DEPARTMENT OF INFORMATION AND
AUTOMATION TECHNOLOGY

SHAPING OF A LASER BEAM

BACHELOR'S THESIS

Supervisor: Ing. Bc. Šárka Němcová, Ph.D.

Prague, 2023   Kaung Htet Zaw

BACHELOR'S THESIS ASSIGNMENT

I. Personal and study details

Student's name:	**Zaw Kaung Htet**	Personal ID number:	**481857**
Faculty / Institute:	**Faculty of Mechanical Engineering**		
Department / Institute:	**Department of Instrumentation and Control Engineering**		
Study program:	**Bachelor of Mechanical Engineering**		
Branch of study:	**Information and Automation Technology**		

II. Bachelor's thesis details

Bachelor's thesis title in English:

Shaping of a laser beam

Bachelor's thesis title in Czech:

Tvarování laserového svazku

Guidelines:

Review of technical solutions of laser beam shaping, with the focus on industrial applications. Design of a shaper converting the circular spot to a rectangular spot. A suggestion how to control the size of the spot. Experimental validation of the theoretical findings.

Bibliography / sources:

[1] I.R.Kenyon: The Light Fantastic, Oxford 2008
[2] E. Derniak: Geometrical and Trigonometric Optics, Cambridge 2008
[3] R. Kingslake: Optical System Design, Academic Press 1983

Name and workplace of bachelor's thesis supervisor:

Ing. Bc. Šárka Němcová, Ph.D.   Division of Precision Mechanics and Optics FME

Name and workplace of second bachelor's thesis supervisor or consultant:

Date of bachelor's thesis assignment: **27.10.2022**   Deadline for bachelor thesis submission: **26.01.2023**

Assignment valid until: _____

_____
Ing. Bc. Šárka Němcová, Ph.D.
Supervisor's signature

_____
Head of department's signature

_____
doc. Ing. Miroslav Španiel, CSc.
Dean's signature

III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

_____27.10.2022_____
Date of assignment receipt

_____
Student's signature

Declaration

I declare that I have worked on this thesis independently assuming that the results of the thesis can also be used as the discretion of the supervisor of the thesis as its co-author. I also agree with the potential publication of the results of the thesis or of its substantial part, provided I will be listed as the co-author.

Prague, ……………………………

…………………………………………………
Signature

Acknowledgement

I would like to express my wholehearted gratitude and give my warmest thanks to my supervisor Ing. Bc. Šárka Němcová, Ph.D. for her insightful comments and suggestions. Her guidance carried me through all the stages of writing my work.

Most importantly, I am forever grateful for my family's unconditional, unequivocal, and loving support throughout my study. My appreciation also goes out to my friends for their encouragement and support they gave me during my studies.

Abstract

In this bachelor's thesis, there are generally 2 big parts, a theory section and a practical section. In theory part, which is the Chapters from 1 to 5, many topics related to laser beam shaping are explained. Basics principle of a laser and ways to quantify the lasers are discussed. A thorough explanation of thin lens and comparison between spherical lenses and cylindrical can be found as well together with how to solve a system with a combination of lenses. A selection of laser beam shaping techniques are explained, including diffractive, refractive beam shaping and beam shaping using a beam integrator in terms of a pair of lenslet arrays. Multiple industrial applications of the laser beam shaping are elaborated, such as laser cutting and laser welding. In the practical part, 3 experiments are carried out to study how to shape a laser beam to get a rectangular spot, checking if the acquired laser spot is a flat top and how the width of the spot size can be changed by adding a zoom system. Plus, some insights on how to design a lens holder to hold the lenslet arrays used in the system can be found here as well.

Table of Contents

List of Figures

1) Introduction

Laser beam shaping is a process of redistributing the irradiance and phase of a laser beam to achieve a specific beam shape that is maintained along the desired propagation distance. This is accomplished via the use of various optical elements, such as diffractive optical elements, refractive optical elements, and other optical components. Common irradiance distributions include Gaussian, in which irradiance decreases with increasing radial distance, and flat top beams, also known as top hat beams, in which irradiance is constant over a given area and the difference can be seen in Figure 1. Laser beam shaping has a wide range of applications across many fields, including material processing, medicine, display technology and more. [1]
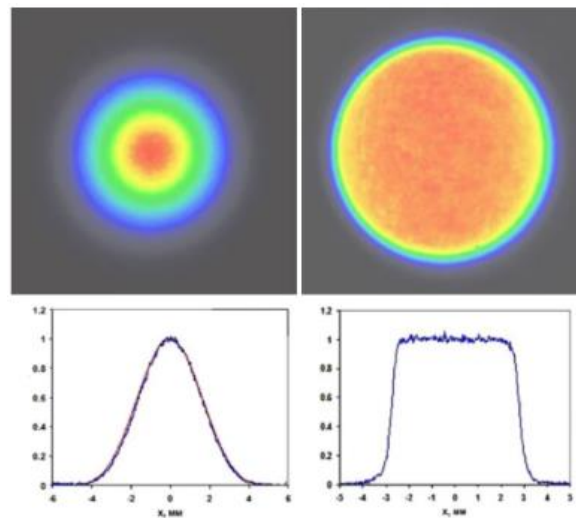
Figure 1: *Gaussian Beam Profile vs Flat Top Beam Profile*

Available at: https://www.edmundoptics.com/resource-page/application-notes/optics/laser-beam-shaping-overview/

In material processing, laser beam shaping can be used to control the shape, size, as well as the irradiance distribution of the area being processed. This allows for precise control over the material removal or modification process, enabling greater precision and efficiency. In medicine, laser beam shaping can be used in laser surgery works. Pulses from an ultraviolet laser can vaporise tissue from the lens of an eye, precisely removing just the right amount to correct vision defect. In display technology, laser beam shaping can be used to create desired projection pattern or to improve the efficiency of a display system. To see this in action, I would strongly suggest watching a video of a live performance of Martin Garrix, who is my favourite electronic dance music producer. [2]

There are several methods for achieving laser beam shaping, which includes the use of diffractive optical elements, which are used to manipulate the phase of a laser beam in order to produce a desired irradiance distribution. Other methods include the use of refractive optical elements, such as lenses, prisms, as well as light modulators which are devices that can dynamically alter the irradiance or phase of a laser beam. For instant, phase modulators achieve the changes by using thermally induced refractive index to change or stretch the length of the optical path. [10]

Overall, laser beam shaping is an important field of study within the field of optics and photonics, as it allows for precise control over the properties of laser beams, enabling them to be tailored to meet the specific requirements of various applications. The mentioned point is the one of the main reasons why I chose to write a thesis on this topic.

2) Lasers

In this chapter, I will be talking about the elephant in the room, when wanting to shape a laser beam. There will be no laser beam without the laser. Therefore, I will get technical about lasers by discussing some important topics related to lasers. I will be talking about how a laser work, how they are classified, how to measure their quality and some measurements used to describe a laser.

2.1) Principle of Lasers

Laser is actually an acronym which stands for "**l**ight **a**mplification by the **s**timulated **e**mission of **r**adiation". Each part of the phrase has a special meaning, so we will look at it one by one, starting from the final word.

Radiation stands for electromagnetic radiation, meaning a massless form of energy that travels at the speed of light. It comes in various forms, including X-ray, ultraviolet, visible light, infrared, microwaves, and radio waves. Light and other forms of electromagnetic radiation behave like both waves and particles and they are called photons. [2]

Stimulated **e**mission tells us the way lasers produce light. The sun, flames and light bulbs emit light spontaneously, in other words, on their own, in order to release extra internal energy. Lasers contains atoms or molecules that release their extra energy only when other light stimulates them. [2]

Amplification means cranking up the amount of light. During the process of stimulated emission, an input light wave stimulates an atom or molecule to release its energy as another identical wave. The stimulated wave, which has the same energy and phase as the input wave can then stimulate other atoms or molecules to emit more waves, producing more amplified light signal. Easier way to explain the process is as follows, one light photon excites or stimulates an atom or molecule so it releases an identical photon, which in turn can stimulate the emission of another identical photon, producing a cascade of photons that amplifies the light. [2]

Light describes the type of electromagnetic radiation produced. This means that the produced light is not only visible light that human eyes can see, but also adjacent parts of electromagnetic spectrum that our human eyes cannot see because it is shorter in wavelength, which is ultraviolet, or longer in wavelength, which is infrared. [2]
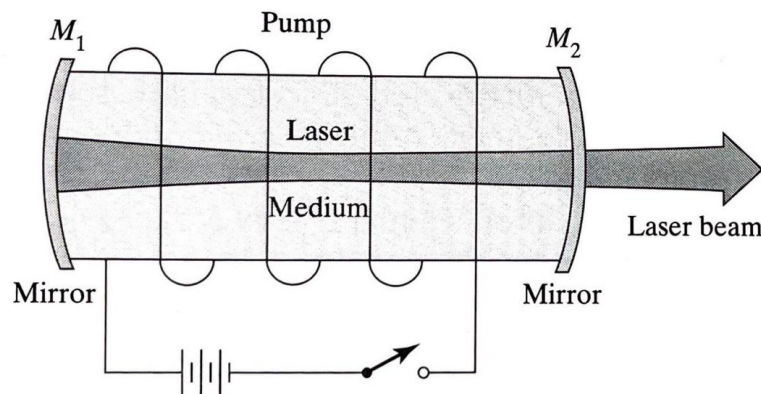

Figure 2: *Laser Construction* [3]

To generate a laser beam, a lasing medium, which is made of materials such as crystals, gases or semiconductors that can be excited to a higher energy state is needed. This lasing medium is placed within a resonator, which is a cavity that is designed to reflect and amplify the light produced by the lasing medium.

The process of stimulated emission begins when an external energy source such as an electrical current or a flash of light is used to excite the atoms or molecules in the lasing medium to a higher energy state. These excited atoms or molecules are then able to release photons of light. These photons are then reflected back and forth within the resonator, where they stimulate additional atoms or molecules to release more photons. This process continues until a sufficient number of photons has been produced to create a beam of light that is coherent and monochromatic. For the laser to be in phase, the distance of the cavity mirrors must be at a distance, d, apart:

$$d = \text{integer} \cdot \frac{\lambda}{2} \quad (1)$$

The resulting laser beam is characterised by its coherence, which refers to how well defined the phase of light waves within the beam is, and its monochromaticity, which means that the beam is composed of a single, well-defined frequency of light. These properties give laser beams a number of unique characteristics such as high intensity, directional emission, and ability to maintain precise focus over a long distance.

2.2) Gaussian Beam

Since the laser beams in many laser optics applications are assumed to be Gaussian, which usually is only valid for lasers with single transverse mode or TEM_{00} mode, we should talk about what a Gaussian beam is. Gaussian beam has an irradiance profile that follows an ideal Gaussian distribution, meaning that the intensity of the beam decreases exponentially the further it is from the centre of the beam and are symmetrical around the centre of the beam. This type of beam has a relatively uniform intensity distribution over a small central region and then falls off rapidly at the edges. The Gaussian beam profile can be seen in Figure 1.

The gaussian distribution can be described by the following equation:

$$I(r) = I_0 e^{\left(\frac{-2r^2}{w(z)^2}\right)} = \frac{2P}{\pi w(z)^2} e^{\left(\frac{-2r^2}{w(z)^2}\right)} \quad (2)$$

In Equation 1, I is the irradiance at a distance r from the centre of the beam, I_0 is the peak of irradiance at the centre of the beam, r is the radial distance away from the axis, w(z) is the radius

of the laser beam where the irradiance is $1/e^2$ (13.5%) of I_0, z is the distance propagated from the plane where the wavefront is flat, and P is the total power of the beam. [4]

Gaussian beams have a number of important properties that make them useful in a wide range of applications. They have a well-defined beam waist and relatively small divergence, which make them well-suited for applications that require a tightly focused beam such as material processing and laser-based measurement systems. A Gaussian beam remains Gaussian also after passing simple kinds of optical elements, which makes them easy to manipulate using optical elements such as lenses and mirrors without optical aberrations. They are also used as the fundamental mode of many laser resonators, as they can be easily produced and focused using lenses and other optical elements and also because of the relatively simple rules to calculate the beam propagation.

2.3) Beam Waist & Rayleigh Length
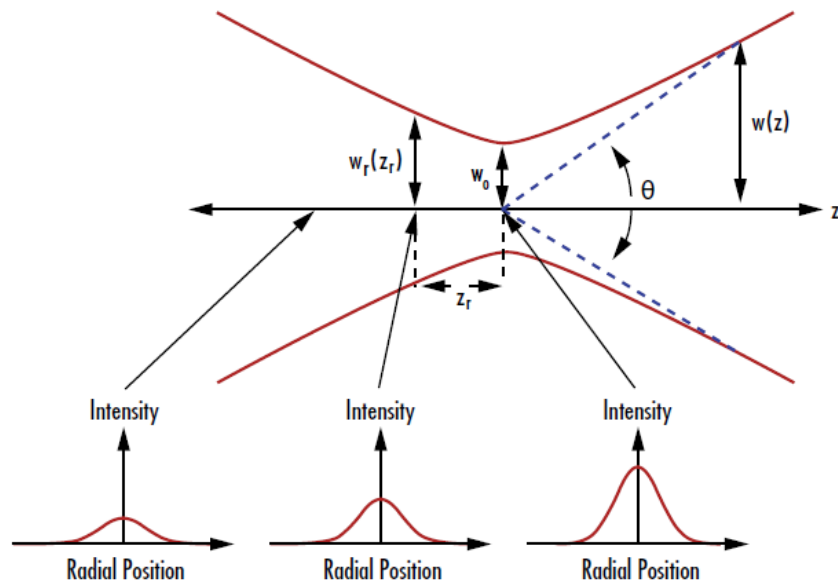
Figure 3: *Beam Waist, Rayleigh Length & Divergence* [11]

The waist of a laser beam is the narrowest point in the beam, where the radius of the beam along the propagation direction is at the minimum. The waist of a laser beam is an important parameter that determines the focusability of the beam. In general, the smaller the beam waist, the tighter is the beam focus and it can be obtained by focusing the beam using a lens with a short focal length

and more importantly, a higher numerical aperture while making sure that the lens aperture is mostly filled by the input beam. A high beam quality is also a necessary condition for tight beam focusing. The waist of the beam is also related to the divergence of the beam, which is a measure of how quickly the beam spreads out as it propagates through space. Beams with small waists tend to have smaller divergences than beams with larger waists. The relation between wavelength, λ, beam waist, w_0, and divergence, θ, can be seen in the following formula: [5]

$$\theta = \frac{\lambda}{\pi \cdot w_0} \quad (3)$$

Now let us focus on another important parameter which is the Rayleigh length. The Rayleigh length of a laser beam is the distance from the waist of the beam, in the direction of propagation, where the beam has expanded twice its original beam area. It is also the length where the beam radius is increased by a factor of square root of 2. Typically, Rayleigh length, z_R, is considered for Gaussian beam and it is determined by the radius of Gaussian ($1/e^2$) beam waist, w_0, and the wavelength, λ: [7]

$$z_R = \frac{\pi w_0^2}{\lambda} \quad (4)$$

The Rayleigh length is also an important parameter that determines the focusability of a laser beam. In general, the longer the Rayleigh length, the more distance in the direction of propagation is required for the beam to expand or contract. This knowledge can be useful in application where beam needs to be focused to a small spot size at a long distance from the beam waist, so we can tell how much the beam will expand over the long distance before reaching the focus. On the other hand, a shorter Rayleigh length means that the beam will expand or contract in a shorter distance, which can be useful in applications where the beam needs to remain focused over a shorter distance. Beams with longer Rayleigh length tend to have smaller divergences than beams with shorter Rayleigh length.

