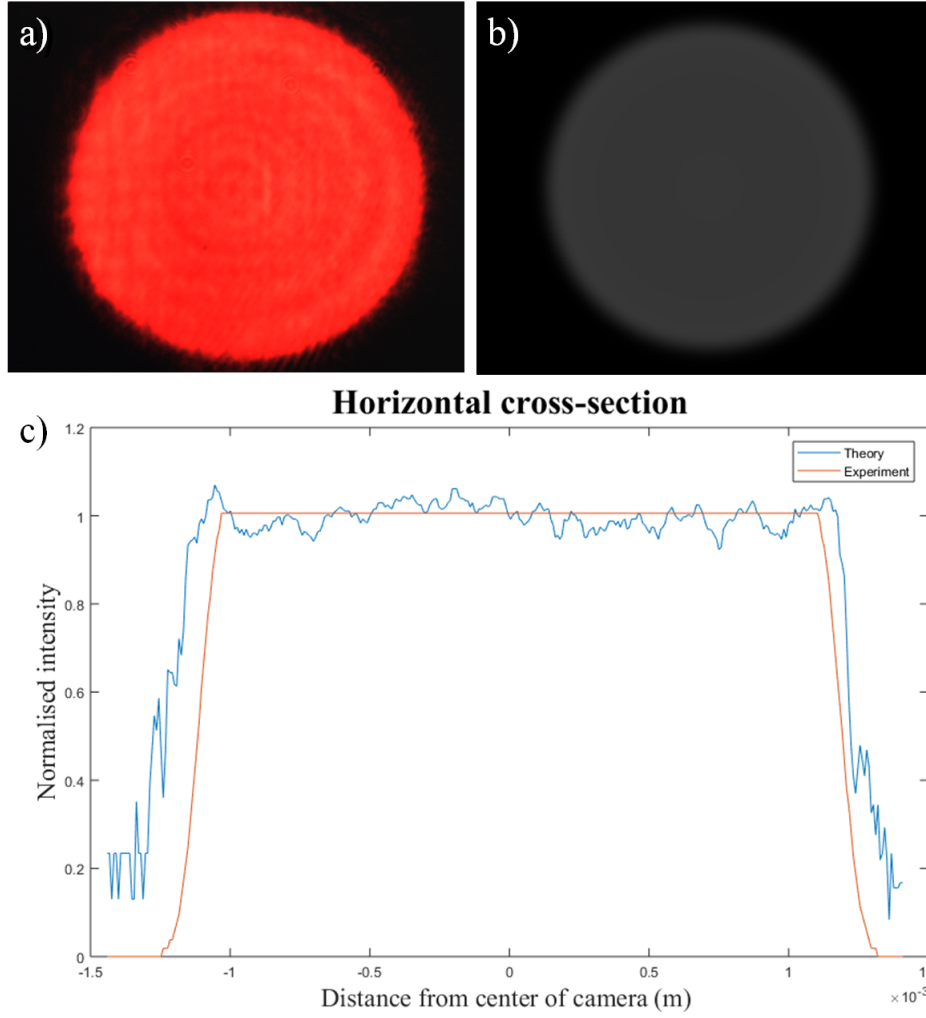


Figure 3.11: (a) Experimentally generated flat-top beam with the corresponding (b) simulated result. (c) A cross-section analysis of the experimental and simulated beam.

Fig. 3.11 shows experimentally generated and simulated results of a flat-top beam. The input size of the input Gaussian and desired flat-top beam was 1 mm and 3.4 mm, with $\beta = 27$. The size of the flat-top beam generated was limited by the active sensor area of the camera. It is seen that the flat-top beam generated through phase modulation is more uniform than the beams generated through amplitude modulation as seen in Fig. 3.8.

3.5 Amplitude and phase modulation

In this section we implement the technique described in section 3.1. The transmission function may be written as

$$T(x, y) = \frac{1}{2} + \frac{1}{2} \text{sign} [\cos (\text{phase} + \text{grating}) - \cos (\arcsin (\text{amplitude}))], \quad (3.35)$$

where the *phase* and *amplitude* are encoded according to the desired beam. The *grating* is encoded as a spatial frequency in units of number of lines per unit length in the horizontal and vertical direction and is also limited by the resolution of the DMD. Fig. 3.12 shows examples of binary computer holograms generated in software and displayed on the DMD screen.

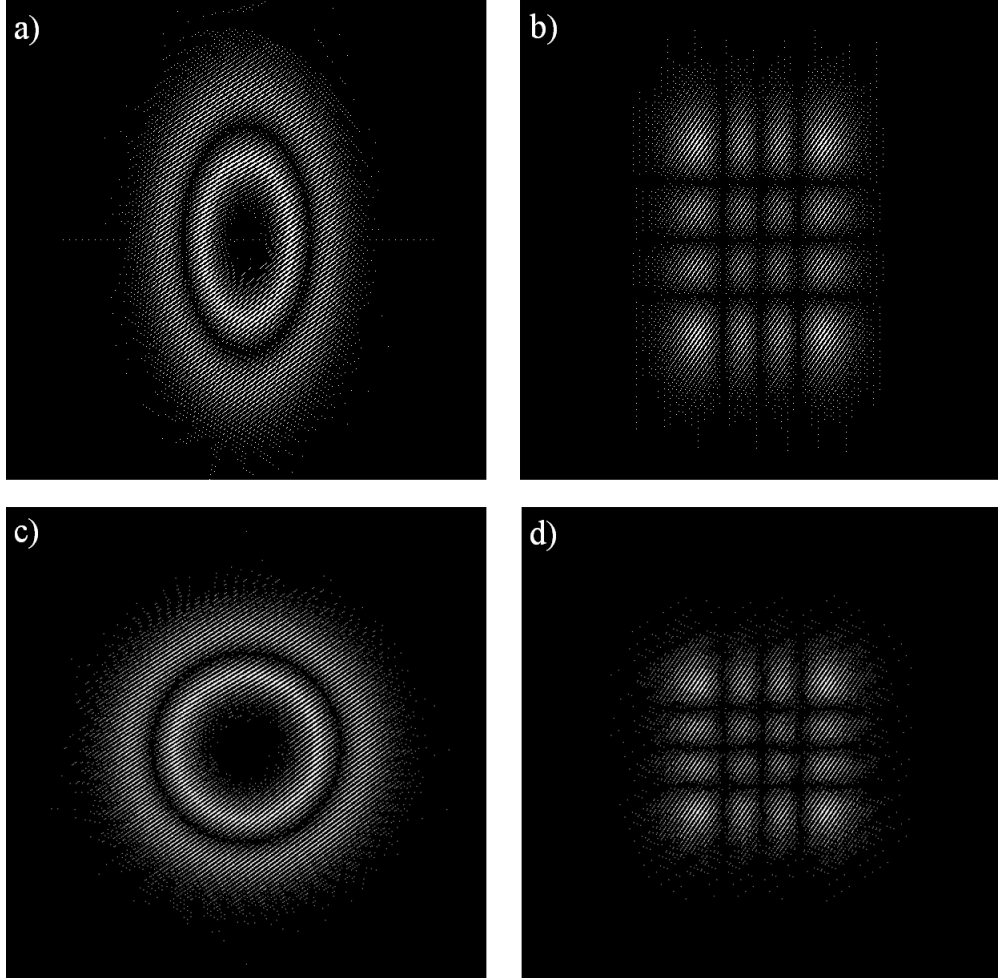


Figure 3.12: Examples of complex amplitude binary computer generated holograms with the correct pixel encoding scheme as generated in software (a) and (b) displayed on the DMD screen (c) and (d). (a) and (c) shows a Laguerre-Gaussian mode with radial index $p = 2$ and azimuthal index $l = 8$. (b) and (d) shows Hermite-Gaussian mode with horizontal n and vertical m index equal to 3.

The desired field is formed in the plane of the DMD together with the unmodulated zero-order of diffraction. A similar experimental set-up to that used in for amplitude modulation in section 3.1.1 is used. The difference lies in the spatial filter which blocks out all other diffraction orders in the Fourier plane of the lens and allows the first order of diffracted light to pass through. To demonstrate full amplitude and phase control implemented on a DMD, we focus on the generation of two families of spatial modes of light, Hermite- and Laguerre-Gaussian modes which are solutions to the Helmholtz equation in Cartesian and cylindrical coordinates, respectively. These are given by

$$\begin{aligned}
LG_{l,p}(r, \phi, z) = & \sqrt{\frac{2^{|l|+1}p!}{\pi(p+|l|)! \omega(z)}} \frac{1}{\omega(z)} L_{p,l} \left(\frac{2r^2}{\omega^2(z)} \right) \left(\sqrt{2} \frac{r}{\omega(z)} \right)^{|l|} \\
& \times \exp \left[-\frac{r^2}{\omega^2(z)} \right] \exp \left[-ik \frac{r^2}{2(z_R^2) + z^2} \right] \exp [il\phi] \\
& \times \exp \left[-(2p+|l|+1) \arctan \left(\frac{z}{z_R} \right) \right],
\end{aligned} \tag{3.36}$$

$$\begin{aligned}
HG_{m,n}(x, y, z) = & \frac{1}{\omega(z)} \sqrt{\frac{2^{1-m-n}}{\pi m! n!}} H_m \left(\frac{x\sqrt{2}}{\omega(z)} \right) H_n \left(\frac{y\sqrt{2}}{\omega(z)} \right) \\
& \times \exp \left[-\frac{(x^2 + y^2)}{\omega^2(z)} \right] \exp \left[i(m+n+1) \arctan \left(\frac{z}{z_R} \right) \right] \\
& \times \exp \left[-\frac{ik(x^2 + y^2)}{2R} \right] \exp [-ikz],
\end{aligned} \tag{3.37}$$

respectively. $\omega(z)$ and z_R is the beam radius and the Rayleigh range given by

$$\omega(z) = w_0 \sqrt{\frac{z^2 + z_R^2}{z_R^2}}, \tag{3.38}$$

$$z_R = \frac{\pi \omega_0}{\lambda}, \tag{3.39}$$

respectively, with wavelength λ and w_0 being the beam waist at the plane $z = 0$. Laguerre-Gaussian beams are characterised by a radial index p and an azimuthal index l and the Hermite-Gaussian beams are characterised by a horizontal index m and a vertical index n . Fig. 3.13 and Fig. 3.14 are examples of Laguerre-and Hermite-Gaussian modes, respectively.