2.4) Gas Lasers (He-Ne Lasers)

Now, let us focus on gas lasers as the type of laser that I will be using the laboratory to do the measurements in the practical part of this thesis is a gas laser, more specifically a helium-neon

(He-Ne) laser. The laser-active entities are either single atoms, ions or molecules and are often used in a mixture with substances that have auxiliary functions. During the operation, the gas is often in plasma state making up of a significant concentration of electrically charged particles. Most gas lasers share many features with the generic gas laser shown in Figure 4. The laser gas medium is contained in a tube or a cavity with mirrors at each end, one totally reflective and one transmitting some light to form the output beam. Most gas lasers are excited by passing an electric current through the gas medium. The operation of a gas laser usually demands a high voltage supply but not necessarily with a high electrical power. Gas lasers can be classified depending on the nature of the lasing medium and are divided into 3 types, which are, neutral atoms, ions, and molecules. [7],[2]
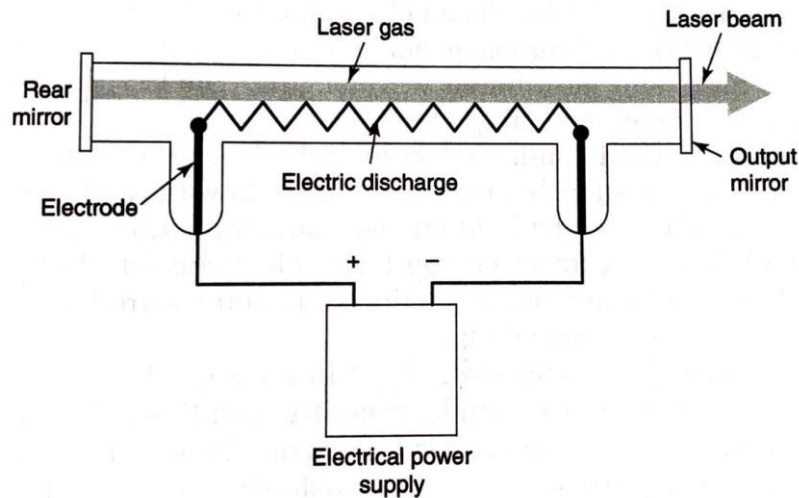
Figure 4: *Generic Gas Laser* [2]

He-Ne laser is a neutral gas laser that operates continuously and is the least expensive of all gas lasers. Most of the He-Ne lasers emit the 632.8 nm red line with excellent beam quality, which will be further discussed in the following chapter.

A direct current (DC) is supplied for the pump and the electrons are passed through the lasing medium, which is a mixture of 5 parts helium and 1 part neon, exciting both of the elements to high energy states, where the more abundant helium atoms collect most of the energy. The excited helium atoms transfer the collected energy to the neon atoms during collisions between the atoms, raising the energy of neon atoms to levels where they become metastable, meaning they stay in this state for comparatively long time, producing a population inversion. The first

He-Ne laser operated at 1153 nm, in the infrared, however, the big demand for visible beams made the 632.8 nm red line the standard for He-Ne lasers. [2]

It is important to produce population inversion for stimulated emission, which is key in making a laser work. Therefore, I will explain more about population inversion. Real atoms can have multiple energy levels but to simplify things, let us consider a population inversion between 2 energy levels. The upper level is the high energy state from which atoms drop after emitting stimulated emission. The lower level is the lower energy state into which atoms drop after emitting light. Under normal conditions, atoms are not naturally excited, meaning they will be in their lowest possible energy level, only having a few in the higher energy states. This condition is called thermodynamic equilibrium and, in this state, photons produced by the collision between atoms in the higher level will then collide with atoms in the lower level and they will be absorbed instead of being duplicated. In other words, the number of atoms, also referred to as the population of atoms, in the lower level is larger than the higher level in this state. For photons to be duplicated constantly, allowing laser action to occur, the population inversion is needed. Population inversion is when more than half of the atoms are in the excited, higher level while less than half are in the lower state. [2], [12]
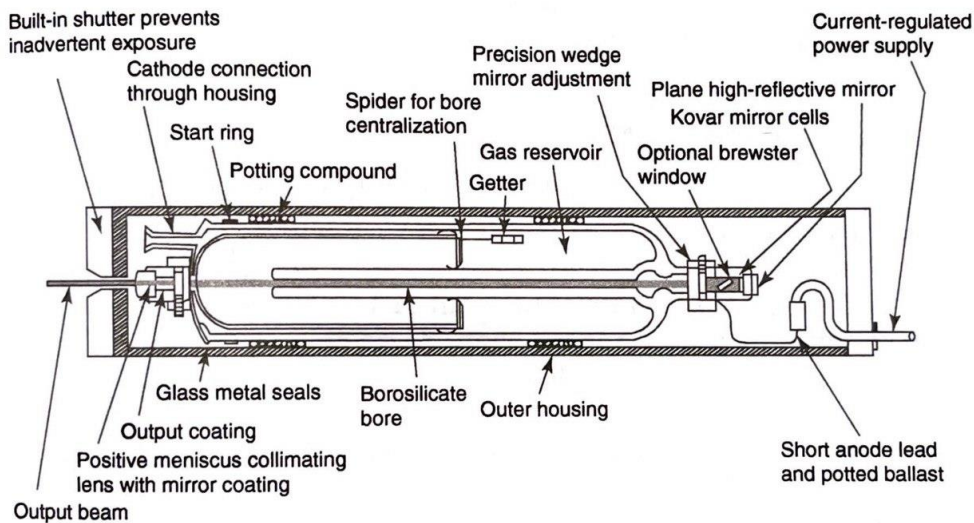

Figure 5: *Construction of He-Ne Lasers* [2]

The internal structure of a typical mass-produced He-Ne lasers can be seen in Figure 5. The discharge passing between electrodes at the opposite ends of the tube is concentrated in the narrow borosilicate bore that can be from one to a few millimetres in diameter. This helps in

maintaining good beam quality and rises efficiency of laser excitation. The majority of the tube is a gas reservoir for extra helium and neon. The rear mirror is totally reflective while the output mirror transmits just a small percentage of the intracavity power to produce the output beam. One or both mirrors have concave curvature to focus the beam inside the laser cavity that is crucial for good beam quality. The output power of He-Ne lasers depends on the diameter of the discharge bore, gas pressure inside the tube, and tube length. The other visible wavelengths such as 543 nm as green, 594 nm as yellow-orange, and 612 nm as red-orange has weaker output power compared to the red line. [2]

One of the main advantages of He-Ne lasers is their coherence and spectral stability. They are able to maintain a constant output power over long periods of time, which makes them well-suited for applications where precise, long-term measurements are required. He-Ne lasers are also easy to maintain, making them a popular choice for many scientific and industrial applications. They are commonly used in construction alignments, as well as in research labs for a variety of purposes.

2.5) Beam Quality

Beam quality, a term which has been used a lot in this chapter, is an important subject, but to measure "quality" quantitatively can be hard as different applications has different requirements. For some applications in measurement, the vital factor is a smooth beam intensity profile, the pattern of power distribution across the beam. For material processing applications like laser machining, the important factor is 'power in the bucket', which is the amount of power delivered within a limited area, such as the welding zone. [2], [8]

The most common way to quantify beam quality are M^2 factor and Beam Parameter Product (BPP), which will be discussed more in detailed in the following chapter. Low values of BPP and M^2 factor means a high beam quality. Another way to quantify a beam's quality is power in the bucket, which describes how much laser power is integrated over a specified "bucket", a target area, most often a spot with a specified radius at the surface of material being processed. Similar to M^2 factor and BPP, lower value of power in the bucket corresponds to a higher beam quality. [9], [8], [2]

In general, high beam quality implies a smooth wavefront, meaning that collimating the beam with a lens, results in a focus with plane wavefronts. Any distortions of the wavefront due to poor quality optical elements, diffractions at apertures or lenses with spherical aberrations can affect the beam quality. [8]

A high beam quality can be crucial in area of laser material processing such as cutting, drilling, and marking where strong focusing of a beam is required. For cutting, a relatively high beam quality allows to have a long working distance, which is hugely desired in order to protect the optics against debris and fumes. Besides that, high beam quality reduces the beam diameters in a beam delivery system, allowing the use of smaller optical elements resulting in a cheaper beam delivery system. [8]

2.6) Effect of BPP and M^2 Factor to Beam Waist Diameter and its Position Behind the Lens

Before talking about the effect of BPP and M^2 factor on the beam waist and the position of it behind the lens, let me explain what BPP and M^2 factor are. BPP can be defined as:
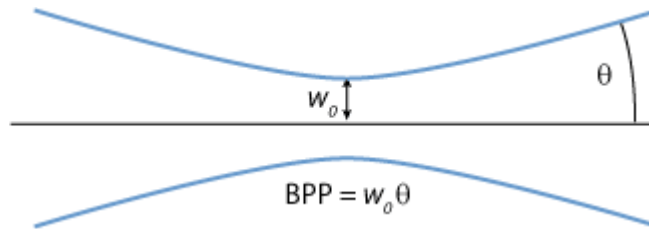
$$BPP = w_0\theta = \frac{M^2\lambda}{\pi} \quad (5)$$

Figure 6: *BPP*

Available at: https://www.rp-photonics.com/beam_parameter_product.html

Where, w_0 is beam waist, θ is half-angle beam divergence. Its relation to M^2 can be seen in Equation 5 as well. BPP is directly proportional to M^2 and the larger the BPP, the worse the beam is. The minimum value of BPP is 0.339 mm-mrad and is of a diffraction-limited Gaussian beam with wavelength of 1.064 μm. The ideal value of BPP can be defined as λ/π. [2], [11]

M^2 factor basically compares the true shape of a beam to that of a Gaussian beam. M^2 factor is defined according to ISO standard 11146 as:
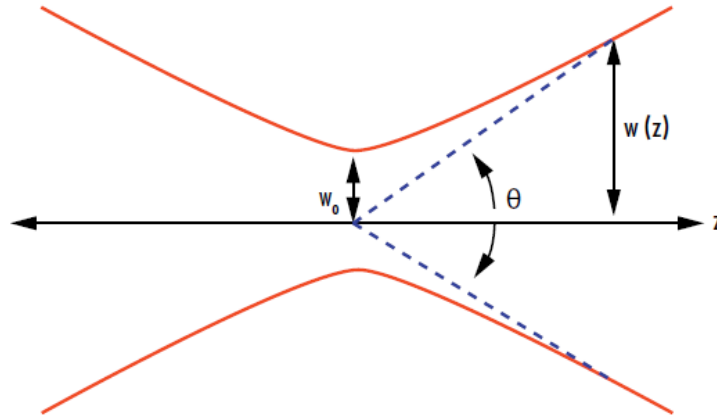
$$M^2 = \frac{\pi w_0 \theta}{\lambda} \quad (6)$$

Figure 7: *M^2 Factor* [11]

Over here, θ is the divergence angle of the laser. The minimum value is 1 for a diffraction-limited Gaussian beam. M^2 factor larger than 1 means there is some deviations from being an ideal Gaussian beam, while a value less than 1 cannot be achieved. M^2 factor is important as it shows how well a laser beam can be focused for a given divergence. Lower M^2 factor values relate to tighter focus, larger potential effective power of the laser and more efficient use of power within the beam. There is a disadvantage to characterise laser beams with M^2 factor compared to other beam quality parameters because it emphasises more on the lower-power density parts of the beam, which are located furthest away from the centre, making it better suited for academic settings rather than industrial applications. [11]

Knowing the value of BPP and M^2 factor of the beam used can allow us to determine where the beam waist will be and its size. In general, a laser with low BPP and M^2 factor value will have a smaller waist diameter and be more focused, while a laser with high BPP and M^2 factor value will have a larger waist diameter and be less focused. Focusing laser beam tightly is particularly important when the laser is being used for manufacturing and imagining as smaller beam waist means that higher power density can be reached, as well as getting a better resolution. [13]

3) Optics

After talking about the laser, we should focus on the theory of the important instruments that will be used to shape the laser beam, which are the lenses. I will explain some important concepts regarding lens, such as how a lens works by explaining it in simplified version as a thin lens, optical apertures and theory behind what happens when combining different type of lens.

3.1) Thin lens (Spherical & Cylindrical Lenses)

In the laboratory experiments I will be using a couple of spherical and cylindrical lenses to steer and focus the laser beam to achieve a particular shape. Spherical lenses come in different shapes and sizes. However, to simplify things when drawing the diagrams and doing ray tracing, and some calculations, the thickness of the lens is neglected. This allows us to represent a lens with a line like in Figure 8. It is important to notice where the arrows on the sides are pointing, if they are pointing outwards, it is a convex lens and if it is pointing inwards, it is a concave lens, it is illustrated in Figure 9.
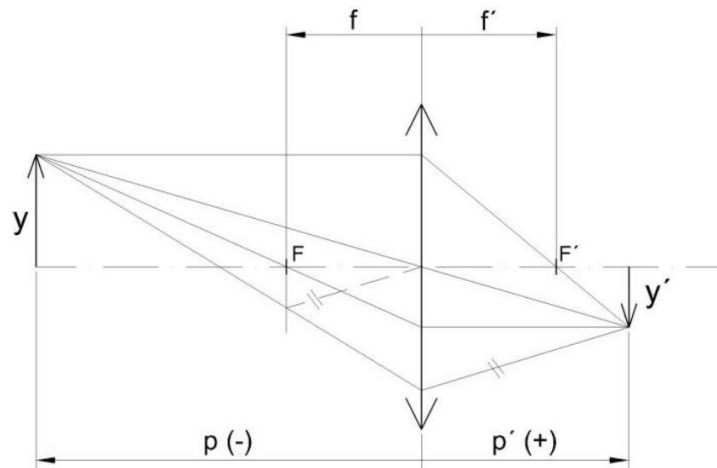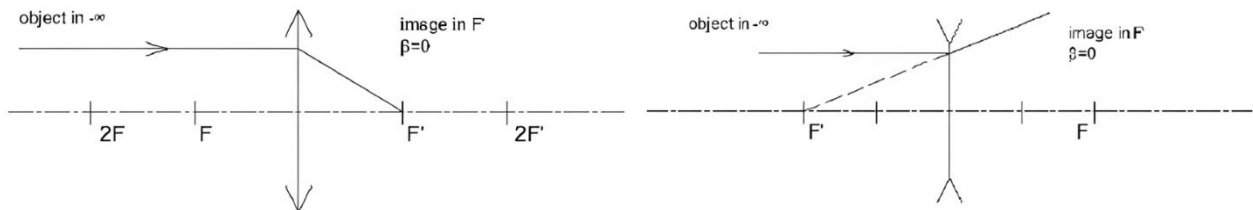

Figure 8: *Thin Lens* [14]

Figure 9: *Convex and Concave Lens* [14]

In Figures 8 and 9, y is the size of the object, y' is the size of the image, p is the object distance, p' is the image distance, F is front focal point of the lens and F' is the back focal point of the lens, while f and f' are front and back focal distances respectively. There is a very important equation that we need to know when dealing with thin lens and it is as follows:

$$\frac{1}{p'} - \frac{1}{p} = \frac{1}{f'} \quad (7)$$

In optics, thin lens is lens that has thickness, d, that is neglectable compared to the radii of curvature of lens, R_1 and R_2, while the lens with the thickness that is not neglectable are called thick lenses.

Lenses come in many shapes and the common ones are, convex, we also called it positive or converging lens, concave, we also call it negative or diverging lens, plano-concave or plano-convex, where one side of the lens is flat and meniscus convex or concave, where both sides of the lens are not flat but they curve to the same side. The different types of lenses are shown in Figure 11. They are used in many optical devices such as spectacles or glasses, cameras, telescope, microscope, and the list goes on.
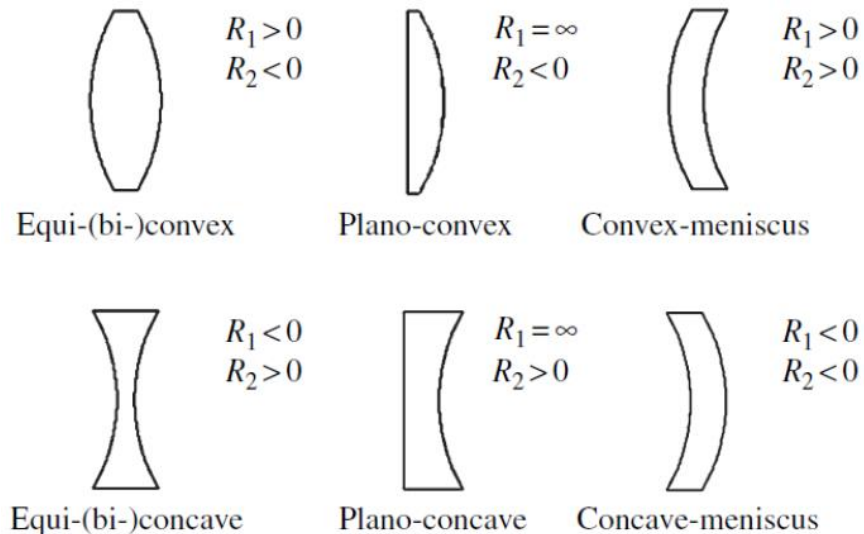

Figure 10: *Types of Lenses* [14]

I will now mention the difference between spherical and cylindrical lens. Basically, spherical lenses can be imagined as lenses that are cut or made from round pieces of glass, while cylindrical lenses are cut or made from cylindrical rods of glass. This can be seen in Figure 11.
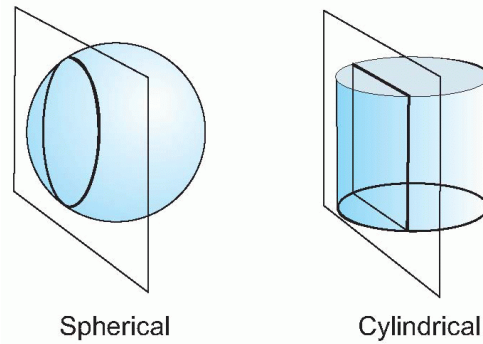
Figure 11: *Spherical vs Cylindrical Lenses* [14]

Spherical lenses focus light onto a single point, which is the focal point of the lens. Meanwhile, cylindrical lenses focus light in only one direction, either horizontal or vertical. They are used to create a thin line of light or to stretch an image in one direction. Thus, when we combine 2 cylindrical lenses and place them in particular order, we can create different types of shapes. Their orientation and how they are places play a big role in getting the desired shape needed. I will be discussing further about their use in laser beam shaping in Chapter 4.

3.2) Optical Apertures

Another important thing to consider when designing an optical system is the optical apertures. Optical apertures limit the amount of light that enters into the system as well as the field of view of the system. For example, within an optical system, there may be an optical component with limited size, such as lenses with a certain diameter. Light outside of that diameter cannot get through into the system. Optical apertures can have both positive and negative effects to the performance of an optical instrument. A negative example can be when truncating a laser beam, hard apertures can cause features like diffraction rings causing the beam quality to be reduced. On the other hand, it can be used to increase the image quality of a camera by preventing light from propagating through the regions of the lens where spherical aberration would be excessive, in the form of a diaphragm or objective of the camera. There can be hard aperture and soft aperture. Most optical apertures are hard apertures, meaning that they either allow full transmission of light or fully block the light within the area of the hole. Soft apertures allow spatial variation of transmissivity, for example, Gaussian apertures allow light to be transmitted through with a profile that can be described by Gaussian function.
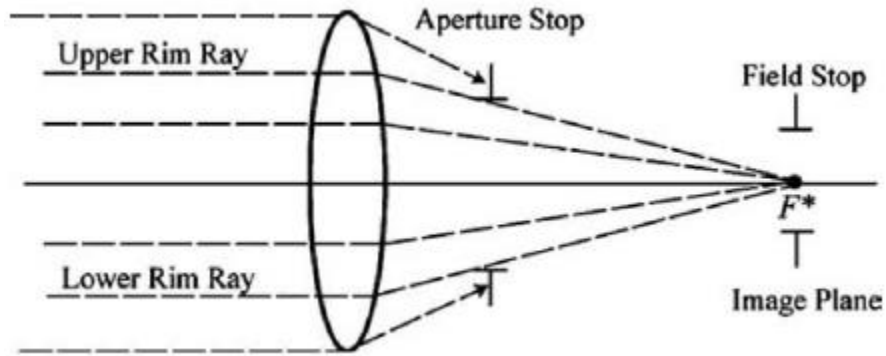
Figure 12: *Optical Aperture* [14]

3.3) Combination of Lenses

In many applications, the lenses are used in sets where multiple types of lenses are used in combination. When combining different kinds of lenses, the resulting system will have combined properties of the individual lenses. The way in which the lenses interact with each other and the light passing through them will depend on the specific characteristics of lenses and the way they are arranged. One common way to combine the lenses is to use them in series, with one lens positioned in front of another. In this configuration, the first lens will refract the light and focus it onto a specific point and the second lens will refract the light again and focus it onto a different point. In general, combining different kinds of lenses allows us to create a more complex optical system with a wide range of focusing properties.
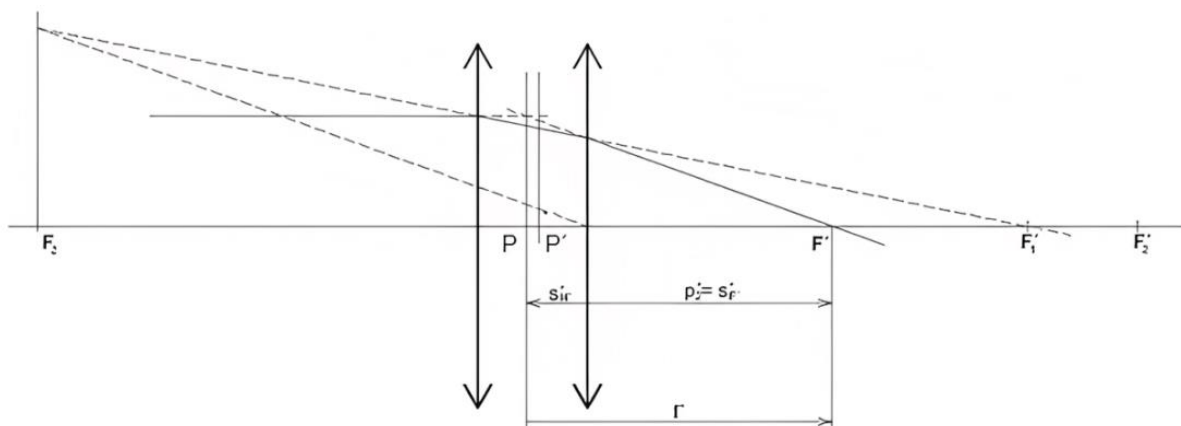

Figure 13: *Combination of Lens* [14]

For example, when combining 2 positive thin lenses, the resulting focal length is different from that of both of the positive lenses. This new focal length is called effective focal length and it can be calculated by knowing the thin lens equation and studying Figure 13. By knowing Equation 7 and that the incoming beam is a beam of parallel rays, we can say that $p_1 = -\infty$ and can find out that $p_1' = f_1'$. Then we need to solve for the second lens and we can find out p_2 by studying the Figure 13 and it is:

$$p_2 = p_1' - d = f_1' - d \quad (8)$$

By plugging in the p_2 value into the lens equation of the second lens, value of p_2' can be found:

$$p_2' = \frac{p_2 f_2'}{p_2 + f_2'} = \frac{f_2'(f_1' - d)}{f_1' - d + f_2'} \quad (9)$$

Finally, the effective focal length is as follows:

$$f' = \frac{p_1' p_2'}{p_2} = \frac{\frac{f_1' f_2'(f_1' - d)}{f_1' - d + f_2'}}{f_1' - d} = \frac{f_1' f_2'}{f_1' + f_2' - d} \quad (10)$$

The equivalent optical power of 2 thin lenses separated by air is as follows: [14]

$$\varphi = \varphi_1 + \varphi_2 - d\varphi_1\varphi_2 \quad (11)$$

4) Laser Beam Shaping and Steering

Now we can go in more detail on the theory behind how a laser beam is being shaped and steered. What optical components are used and what are the different techniques that are used in the industry? I will be giving all the answers to that question in this chapter.