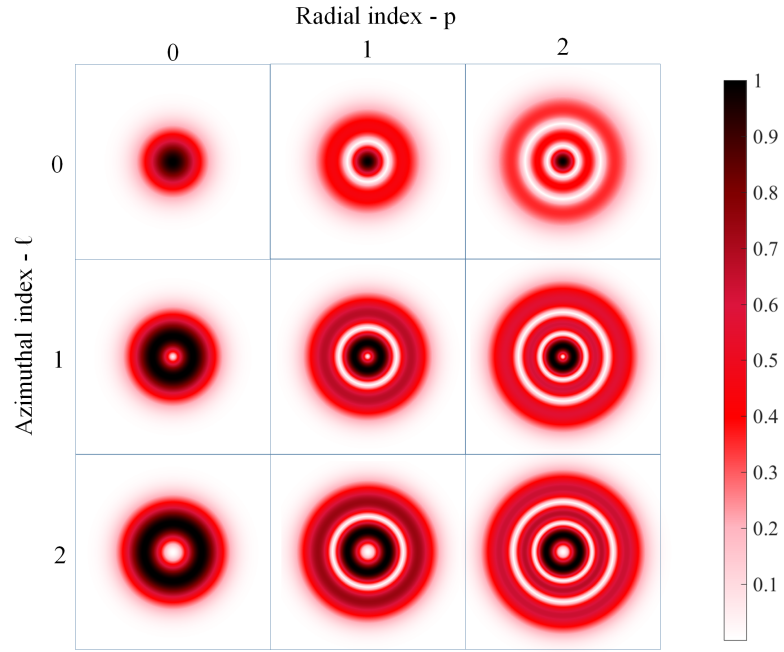


Figure 3.13: Simulated intensity pattern of some Laguerre-Gaussian beams.

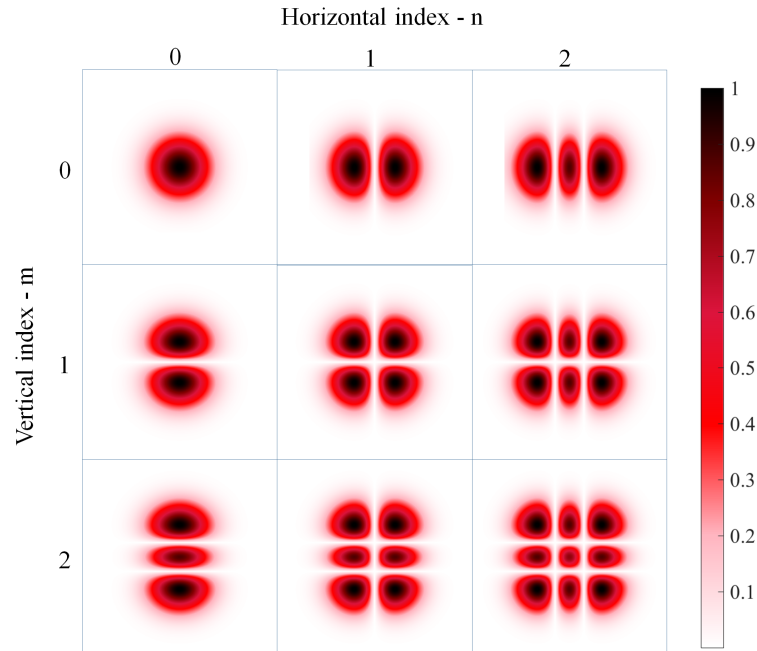


Figure 3.14: Simulated intensity pattern of some Hermite-Gaussian beams.

3.5.1 Simulation

The desired output shaped beam is formed at the plane of the DMD along with other diffraction orders including the zero diffraction order. An encoded diffraction grating is therefore necessary as a spatial filtering process is implemented for the isolation of the first diffraction order. Fig. 3.15(a) shows an example of a binary computer generated hologram for an LG_{11} mode with a beam waist of 0.2 mm. The hologram has a grating frequency of 76 and 110 pixels per unit length in the vertical and the horizontal direction respectively. Fig. 3.15(b) shows a simulation of the diffraction pattern at the focal plane of the first lens of a spatial filtering system after the DMD. With the use of an aperture, the first order of diffraction is isolated, and the desired mode observed in the image plane of the 4-f system as seen in figure Fig. 3.15(c).

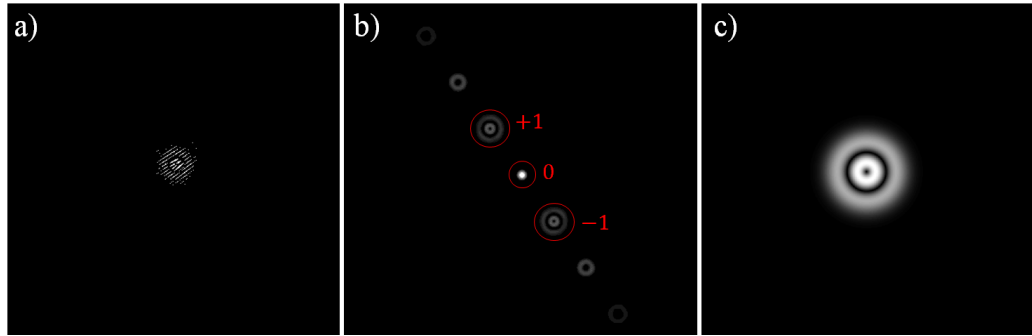


Figure 3.15: Simulation of the generation of spatial modes of light. (a) Hologram of desired LG_{11} mode. (b) Simulation of the corresponding Fourier plane intensity. (c) Simulation of the corresponding image plane intensity.

3.5.2 Experimental implementation

We consider the two different alignment configurations of the DLP 3000 series 220 DMD as discussed in section 2.2.4. Fig. 3.16 shows a schematic of the experimental setup used, along with the simulations at the appropriate positions in the setup. The source beam is expanded and collimated by lenses l_1 and l_2 . Pinhole P_1 controls the size of the expanded beam. The beam at this plane is indicated by position A in Fig. 3.16 and is imaged onto the DMD by a 4-f imaging system created by lenses l_3 and l_4 and corresponds to Fig. 3.15(a). Position B is representative of the plane of the DMD with a hologram displayed. The plane at pinhole P_2 is indicated by position C and corresponds to the Fourier plane of lens l_5 and Fig. 3.15(b). The first diffraction order reflected off the DMD is isolated by pinhole P_2 and imaged onto the camera by lenses l_5 and l_6 . The plane of the camera is indicated by position and corresponds to the simulation in Fig. 3.15(c). Fig. 3.17 and Fig. 3.18 show range of experimentally generated Laguerre- and Hermite-Gaussian modes.

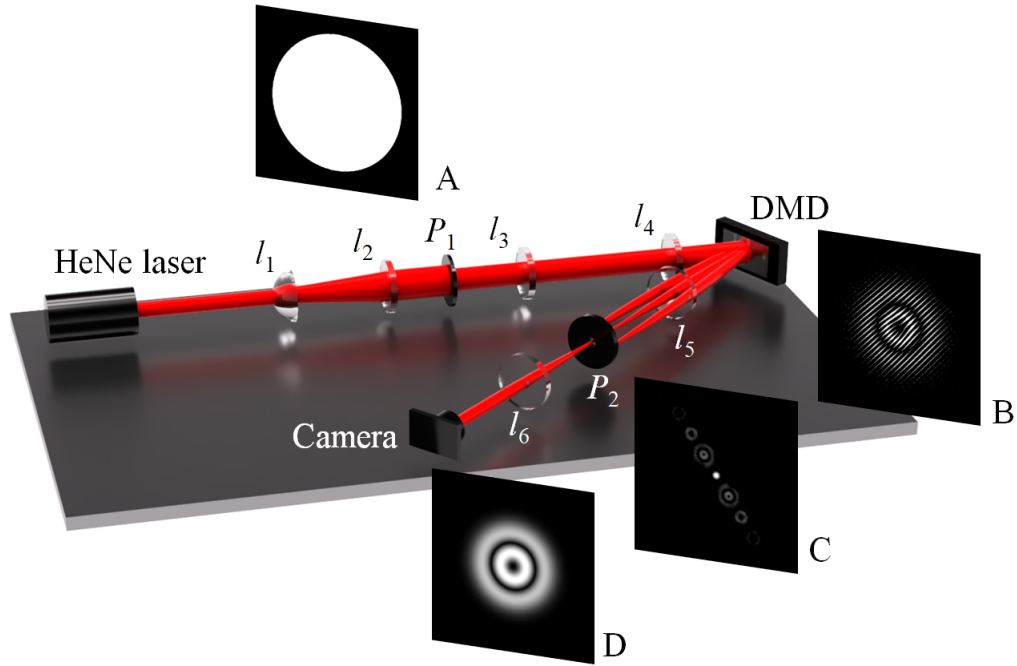


Figure 3.16: Experimental set-up used for the generation of spatial modes of light with simulated results at the respective planes.

We examine the quality of the modes according to the different alignment schemes. Fig. 3.19 shows computer generated binary holograms together with the experientially LG_{55} mode under the different alignment configurations in section 2.2.4 and pixel encoding schemes outlined in section 3.2. It is seen that with the initial encoding scheme, the generated modes are vertically elongated with the elongation more prominent when the device is aligned at 12° .

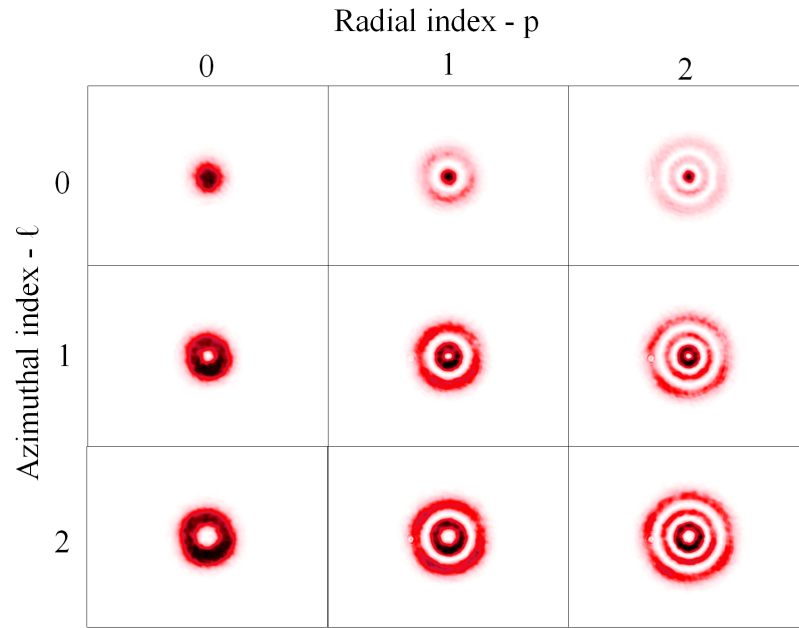


Figure 3.17: Experimentally generated Laguerre-Gaussian modes.