4.1) Uses of Cylindrical Lenses and Lenslet Arrays in Laser Beam Shaping

Cylindrical lenses are commonly used to shape and manipulate a laser beam, mainly to correct an asymmetric beam, create a line or generate a light sheet. Another application is to circularise the elliptical output from a diode to create a collimated and symmetric beam. To achieve a

rectangular shape, 2 cylindrical lenses need to be arranged in order as in Figure 14. To achieve a circular shape, 2 cylindrical lenses need to be arranged as in Figure 15. [15]
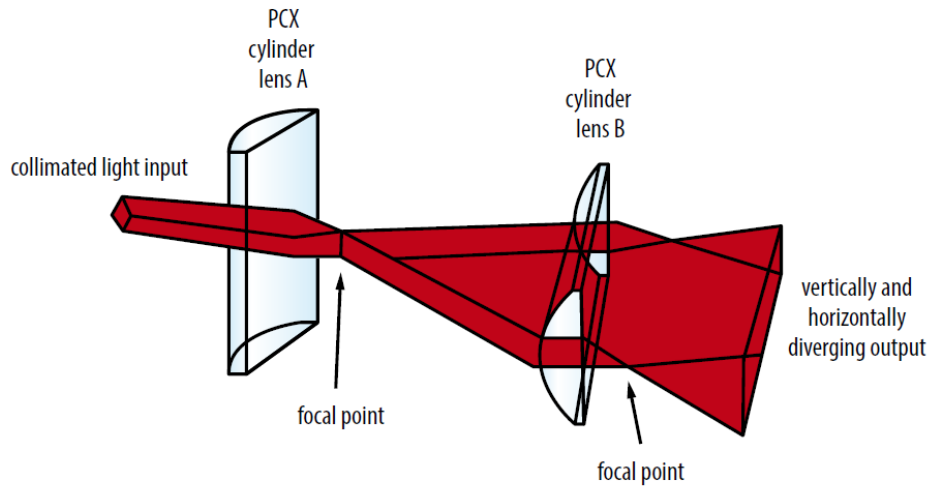

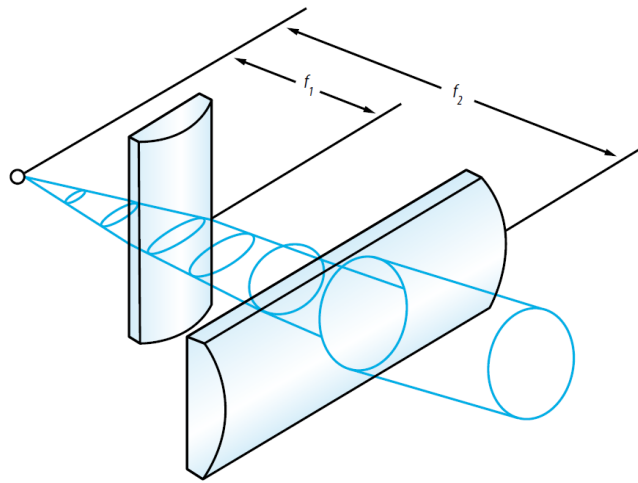Figure 14: *How to Get Rectangular Shape* [15]

Figure 15: *How to Get Circular Shape* [15]

Lenslet array is an optical component that contains several individual small lenses arranged and aligned precisely to make up one component all together. The lenses are usually spherical lenses but there could be arrays with cylindrical lenses as well. They are commonly used to control the phase of a laser beam spatially and also to collimate a laser beam. Typically, arrays are used in pairs and in the figure below, it is used in an imagining illumination system to smooth out the nonuniformities from the light source. [16], [17]
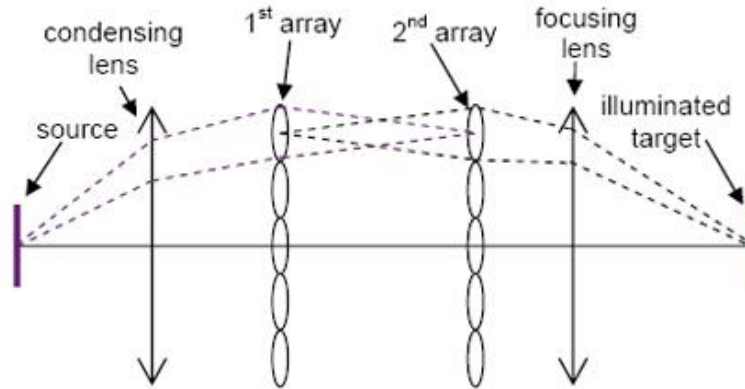
Figure 16: *Lenslet Arrays Application Example* [17]

4.2) F-Theta Lens and Galvo Mirrors for Steering

F-Theta lens can deliver the highest performance in laser scanning or engraving systems. These lenses are perfect for material processing, image transfer, engraving and labelling systems. A planar image is ideal for many laser scanning and engraving applications in order to achieve the best results. Only along a circular plane can be imaged by a spherical lens, it can be seen in Figure 17 A. This issue can be fixed by using flat-field scanning lenses. The displacement of the beam, however, is dependent on the product of the effective focal length, f, and the tangent of the deflection angle, θ, which can be seen in Figure 17 B. [18]

While the right software algorithms can account for this nonlinear displacement, producing a linear displacement is the best option. Barrel distortion is a feature of f-theta lenses that produces displace that is linear with θ, which is shown is Figure 17 C. This straightforward response eliminates the need for intricate technological correction and enables a quick, reasonably cheap, and small scanning system. [18]

Many of the issues with laser scanning are resolved by f-theta lenses. Additionally, the f-theta lens's compact structure enables the user to use fewer optical components to produce a flat image plane. These lenses are able to produce smaller spot sizes, which translates into better scanning or printing resolutions as well as better engraving or welding intensities. The most significant aspect is that the spot size's resolution and intensity are almost consistent across the entire image plane. [18]
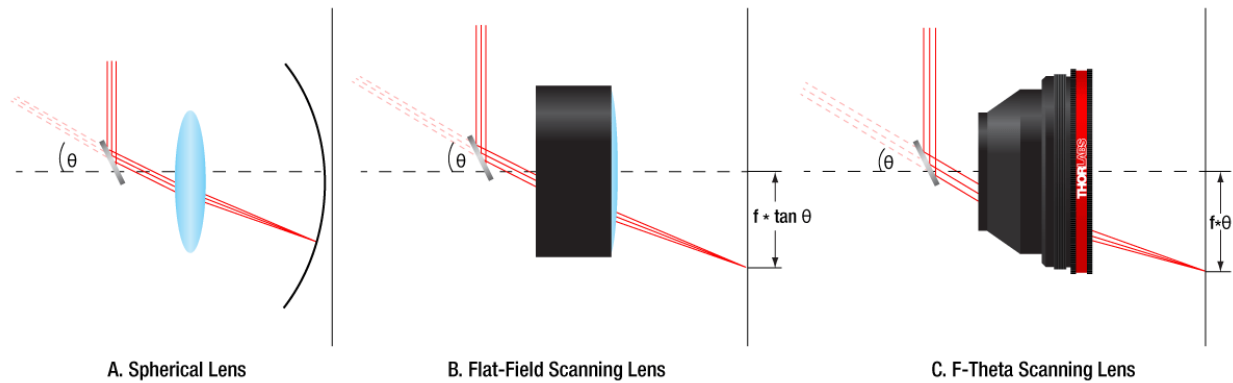
A. Spherical Lens
B. Flat-Field Scanning Lens
C. F-Theta Scanning Lens

Figure 17: *Comparison Between Some Lenses for Scanning* [18]

A galvo mirror is a small, fast-moving mirror that is used to steer a laser beam. It is frequently used in scanning and other applications where precise control of the laser beam is necessary. The galvo mirror comprises of a small mirror mounted on a galvanometer, which is a type of electric motor that is designed to rotate the mirror swiftly and precisely. The mirror is mounted on a pivot point and the galvanometer is used to move the mirror back and forth in a certain direction, causing the laser beam to be deflected in that direction. The laser beam can be directed by a pair of galvo mirrors in any direction within a specific range. The performance of the laser scanning system is significantly influenced by the speed and precision of the galvo mirrors.

In order to increase their reflectivity and endurance, galvo mirrors are often coated with a dielectric layer and composed of a high- reflective material, such as aluminium or gold. They are often mounted on a sturdy platform to ensure precise and reliable functioning and are made to work with a certain wavelength of light.
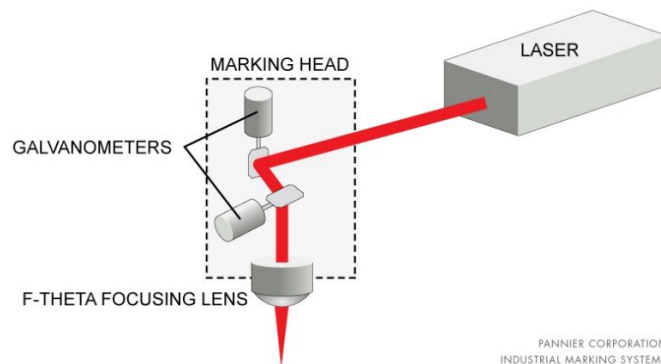

Figure 18: *Galvo Mirrors and F-Theta Lens Used Together*

Available at: https://www.pannier.com/laser/flatbed-vs-galvo-lasers/

4.3) Diffraction

Diffraction is an important phenomenon to know when dealing with laser and how it can change the energy distribution in the beam or light wave. Diffraction is a process where waves, such as sound and light waves, bend and spread out when they come into contact with something or pass through a gap. When a wave encounters an obstacle or passes through an opening, it is scattered in many directions, causing the wavefront to bend and spread out. This can result in patterns of constructive and destructive interference, which can affect the intensity and distribution of the wave. The size of obstruction or opening in relation to the wavelength determines how much diffraction occurs. The smaller the obstruction or opening, the more pronounced the diffraction for the same wavelength.

During the diffraction process, the energy of the wave is distributed over a larger area. The intensity and distribution of the energy in the wave can be impacted by patterns of both constructive and destructive interference caused by diffraction. While destructive interference happens when 2 waves cancel each other out, constructive interference happens when 2 waves merge to produce a wave with a bigger amplitude. These patterns can result in changes in the energy distribution of the wave. This is the reason why there are regions with light, caused by constrictive interference, and then there are regions that are dark, caused by destructive interference, in Figure 19.
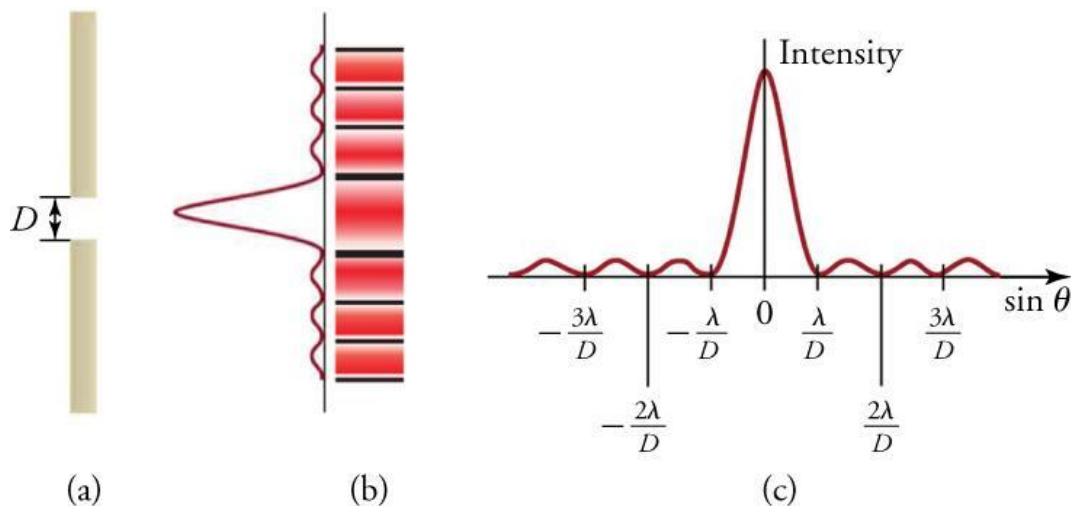

Figure 19: *Diffracted Light Intensity Distribution*

Available at: https://www.texasgateway.org/resource/171-understanding-diffraction-and-interference

4.4) Techniques

Now let us discuss about different techniques available to shape and steer a laser beam. I will highlight 3 techniques that are commonly used in the industry. They are refractive beam shaping, diffractive beam shaping and beam shaping using laser beam integrators.

Refractive beam shaping can be used in low-performance systems when cost is a deciding factor. Gaussian beams may be physically truncated by an aperture to generate a pseudo-flat top profile. Although this is ineffective and wastes energy on Gaussian profile's outer parts, it reduces system complexity and expense. [11]

Laser beam shapers that are either diffractive or refractive are frequently used in higher-performance applications that demand greater efficiency. The irradiance and phase profile of laser light are often redistributed in these assemblies using field-mapping elements, such as aspheric or freeform lenses and diffractive elements. An illustration of the layout of a refractive field mapper that uses wavefront distortion and the energy conversion condition to convert a Gaussian beam profile to a flat top profile is shown in Figure 20. In a Galilean or Keplerian lens assembly, the incident beam's amplitude and phases are altered after passing through both elements. Within the boundaries of the design, the resulting beam shaping is extremely effective (>96% throughput) and wavelength independent. Flat phase fronts and uniformly distributed irradiance are made possible by refractive beam shaper. [11]

However, because the lens will modify the beam profile, focusing a flat top beam through a lens will not produce a flat top profile at the final focused spot. Instead, when a flat top spot is required, field mappers are employed to transform Gaussian beams into collimated Airy disc profiles, which after being focused by diffraction-free lens, generate flat top spots. [11]
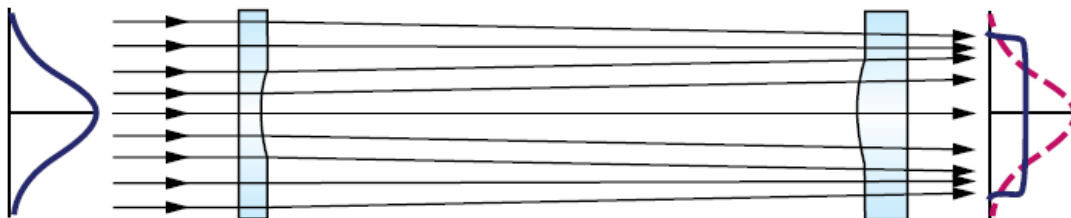

Figure 20: *Example of Refractive Beam Shaping Using Field Mapping* [11]

Diffractive beam shapers modify the laser beam into a certain irradiance distribution by using diffraction rather than refraction. Etching is a technique used by diffractive elements to make a

specific micro- or nanostructure in a substrate. Usually, the height and zone spacing have an impact on the element's function and design wavelength. Therefore, it is crucial to use a diffractive optical component at their designated wavelength to prevent performance issues. Diffractive elements are also more reliant on alignment, divergence, and beam position in the plane of the nominal working distance compared to refractive beam shapers. However, since the diffractive optical elements often consist of a single element rather than a number of refractive lenses, they are far more favourable in laser setups with limited space. [11]

A laser beam integrator or homogenizer is composed of a number of lenslets that divide the beam into an array of smaller beams or beamlets, accompanied by a lens or other focusing element that superimposes the beamlets at the target plane. Example of this case is illustrated in Figure 21, where a lenslet array, marked as L1, and f-theta lens are used in combination to form a flat top beam. Both coherent laser light and other incoherent light sources can be employed with them. The sum of the diffraction pattern determined by the lenslet array typically represents the final output beam profile. A homogenised flat top profile is produced by most laser beam integrators using incident Gaussian beams. Typically, random irradiance fluctuation in beam homogenizers cause an imperfectly flat beam profile. For incident light that is spatially incoherent, non-diffraction-based beam integrators like imagining integrators or waveguides are also feasible.
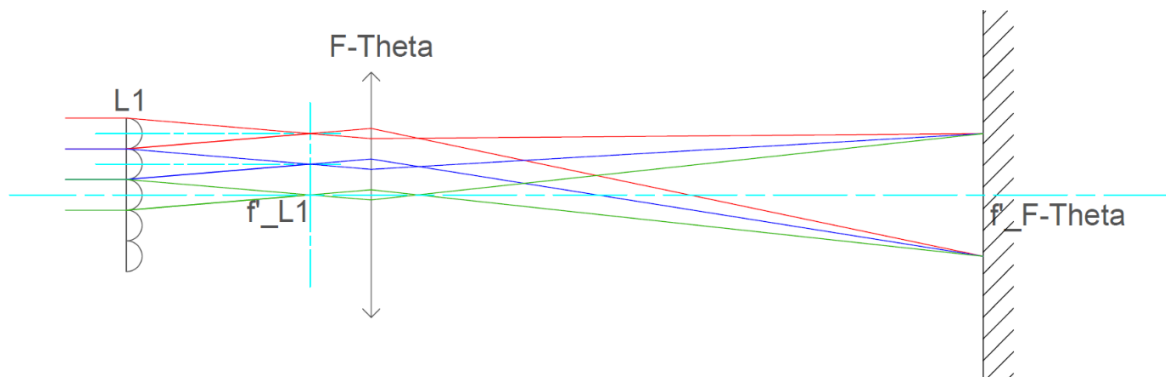

Figure 21: *Combination of Lenslet Array and F-Theta*

In the figure below, the comparison between the techniques I mentioned is shown.