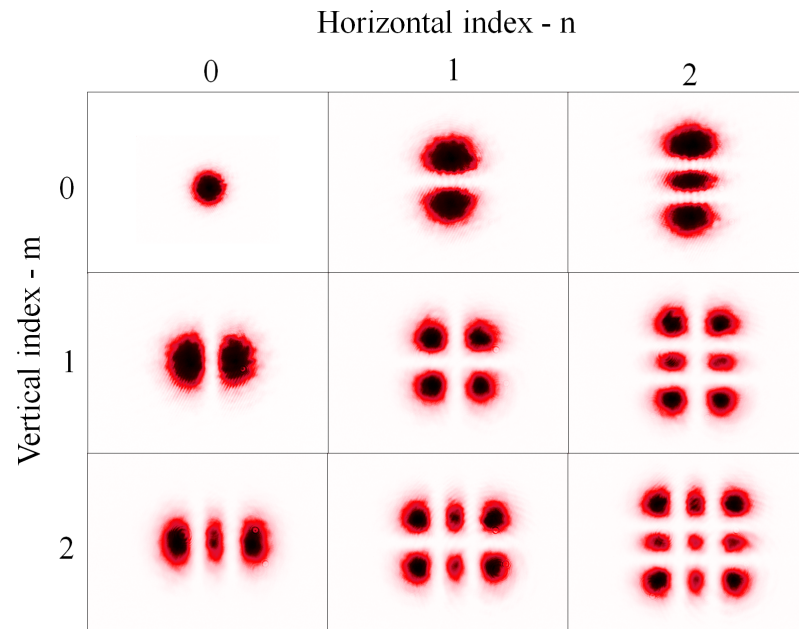


Figure 3.18: Experimentally generated Hermite-Gaussian modes.

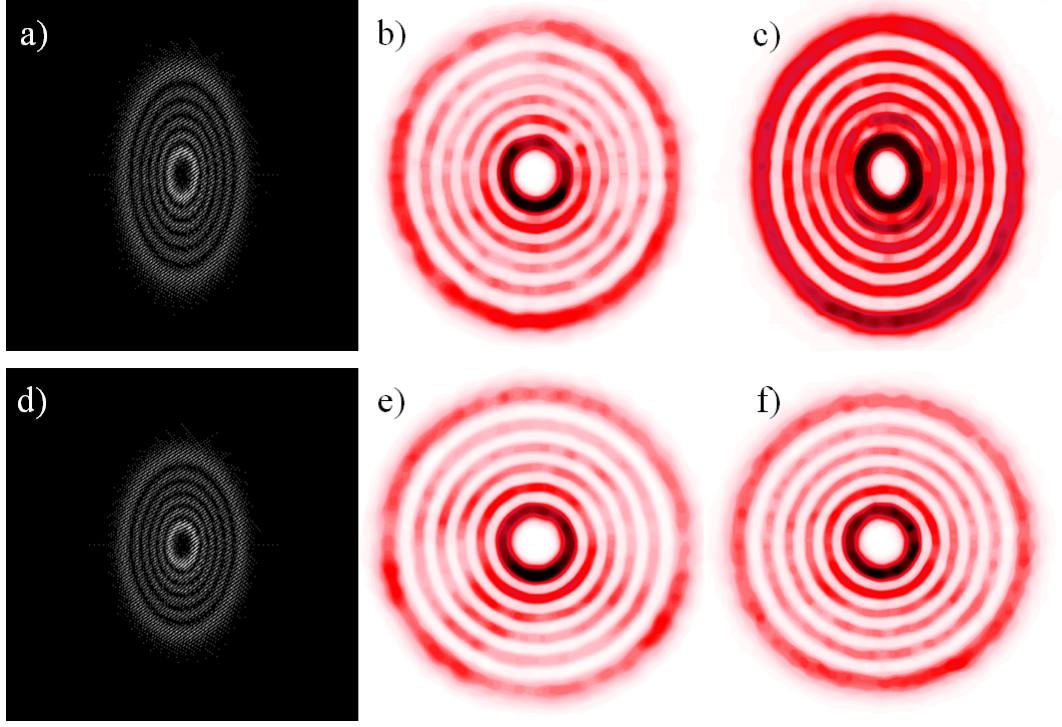


Figure 3.19: Computer generated binary holograms (a) and (d) with the experimentally generated LG_{55} mode along side with the DMD aligned at 0° (b) and (e) and at 12° (c) and (f).

The quality of the experimentally generated beams was tested and quantified with a correlation of the intensity profiles with the corresponding theoretical intensity profiles. We express the correlation as a percentage, 0% for non-identical images and 100% for completely identical images. This may be expressed as

$$C = \frac{\sum_i \sum_j (A_{ij} - \bar{A}) (B_{ij} - \bar{B})}{\sqrt{\sum_i \sum_j (A_{ij} - \bar{A})^2 (B_{ij} - \bar{B})^2}} \times 100, \quad (3.40)$$

where A_{ij} and B_{ij} are the intensity values of the individual pixels at row i and column j respectively and $\bar{A}$ and $\bar{B}$ are the mean intensity values. We perform a correlation analysis using an LG_{55} . Fig. 3.20 and Fig. 3.21 shows the results of a correlation analysis with a plot of a horizontal cross-section of the theoretical and experimentally generated beams for the different alignment pixel encoding schemes. It is observed that the highest correlation of 96.88% is obtained with optimal pixel encoding and when the DMD is aligned at 12° . The correlation drops by 0.7% with the DMD aligned at 0° . With the DMD aligned at 0° with an initial pixel correction encoding scheme, the correlation drops to 97%. A fairly low correlation of 72% in comparison is obtained with the device aligned at 12° with an initial pixel encoding scheme implemented.

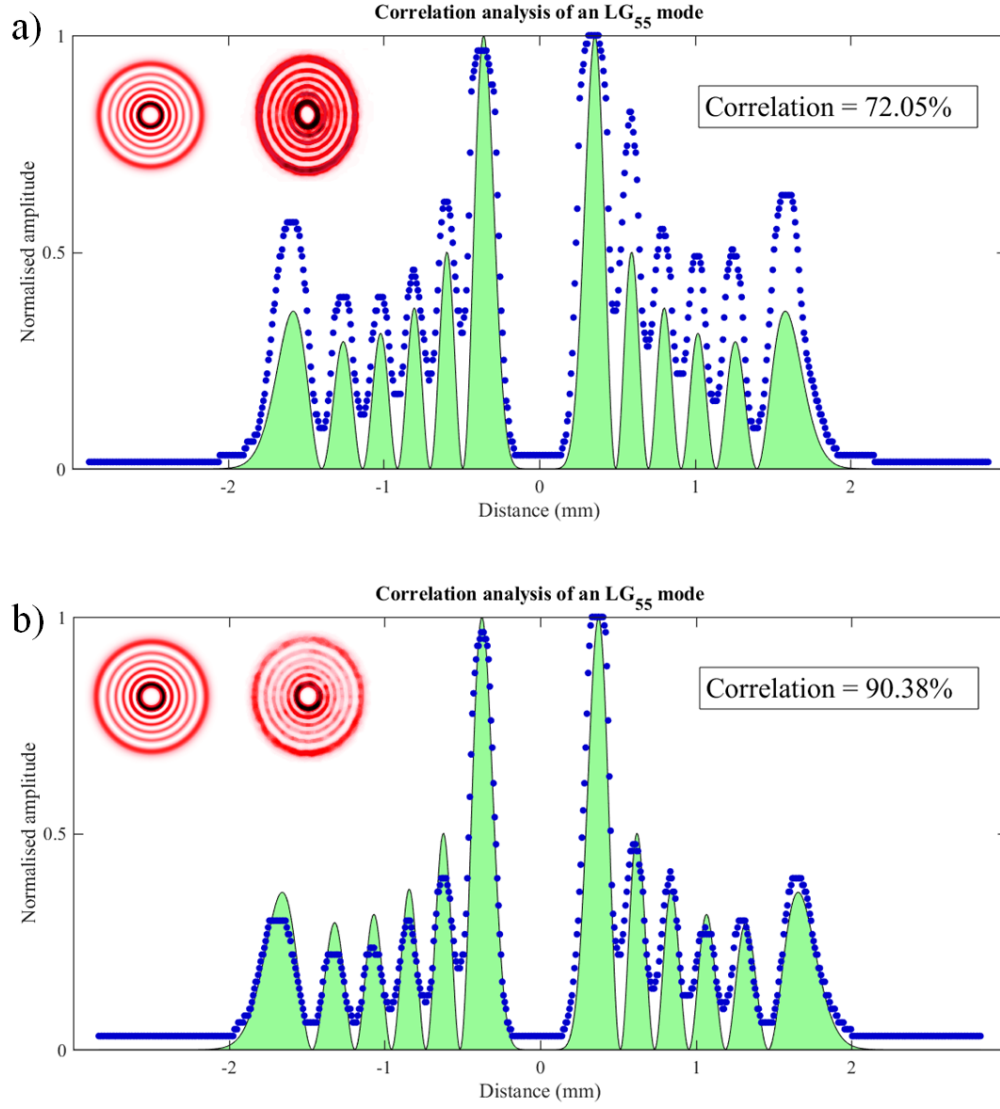


Figure 3.20: Correlation between theoretical and experimental of an LG_5^5 mode under the initial pixel encoding scheme aligned at (a) 12° and (b) 0° .