	Refractive	Diffractive	Beam Integrators
Shaping Principle	Deterministic	Deterministic	Random or quasi-random
Random Fluctuations	Low	Low	High
Alignment Sensitivity	Low	High	High
Output Beam Uniformity	High	Medium-high	Low
Cost	High	Medium	Low
Footprint	Large	Small	Small

Figure 22: *Comparison of Typical Beam Shaping Techniques* [11]

5) Laser Material Processing

Now that we have gone through the theory behind the terms that are important and components and techniques that are used in laser beam shaping, let us delve deeper into how laser beam shaping is applied in real life. There are many applications but I will focus only on 3 applications and they are laser machining, laser welding and laser marking. Each of them falls into different category of laser processing, which we will discover in this chapter.

5.1) Laser Machining

The term "machining" exclusively refers to subtractive material processing methods, which means that it falls under the category of selective removal of some material. Laser machining includes laser cutting and drilling and these are the 2 processes that I will be focusing on in this topic. [19]

Laser cutting, which involves separating solid parts by creating a narrow gap, which is also known as kerf and it can be seen in Figure 23. Various types of metals, such as steel, titanium alloys, brass, copper, and aluminium, as well as ceramics, glasses, semiconductors and other crystals are among the materials that can be cut using a laser. Few alternative cutting techniques would be available for some of those materials, while others would be in direct competition with conventional methods like punching or plasma cutting. Even in those industries, laser cutting is gradually becoming more crucial because of some hard steels used in automobile production that allows for lighter solutions, which have issues being punched by punching machinery. [19], [20]
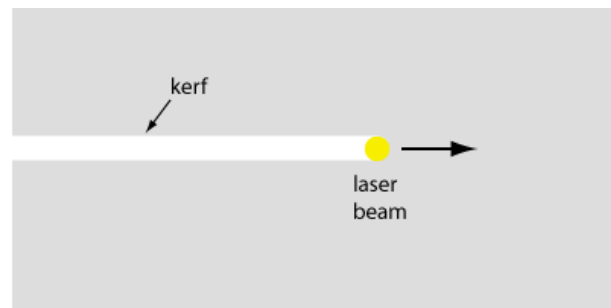

Figure 23: *Laser Cutting* [20]

Solid-state lasers have mostly substituted carbon dioxide (CO_2) lasers, but CO_2 lasers are still widely used, especially for cutting thick metal sheets since they are strong, durable and power efficient. They are frequently used for cutting other materials as well, particularly those with low heat conductivity and high long-wavelength radiation absorption. Nowadays, diode-pumped solid-state laser are widely utilized, particularly for precision machining. They frequently have pulses with nanosecond durations, but they also can have pulses with picosecond or even femtosecond durations. [20]

Typical advantages of laser cutting include the non-contact process, which avoids the deterioration of mechanical tools in particular, and practical integration into sophisticated computer-controlled machinery, which produces high speed and significant flexibility. One disadvantage of laser cutting is high electricity consumption compared to mechanical tools, such as punching, nevertheless, the consumption is still considerably lower than plasma cutting. [20]

Laser drilling is a process of producing holes. It is typically used for holes up to a few millimetres in diameter, but it is also frequently used for much smaller sizes, below 100 μm, and in extreme cases, even for sub micrometre holes, it is considered as micro-drilling at this point.

They either penetrate some metal plates completely or only to a certain, preferably well-defined depth, so called blind holes. Although they can be manufactured at multiple angles, the holes are commonly produced perpendicularly to the surface of the workpiece. Similar to laser cutting, a wide variety of materials, including metals, as well as very hard metals, like stainless steel or titanium alloys, ceramics, glasses semiconductors and some crystals can be processed. Alternative drilling techniques are frequently unavailable for such materials. [21]
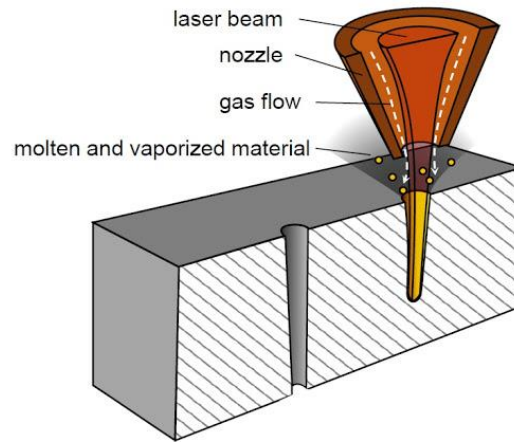

Figure 24: *Laser Drilling*

Most of the time, laser drilling is carried out using pulsed lasers, usually nanosecond lasers. For instance, one may apply a peak intensity of 10^9 W/cm^2 for 20 ns at a workpiece. This results in a pulse energy of about 6 mJ, for example, if the laser beam radius is 100 μm. Therefore, with the exception of very small holes, millijoules pulses are typically required. Drilling involves pulsed solid-state nanosecond lasers, such as Q-switched lasers, most frequently. Ultrafast lasers are deployed more and more for the finest processing results, like smallest holes with highest processing quality. A few examples of fairly remarkable outcomes made possible by the ongoing performance improvements include the multi-beam drilling of thousands of sub-micrometre holes per second. [21]

The advantage of laser drilling is that it can be used to create very small holes with a high aspect ratio, which is the ratio of length to diameter, where it would be challenging with traditional mechanical methods. Additionally, for delicate materials that might fracture when subjected to mechanical processes, it is often the primary option. [21]
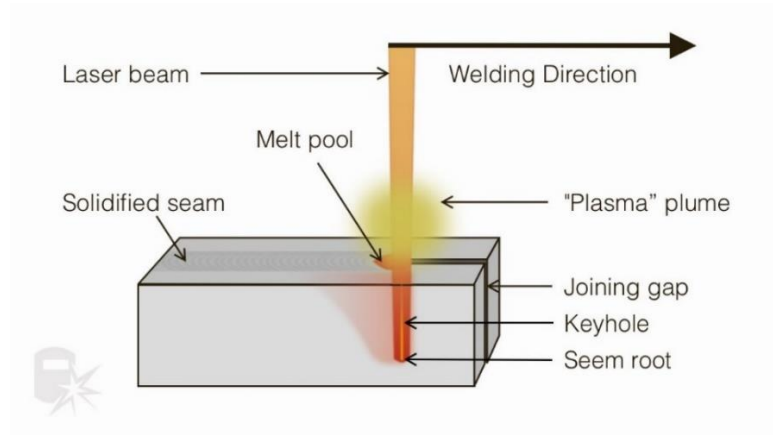
5.2) Laser Welding

Figure 25: *Laser Welding*

Available at: https://weldguru.com/laser-welding/

Laser welding falls under the category of joining materials. In the case of laser welding, the heating process is carried out by absorbing laser light, which enters the workplace as a laser beam. Most of the time, laser radiation, often infrared, is continuous when the beam or workpiece is moved slowly, while sometimes laser pulses, such as those produced from TEA CO_2 lasers, ae used. Laser welding is one of the most crucial methods used in industrial material processing. Although it can be used with many different metals, not all technologically important metals are suitable for welding. Some materials have a tendency to develop seams that are of low quality, which are difficult to improve even with advanced technologies. There are many alternative welding geometries that can be used, each having its own benefits and drawbacks, such as preparation efforts, accessibility, and mechanical stability realised. Metal components can be joined, for instance, by placing them face to face, or alternatively with some overlap, after the faces have been bent, or at a 90° angle. In other instances, it is applied to cylindrical parts with closed-path seam. [22]

Infrared lasers are typically used for laser welding. Although pulsed lasers are applied in some welding applications, continuous-wave operation is useful in many applications. High-power CO_2 lasers are still commonly utilised, especially for large machinery. [22]

Some of the advantages of laser welding is that it can be used in challenging situations involving intricate shapes or combination of different materials and clean and narrow seams can be obtained with less post-processing to provide high quality results. Although frequently superior

to those of more traditional techniques like arc welding or resistance welding, the outcomes of laser welding are typically not flawless. Common flows or imperfections include voids, such as tiny gas pores or large voids, can emerge in the seam, for example, if the volume is not completely filled with melt before it hardens. Also, the seam itself may crack. Such voids have the potential to seriously reduce the seam's mechanical strength. Besides that, the top and bottom surfaces could be convex or concave rather than completely flat. For instance, a convex shape develops when the groove is only partially filled due to and excessively big gap. How the components were initially oriented can have a significant impact on such details as well. [22]
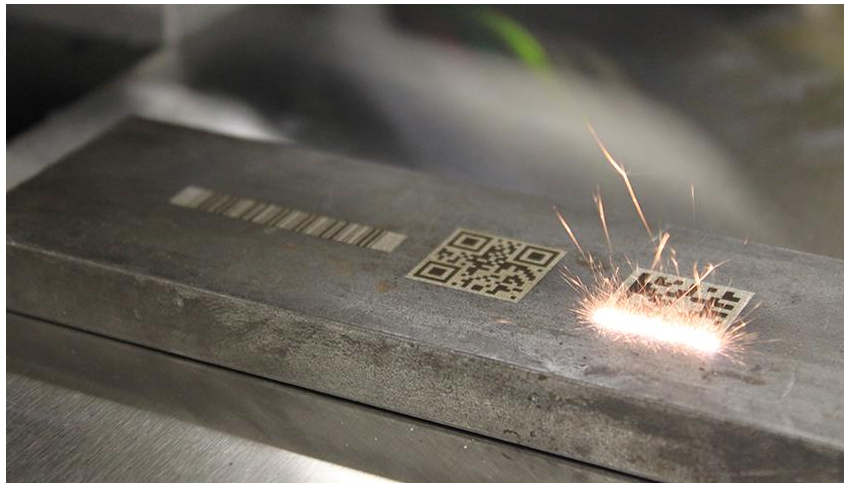
5.3) Laser Marking

Figure 26: *Laser Marking*

Laser marking falls under the category of producing visible structure in laser material process. Using a laser to label various types of things is a common method known as laser marking. The basic idea behind laser marking is that a laser beam either ablates a material or modifies the optical appearance of the surface it hits. A lot of industrial products, including machine tools, printed circuit boards (PCBs), integrated circuits, cables, keyboard button, credit cards, food packages and bottles, must have labels with model and serial numbers, logos, bar codes, expiry dates and other information on them. Frequently, the details of the labels must vary for every single item, making a simple stamping impractical. [23]

CO_2 lasers with relatively low-power seal are often used to mark plastic, wood, cardboard, paper, leather and acrylic. Here, continuous-wave operation is usually practical. Due to low absorption at their long wavelengths, around 10 µm, CO_2 lasers are less suitable for metallic surfaces. Instead, laser wavelengths in the 1 µm region, which can be obtained, for example, with lamp- or diode-pumped Nd:YAG, neodymium-doped yttrium aluminium garnet, typically Q-switched or with fibre lasers, are more suitable. Metals are typically marked with pulsed solid-state lasers of moderate average power, while ceramics, paper, cardboard, and wood are frequently marked with CO_2 laser. [23]

In comparison to other marking technologies like ink jet printing and mechanical marking, laser marking offers a number of benefits, including extremely fast processing speeds, low operation costs, since consumables are not required, consistent high quality and durability of the results, prevention of contaminations, the ability to write incredibly small features, and high automation flexibility. However, it frequently calls for quite pricey laser marking equipment. [23]

6) Practical Work

Here I will be mentioning all the experiments I did for the thesis to see if the theory and what happens in real life match. I will also be discussing the lens holder design that made to hold the lenslets arrays used in the experiments.