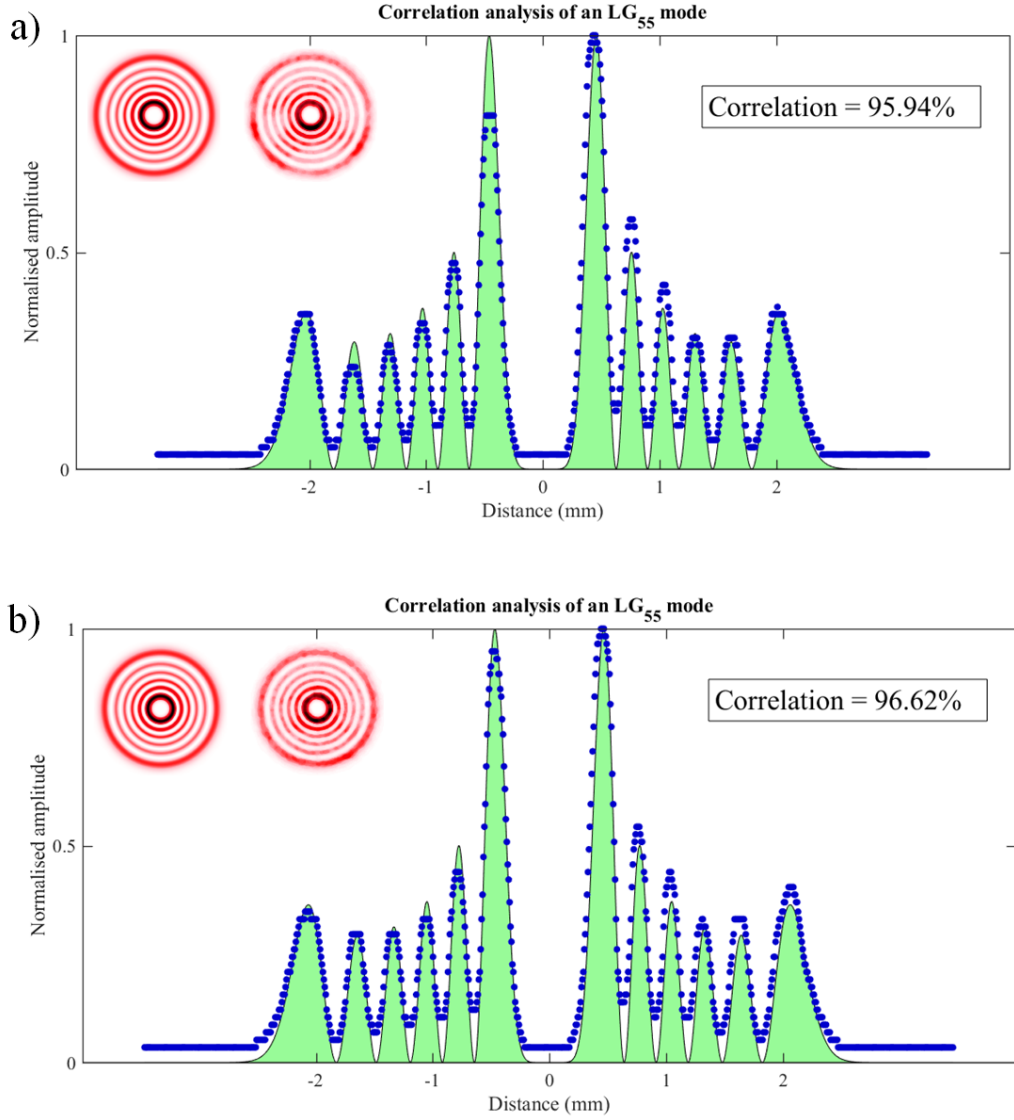


Figure 3.21: Correlation between theoretical and experimental of an LG_5^5 mode under the correct pixel encoding scheme aligned at (a) 12° and (b) 0° .

We utilise the fast mirror cross-over frequency (3.57 kHz) of the DMD and demonstrate rapid beam shaping. A colour camera with a resolution of 1280×960 pixels was used to record a video at a rate 15 frames per second. Fig. 3.22 shows a series of 12 frames (approximately 0.84 seconds) of the video. A series of holograms of 1 bit depth is uploaded and stored in the memory of the device. We program the DMD to allow each be displayed for 0.8 seconds. This allows the camera to resolve captured images. The time for which each hologram is displayed does not perfectly match the frame rate of the camera as frame 4 captures the transition from HG_{21} to an LG_{21} mode and frame 5 captures the transition from LG_{21} to an HG_{22} mode. A similar case is present in frames 6, 10 and 11.