6.1) Getting a Rectangular Spot

In this section, I will be showing how a rectangular spot can be achieved by using 2 sets of cylindrical lenslet arrays and see if their relative position can affect the spot size. Rectangular spot can be achieved by arranging the 2 cylindrical lenslet arrays as in Figure 14. By studying the figure closely, we can see that the first lenslet array affects the width of the spot while the second lenslet array affects the height of the spot. Before going to the lab, I made some calculations to see what affects the width and height of the spot. The calculation is made based on the knowledge from geometrical optics, by drawing the scenario, comparing the triangles, formed in the drawing, and also using the lens formula. The drawing I made can be seen below:
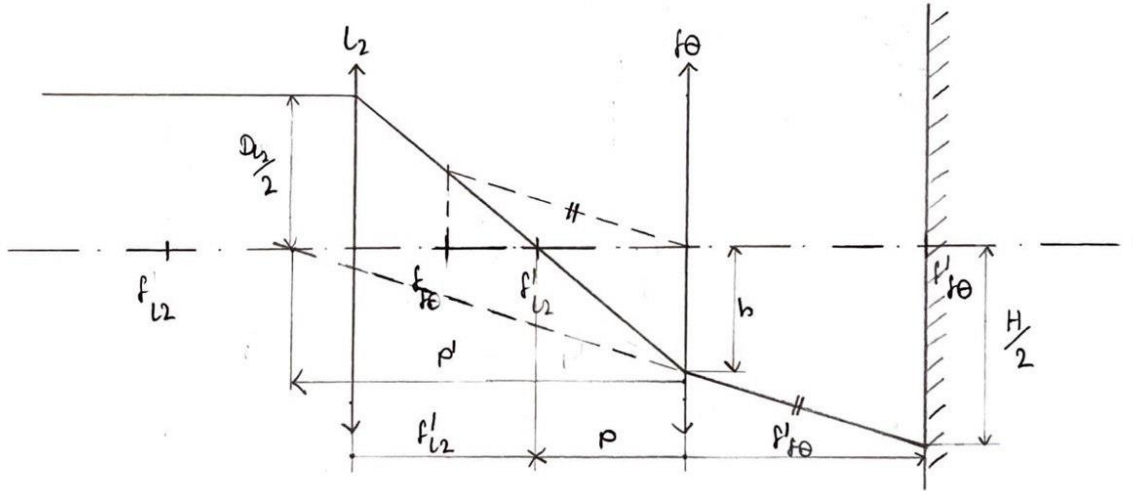
Figure 27: *Drawing for Calculation*

I only included L2, which is the second cylindrical lenslet array, to see what affects the height and the drawing's perspective is from the side. Here, fθ stands for f-theta lens. In the drawing, I did not project the beam of parallel rays to the edge of the lens to make the drawing looking nicer but it is assumed in the calculation that the part that the parallel beam bends is the edge of the lens. That is why the distance of the beam from the centreline is marked as $D_{L2}/2$. The calculation is as follows:

$$\frac{1}{p'} - \frac{1}{p} = \frac{1}{f'_{f\theta}}$$

$$p' = \frac{f'_{f\theta} \cdot p}{p + f'_{f\theta}} \dots \{1\}$$

$$\frac{\frac{D_{L2}}{2}}{f'_{L2}} = \frac{h}{-p}$$

$$h = \frac{-pD_{L2}}{2f'_{L2}}$$

$$p = \frac{-2hf'_{L2}}{D_{L2}} \dots \{2\}$$

$$p' = \frac{f'_{f\theta} \cdot \frac{-2hf'_{L2}}{D_{L2}}}{\frac{-2hf'_{L2}}{D_{L2}} + f'_{f\theta}} = \frac{\frac{-2hf'_{L2}f'_{f\theta}}{D_{L2}}}{\frac{f'_{f\theta}D_{L2} - 2hf'_{L2}}{D_{L2}}} = \frac{-2hf'_{L2}f'_{f\theta}}{f'_{f\theta}D_{L2} - 2hf'_{L2}} = \frac{2hf'_{L2}f'_{f\theta}}{2hf'_{L2} - f'_{f\theta}D_{L2}} \dots \{3\}$$

$$\frac{h}{-p'} = \frac{\dfrac{H}{2}}{f'_{f\theta} + (-p')}$$

$$p' = \frac{2hf'_{f\theta}}{2h - H} \quad ... \{4\}$$

Equations {4} and {5} can be equated to one another:

$$\frac{\cancel{2h}f'_{f\theta}}{2h - H} = \frac{\cancel{2h}f'_{L2}f'_{f\theta}}{2hf'_{L2} - f'_{f\theta}D_{L2}}$$

$$\cancel{2hf'_{L2}} - f'_{f\theta}D_{L2} = \cancel{2hf'_{L2}} - Hf'_{L2}$$

$$H = \frac{f'_{f\theta}D_{L2}}{f'_{L2}} \quad ... \{5\}$$

Cylindrical lenses only effect the rays in 1 direction. When looking at the system from the side, as in my drawing, we can see the height of the spot size and the first cylindrical lenslet array can be treated as a plane parallel plate. To see the width, we need to draw the system from above, and this time, the second cylindrical lenslet array becomes a plane parallel plate. Therefore, in each side, we are only dealing with a set of 2 lenses, for example, one of the 2 cylindrical lenslet arrays and the f-theta lens. This is the reason why we can say that for the width, we can just substitute L2 with L1 in the equation for height, in equation {5} getting the following equation:

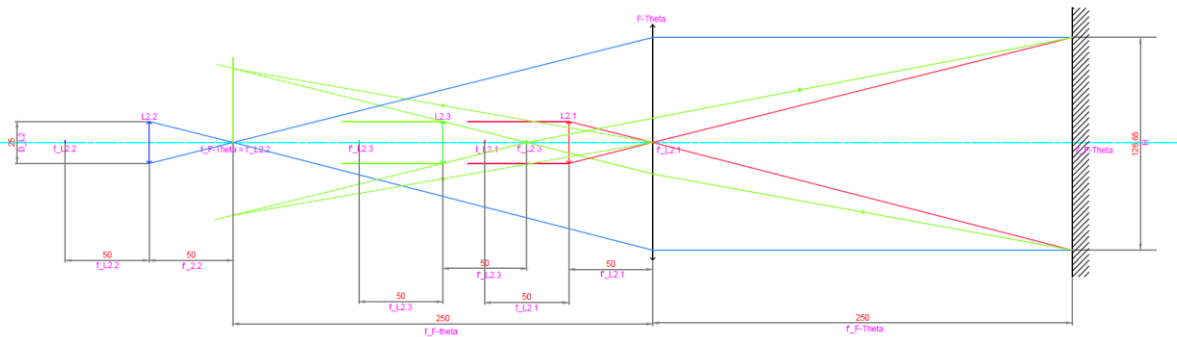$$W = \frac{f'_{f\theta}D_{L1}}{f'_{L1}} \quad ... \{6\}$$

Figure 28: *Effects of Different Positions of the Lenslet*

From the equations {5} and {6}, we can see that the width and height of the spot size is only affected by the focal lengths of the 2 cylindrical lenslet arrays and f-theta lens and the diameter of each cylindrical lens in the lenslet arrays. This means that the positions of the 2 cylindrical lenslet arrays and f-theta lens affect neither the width nor the height of the spot size. This is proven by doing some ray tracing in AutoCAD and it can be seen in the Figure 28. The ray tracing is done to scale with some chosen values for the focal lengths and diameter of lenses. Therefore, the picture is quite long so I will put it vertical in the Appendix section, page b, to view it clearer.

I set up the following setup to see the difference between the calculated and measured values of the spot size to show that the equations work and I also played with the position of the lenslet arrays along the optical axis and it does not change the size of the spot size.
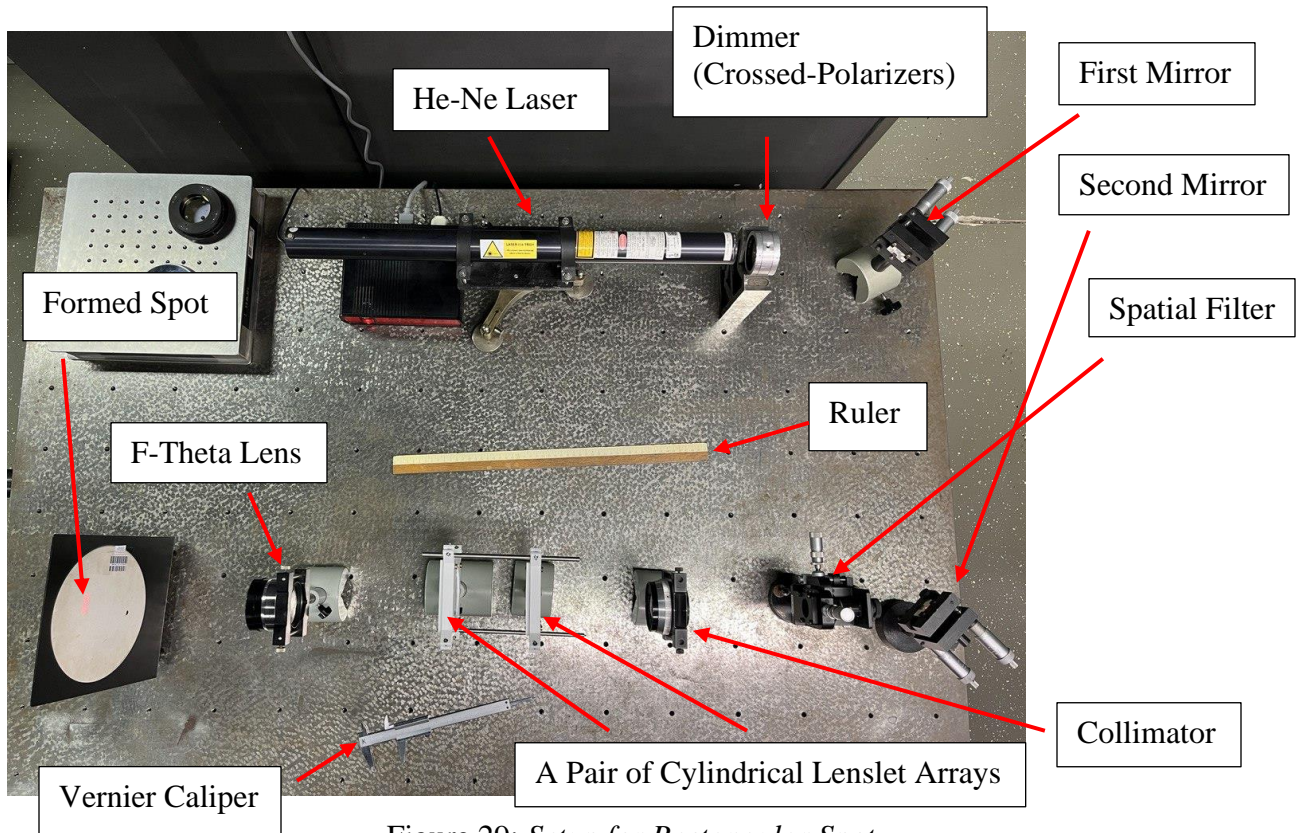

Figure 29: *Setup for Rectangular Spot*

The parameters are as follows:

Focal length of first cylindrical lenslet array, $f'_{L1} = 44$ mm

Focal length of second cylindrical lenslet array, $f'_{L2} = 115$ mm

Width of 1 cylindrical lens in the array, $D_{L1} = D_{L2} = 5$ mm

Focal length of f-theta lens, $f'_{f\theta} = 250$ mm

The calculated values, which are calculated using the formulas {5} and {6}, and the measured values can be seen in the table below:

	Height, H [mm]	Width, W [mm]
Calculated values	10.87	28.41
Measured values	10.5	28.5

Table 1: *Rectangular Spot Size Values*

We can see that the calculated and measured values are almost identical just a small difference which can be caused by observational random error such as when reading the measurement, I did not mark the spot size accurate enough or the beams not travelling as expected because of dust or not perfectly cleaned surface in the optical instruments used. The difference can also be caused by the high sensitivity of alignment of the system used to shape the beam as mentioned in Chapter 4.4 about the beam integrators, which is the use of lenslet arrays.

There is an important point to note from this chapter. It is the reason why the spot is sharp at the back focal plane of the f-theta lens and its size is not affected by the position of the lenses. The reason for this is that the sharp spot we are seeing is not the image of the system, but rather the exit pupil of the system. Besides that, it is also good to know that the aperture stop of the system is the width of the lenslet arrays.

6.2) Zoom Feature to Change Width of the Spot

To change the width of the spot, focal length of one of the cylindrical lenslet arrays need to be changed. To do that I will be adding another cylindrical lenslet array, but this one is a negative cylindrical lenslet array. It will be placed behind the first positive cylindrical lenslet array which is responsible for the width of the spot. For calculations, it means that we just need to change the focal length of L1, the first one of the 2 positive lenslet arrays, to the effective focal length of combination of L1 and LZ, $f'_{L1,LZ}$. From Equation 10, I can get the following:

$$f'_{L1,LZ} = \frac{f'_{L1} \cdot f'_{LZ}}{f'_{L1} + f'_{LZ} - d} \cdots \{7\}$$

Where, d is the distance between L1 and LZ. Equation {7} can be plugged into Equation {6} to figure out the important parameters to the zoom feature. In this experiment, I will be measuring the width of the spot but will observe the difference between the measured and calculated values of d. For calculation, the following equation is used:

$$W = \frac{f'_{f\theta} \cdot D_{L1}}{f'_{L1,LZ}}$$

$$f'_{L1,LZ} = \frac{f'_{f\theta} \cdot D_{L1}}{W}$$

$$\frac{f'_{L1} \cdot f'_{LZ}}{f'_{L1} + f'_{LZ} - d} = \frac{f'_{f\theta} \cdot D_{L1}}{W}$$

$$f'_{L1} + f'_{LZ} - d = \frac{f'_{L1} \cdot f'_{LZ} \cdot W}{f'_{f\theta} \cdot D_{L1}}$$

$$d = f'_{L1} + f'_{LZ} - \frac{f'_{L1} \cdot f'_{LZ} \cdot W}{f'_{f\theta} \cdot D_{L1}} \cdots \{8\}$$

I made some ray tracing drawings, with some chosen values for the focal length of the lenses but it was drawn to scale, to see the effects of adding the extra lens to confirm my theory. The Figure 31 illustrates it but as in the previous chapter, it is quite unclear because of the small size so I will add the vertical, bigger and clearer version in the Appendix page a. LZ is the name I will be using for the new lens that is being added to the system, where Z stands for zoom as I am calling it a zoom feature to change the width of the spot.

I drew another version to see if the results are similar to when the LZ is placed after the back focal length of L1. It does not give the same effect as in the first case, the effect is inverted. It can be seen in Figure 32. However, it will be a bit compact and hard to see so I will put it a bigger, clearer version in the Appendix page c.

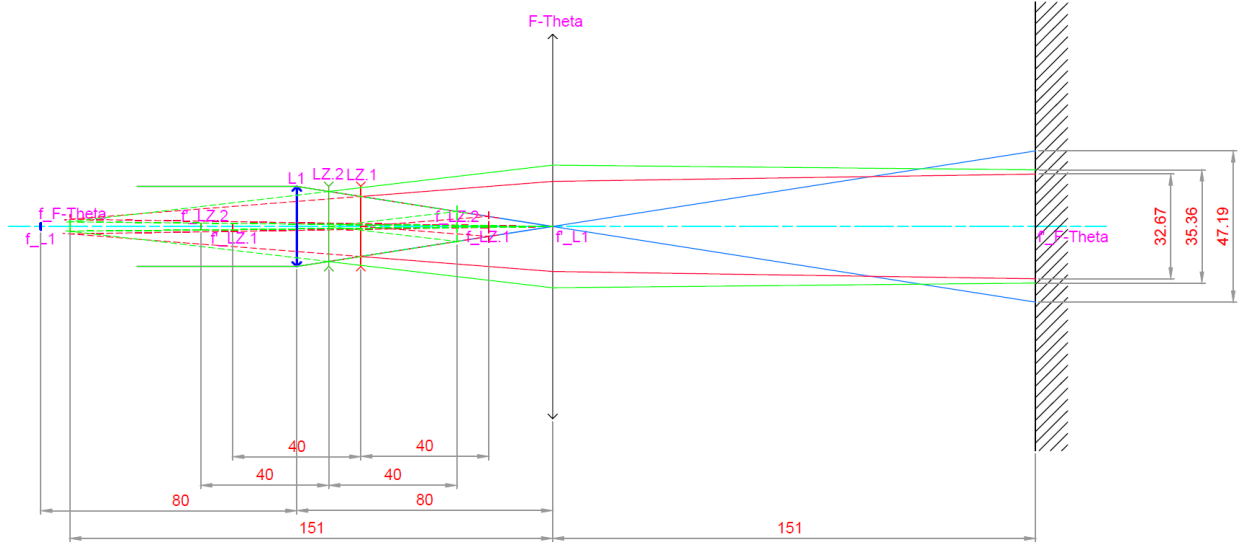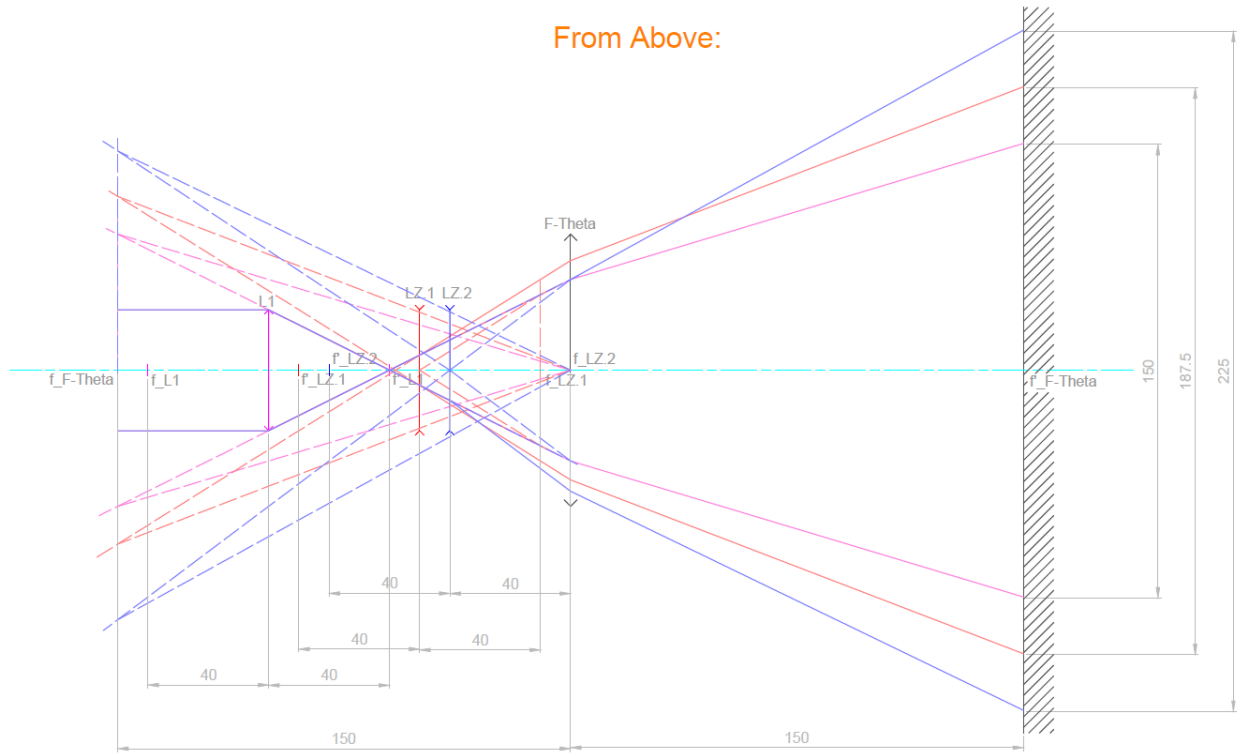Figure 30: *Effects of LZ Before f' of L1*

Figure 31: *Effect of LZ after f' of L1*

From the 2 figures above, we can see that the effect is dependent on where the LZ is placed with respect to L1. Therefore, we need to know if the LZ is place before or after the back focal point of L1, f'_{L1}, to know the effects it will make when changing its position. For this experiment, I

34

used almost the same the set up as in Figure 31 to carry out the experiments with the zoom feature. The only difference from the other setup is the addition of the zoom lens and I will put a close-up picture of the 3 cylindrical lenslet arrays in the lens holder I designed, which will be discussed in the following chapter. The zoom lens is the one in the middle.
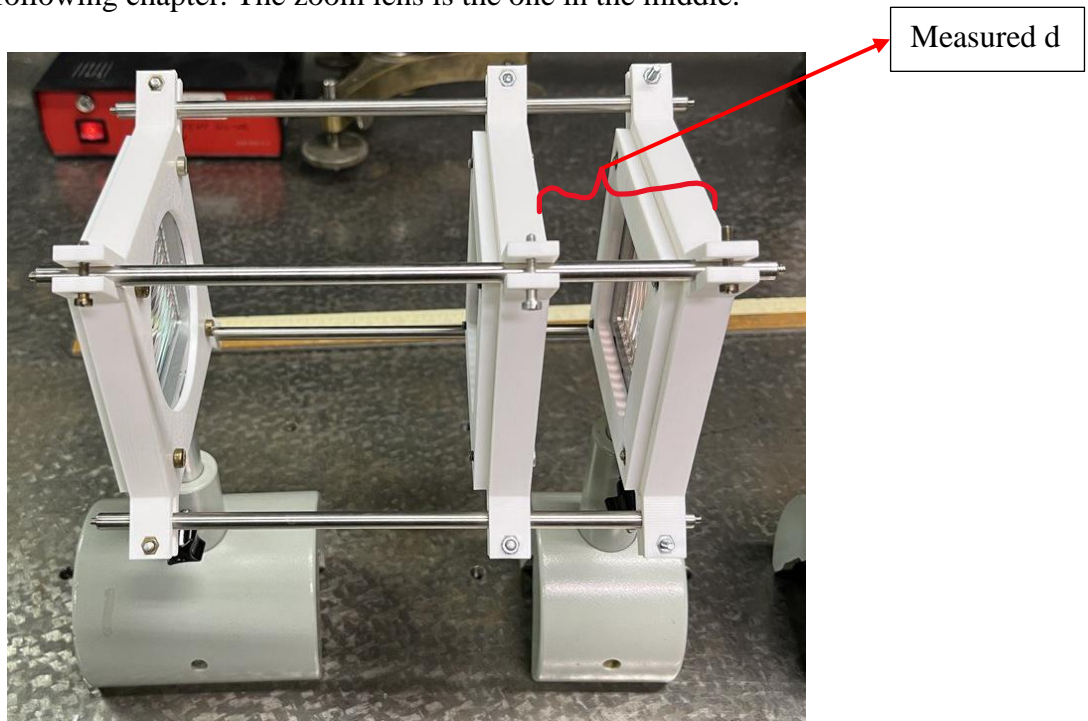

Figure 32: *Zoom Feature*

There are some things to keep in mind for this part of the experiment, the result obtain is not very accurate because, we could not find the focal length of the negative cylindrical lenslet array used because it is harvested from other devices and it is hard to find out the focal length of a lenslet array. It being a negative lenslet array makes it even harder to measure and find out the focal length of it. I calculated the value of the focal length based on the change of d we measured. The value I got in the end was -57 mm for focal length of the negative cylindrical lenslet array. Another thing is that the measured value of d is not the actual distance between the distance of the principal planes of the lenslet arrays because I cannot tell exactly where the principal plane is located for the measurements and I measured the distance between the front face of the lens holder to the front face of the other lens holder, I made some illustration of it in Figure 32.

The known values of the experiment are as follows:

Focal length of L1, $f'_{L1} = 44$ mm

Focal length of f-theta lens, $f'_{f\theta} = 250$ mm

Diameter of one cylindrical lenslet, $D_{L1} = 5$ mm

Supposedly known value but I had to calculate:

Focal length of LZ, $f'_{LZ} \approx -57$ mm

Measured values:

Width of spot, W [mm]

Measured distance between L1 and LZ, d_m [mm]

Calculated values:

Calculated distance between L1 and LZ, d_c [mm]

The results are as follows:

Width of spot, W [mm]	Calculated distance between L1 and LZ, d_c [mm]	Measured distance between L1 and LZ, d_m [mm]
33	53.21	50
30.5	48.20	45
28	43.18	40
25.5	38.16	35
23	33.15	30
20.5	28.13	25

Table 2: *Measured and Calculated Values of d*

The resulting data presented here must be taken with a grain of salt because of the uncertainties mentioned above. However, it proves the theory and the ray tracing I made, as we can see that the width of the spot increases as the distance between L1 and LZ increases. The crucial point to note is that in the experiment, the LZ positioned that I measured are the ones behind the f' of L1,

as the L1 has a relatively small focal length and because of my holder design that does not allow me to get the lens too close to each other, I cannot measure the other case.
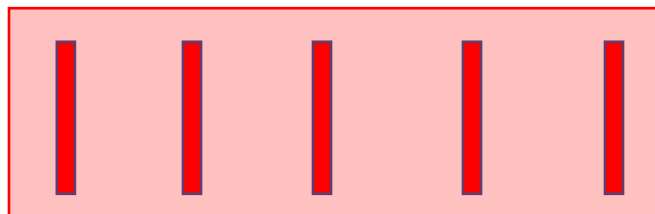
The values of d in terms of W are plotted in the following graph:
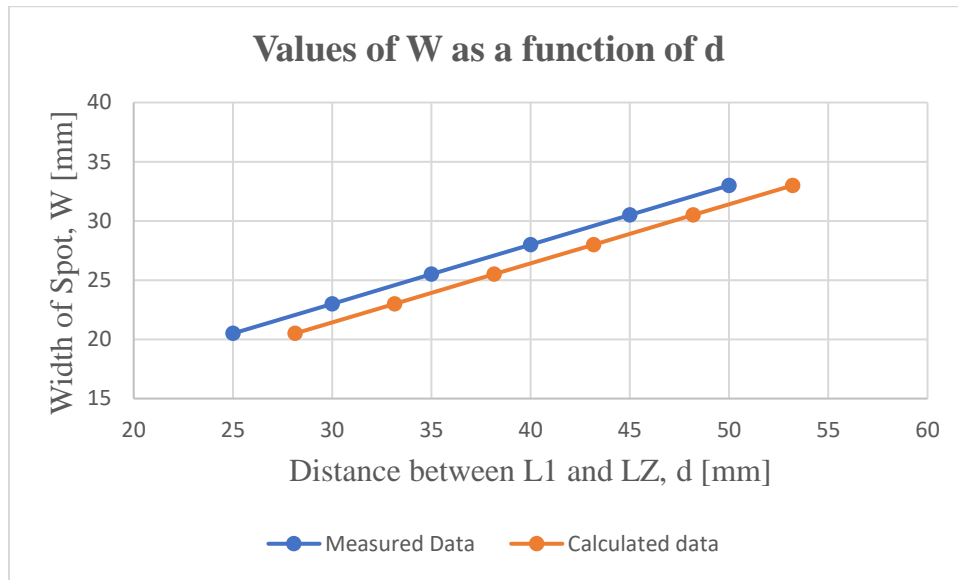
6.3) Proving the Spot is a Top Hat

To show that the spot formed is indeed a top hat, we used a digital light meter to measure the intensities of small areas across the spot. The setup of the measurement can be seen in Figure 33. I measured the following regions, marked in dark red, of the spot size:

Where I will name the measured regions by numbers from left to right and the measured intensity values can be seen in the following table:

Measured region	1	2	3	4	5
Measured intensity [nW]	700	660	640	610	670

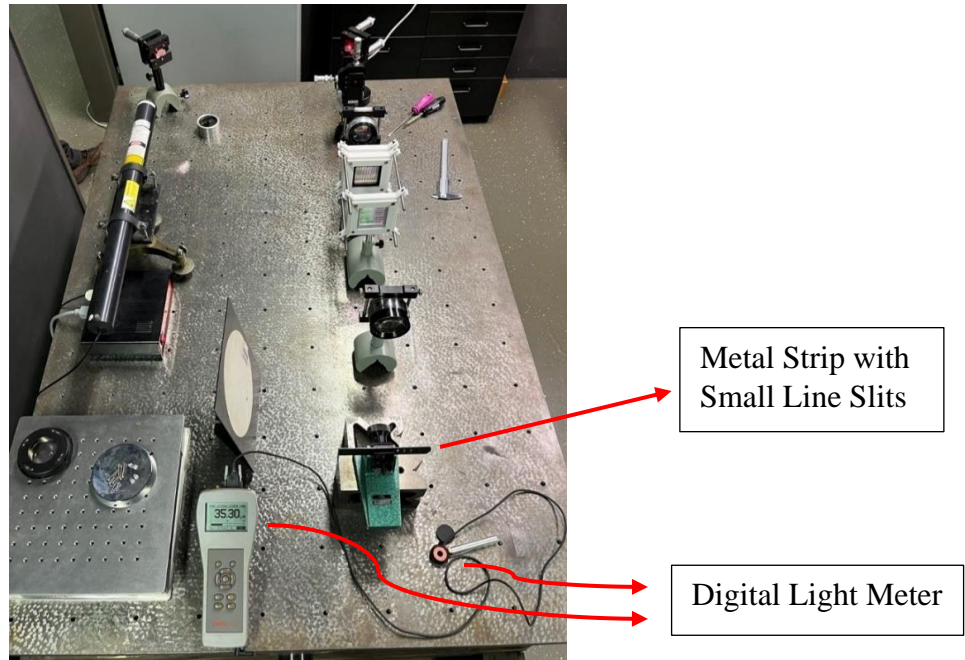Table 3: *Intensities of Different Regions on the Spot*

Figure 33: *Top Hat Spot Measurement Setup*

According to the measurements, we can say that the spot is actually a top hat because the intensities across the spot are relatively close. The value to read on the digital light meter is very sensitive and it keeps fluctuating so I have to choose a value to put into the measurement. However, even with that the difference between the values are small as these are in nanowatts.