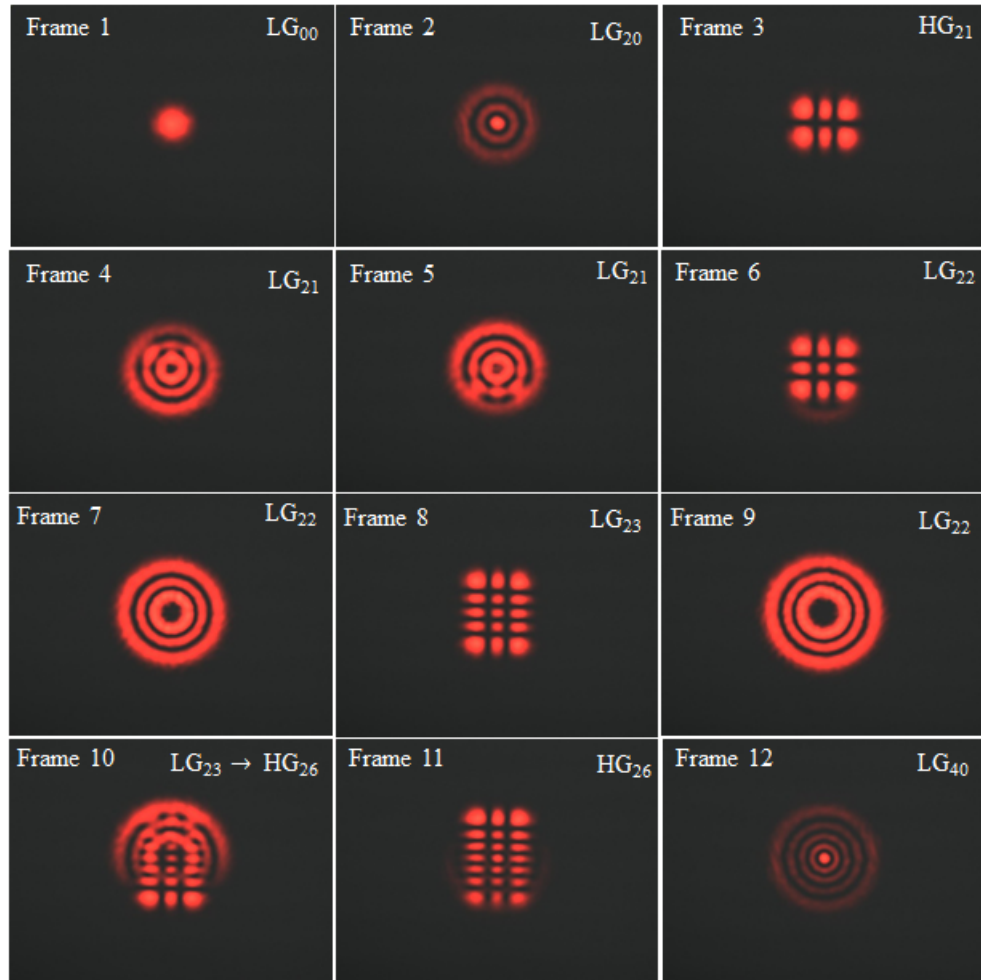


Figure 3.22: Series of 12 frames extracted from a video recorded showing rapid beam shaping.

Chapter 4

Conclusion

The focus of this work was to investigate the characteristics and properties of DMDs and implement laser beam shaping on these devices. As these devices are computer controlled and composed of pixelated micromirror arrays, laser beam shaping is implemented by means of digital holography in a similar manner to that of traditionally used LCSLMs.

In chapter 1, we reviewed the general concept underlying beam shaping and provided a brief overview of the history of shaping light. Different modern methods and instrumentation were briefly discussed, from refractive and diffractive physical optical elements, to computer controlled liquid crystal phase-only modulating SLMs, outlining their advantages and disadvantages. A review of the history, development and fabrication of DMDs was given from the first device to present models, as well as a brief time-line of its applications in fields ranging from industrial, automotive and commercial applications to research involving structured light, imaging and illumination systems.

Chapter 2 provides a detailed characterisation and calibration of DMDs. Although emphasis was made towards a particular DMD - *DLP 3000*, the analysis can be carried out to any other DMD chipset. The *DLP 3000* DMD used in this research was accompanied by additional electronics and a set of projection optical elements of which needed to be removed for use in optical experimentation. Selected physical and optical characteristics obtained from official Texas Instruments documentation are provided. From the characterisation of the surface of the DMD by interferometric methods, we have showed the surface is curved with a relatively large radius of curvature. A method of correcting for surface aberrations on the DMD is necessary. Despite various claims of the DMD acting as a blazed diffraction grating, we have shown that this is not the case, and have developed a new model that accurately describes the diffractive nature of the device. We also demonstrated the high mirror crossover rate of the device.

With the operational nature of the device taken into account, an analysis of a method of implementing amplitude and phase control of an incident beam

on DMDs was carried out in chapter 3 and we implement our findings from chapters 1 and 2 to experimentally demonstrate amplitude and phase modulation of light to create different structures of light. We successfully show this by means of generating arbitrary shapes of light such as a square, a circle and the “DMD” abbreviation; flat-top beams and spatial modes of light of high quality. We have also used the fast operational speed of the device to demonstrate rapid beam shaping.

We have successfully demonstrated the use of DMDs for structuring light via amplitude and phase control with an amplitude-only light modulating device and as such demonstrated an alternative to physical optical elements and LCSLMs. The use of DMDs for laser beam shaping provides many advantages (fast frame rates, polarisation insensitivity and cost effective) and have been applied in commercial and industrial products and used in scientific research. Despite the advantages of using DMDs, the main disadvantage of using these devices is the low first order efficiency, compared to LCSLMs. As such, the use of DMDs as an alternative to LCSLMs and physical optical elements depends on the user’s discretion. Taking into account the requirements for a desired application it is up to the user to determine a feasible solution for his/her particular application. For example, one might desire a high first order efficiency and are therefore motivated to choose LCSLMs over DMDs. Other applications require high operational speeds with less priority given first order efficiency, in which case the user will choose DMDs.

In this work we have successfully reverse-engineered a commercially sold product and demonstrated the use of the key component, DMD which is a MEMS-based device, for laser beam shaping at a very high rate. Applications of beam shaping using DMDs in high powered laser systems, digital propagation, speckle reduction and beam homogenisation will be considered in future work.

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