6.4) Designing a Holder for the Lenslet Arrays

Part of the thesis is to design a mechanical holder to hold the lenslet arrays. I made the design in a 3D designing software called Onshape and is exported with medium resolution, then it is 3D printed using PLA filament. I will include the design models in STL file format in the CD attached.

The design of the lens holder I designed and will be used in the experiments is as follows:
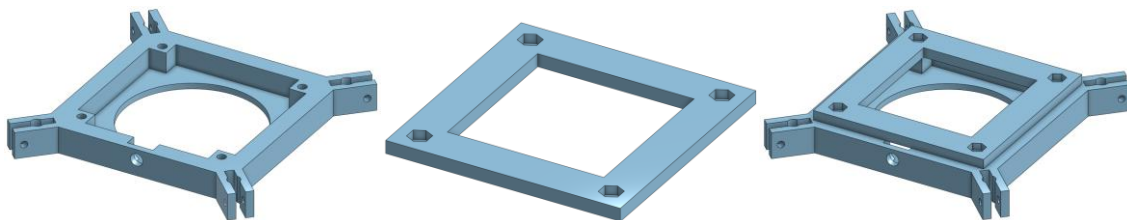

Figure 34: *Design of Lens Holder*

The design is inspired by the cage system from Thorlabs and it can be seen in the figure below:
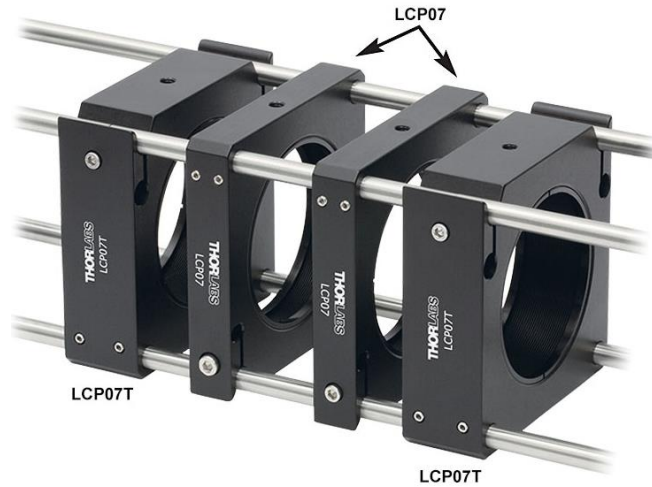

Figure 35: *Thorlabs Cage System*

Available at: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=5509

This design works perfectly in terms of fitting the nuts and screws and metals rods for the cage system and especially, the lens fits perfectly. However, when the lens is needed to be taken out, it is really not the best because of the number of screws that I need to undo. Apart from that, the holder works well as it is intended.
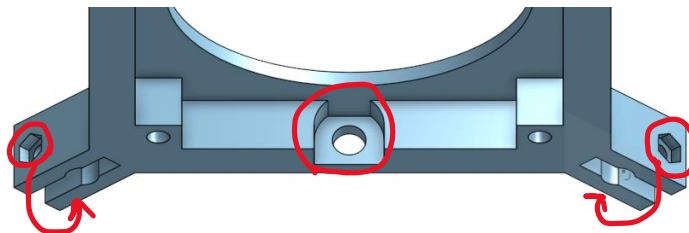

Figure 36: *Improvable Areas*

Even though it works well, there are still some improvements that I would make. It is mainly at the base of the design, where the place to put the M6 nut for the optical post it is not restricted like other places for nut. Before using it in person, I thought it would be nice to be able to easily slide the nut out of the cover. However, when I have to mount it on the optical post and its holder, I found out that it would be better to make it with the outer shape like the rest. Another one is that I would put the holes for the nuts at the bottom, for the lower pair of metal rod holders at the sides. This is because when I mounted the holder onto the optical post and its holder, it was hard to screw the rod holders tight because the optical post is in the way of the screwdriver.

Figure 37: *Optimal Design*

The cage system works perfectly, I had no issues sliding the holders on the metal rods. To improve the lens holder design for the cage system, I would make it so that there will be no extra material in between the lens like in this design, so that the lens can be close to each other for some measurements. The optimal design can be seen in the figure above. The holders fully assembled in the cage system can be seen in the figure below:
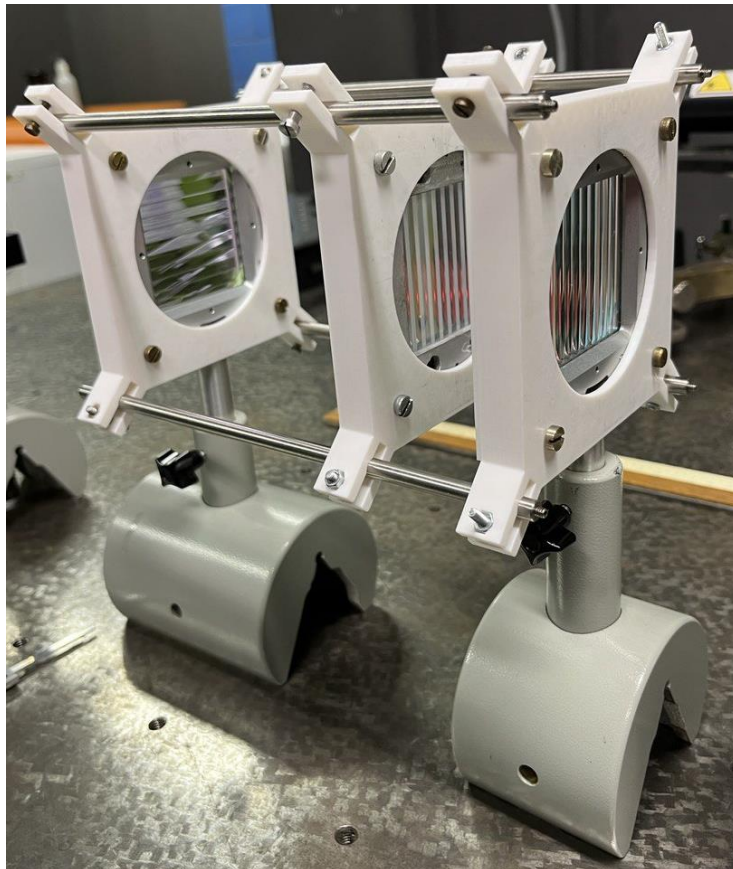

Figure 38: *Fully Assembled Designed Lens Holder*

7) Conclusion

In conclusion, I am sure this thesis meets all the given assignments. I managed to find a way to design a lens system that can convert a circular spot to a rectangular spot. It is achieved by using a pair of cylindrical lenslet arrays, and to map the spot onto a flat plane, an f-theta lens is used as well. The theory about the mentioned optical components and their working principle is explain in the theory part. The beam shaper system is also supported by calculations, geometrical optics with ray tracing and also by an experiment. It is found that the positions of the lenslets arrays do not affect the size of the rectangular spot, it is only sensitive to the change in focal length of the first cylindrical lenslet and the diameter or the width of the lenslet arrays.

The next point is to find a way to control the size of the spot in one direction, either the width or the heigh. I chose to study a way to change the width of the laser spot. It is done by introducing a negative lenslet array, which is named as a zoom lens, in between 2 positive lenslet arrays used to create the initial rectangle spot size. I found that the size can be change by moving the zoom lens but the position of it relative to the first lenslet array is important. If the zoom lens is move closer to the L1, the width of the spot will increase, when it is being moved before the back focal length, f', of L1. If the zoom lens is moved away from L1 after the f' of L1, the size will increase again. Therefore, if this zoom system were to be used in an actual application, it is super important to prescribe the distances that it can be adjusted to always get the desired outcome.

In addition, I also designed a lens holder to host the 3 lenslet arrays used to change the width of the spot in the experiments. For the lens holder to be industrial ready, I will need to make some tweaks to the design and they are discussed in Chapter 6.4. From here, what else can be done to make it usable in practice is to design a cover for the whole system and to have 2 separate end holders for the metal rods in the end so that the lens holders can be easily taken out of the cage system and put back. Better way to tighten the holders in place.

References

[1] Edmund Optics (no date) *Laser Beam Shaping Overview*. [Online]. Available at: https://www.edmundoptics.com/resource-page/application-notes/optics/laser-beam-shaping-overview/ (Accessed: 2 January 2023)

[2] Hecht, J. (2019) *Understanding Lasers*. 4th edn. United States of America: Wiley

[3] Pedrotti, F.L., Pedrotti, L.M. and Pedrotti L.S. (2018) *Introduction to Optics*. 3rd edn. United Kingdom: Cambridge University Press

[4] Edmund Optics (no date) *Gaussian Beam Propagation*. [Online]. Available at: https://www.edmundoptics.eu/knowledge-center/application-notes/lasers/gaussian-beam-propagation/ (Accessed: 3 January 2023)

[5] Paschotta, R. (no date) *Beam Waist*. [Online]. Available at: https://www.rp-photonics.com/beam_waist.html (Accessed: 3 January 2023)

[6] Pachotta, R. (no date) *Rayleigh Length*. [Online]. Available at: https://www.rp-photonics.com/rayleigh_length.html (Accessed: 3 January 2023)

[7] Pachotta, R. (no date) *Gas Lasers*. [Online]. Available at: https://www.rp-photonics.com/gas_lasers.html (Accessed: 3 January 2023)

[8] Pachotta, R. (no date) *Beam Quality*. [Online]. Available at: https://www.rp-photonics.com/beam_quality.html (Accessed: 9 January 2023)

[9] Edmund Optics (no date) *Beam Quality and Strehl Ratio*. [Online]. Available at: https://www.edmundoptics.eu/knowledge-center/application-notes/lasers/beam-quality-and-strehl-ratio/ (Accessed: 9 January 2023)

[10] Pachotta, R. (no date) *Phase Modulators*. [Online]. Available at: https://www.rp-photonics.com/phase_modulators.html (Accessed: 9 February 2023)

[11] Edmund Optics (2022) *Laser Optics Resource Guide*. [Online]. Available at: https://www.edmundoptics.com/knowledge-center/application-notes/lasers/laser-optics-resource-guide/ (Accessed: 9 anuary 2023)

[12] Gentec-EO (2022) *What is population inversion in a laser?* [Online]. Available at: https://www.gentec-eo.com/blog/population-inversion-in-laser (Accessed: 10 February 2023)

[13] Theriault, G. (2018) *The beginner's guide to laser beam quality and M2 measurement*. [Online]. Available at: https://www.gentec-eo.com/blog/laser-beam-quality-measurement-m2 (Accessed: 10 February 2023)

[14] Nemcova, Sarka (2022) *Optics Course Lecture Notes*. [Online]. Available at: https://moodle-vyuka.cvut.cz/course/view.php?id=1159 (Accessed: 15 February 2023)

[15] Adams, D. (2018) 'Cylinder Lenses for Beam Shaping' in *Laser Technik Journal*. [Online]. Availabale at: https://onlinelibrary.wiley.com/doi/10.1002/latj.201800002 (Accessed: 11 February 2023)

[16] Paschotta, R. (no date) *Microlens Arrays*. [Online]. Available at: https://www.rp-photonics.com/microlens_arrays.html (Accessed: 11 February 2023)

[17] Arecchi, A.V., Messadi, T. and Koshel, R.J. 'Lenslet Arrays' in *Field Guide to Illumination*. [Online]. Available at: https://spie.org/publications/fg11_p68_lenslet_arrays?SSO=1 (Accessed: 11 February 2023)

[18] Thorlabs (no date) *F-Theta Lenses*. [Online]. Available at: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=10766 (Accessed: 12 February 2023)

[19] Paschotta, R. (no date) *Laser Machining*. [Online]. Available at: https://www.rp-photonics.com/laser_machining.html (Accessed: 13 February 2023)

[20] Paschotta, R. (no date) *Laser Cutting*. [Online]. Available at: https://www.rp-photonics.com/laser_cutting.html (Accessed: 13 February 2023)

[21] Paschotta, R. (no date) *Laser Drilling*. [Online]. Available at: https://www.rp-photonics.com/laser_drilling.html (Accessed: 13 February 2023)

[22] Paschotta, R. (no date) *Laser Welding*. [Online]. Available at: https://www.rp-photonics.com/laser_welding.html (Accessed: 13 February 2023)

[23] Paschotta, R. (no date) *Laser Marking*. [Online]. Available at: https://www.rp-photonics.com/laser_marking.html (Accessed: 13 February 2023)
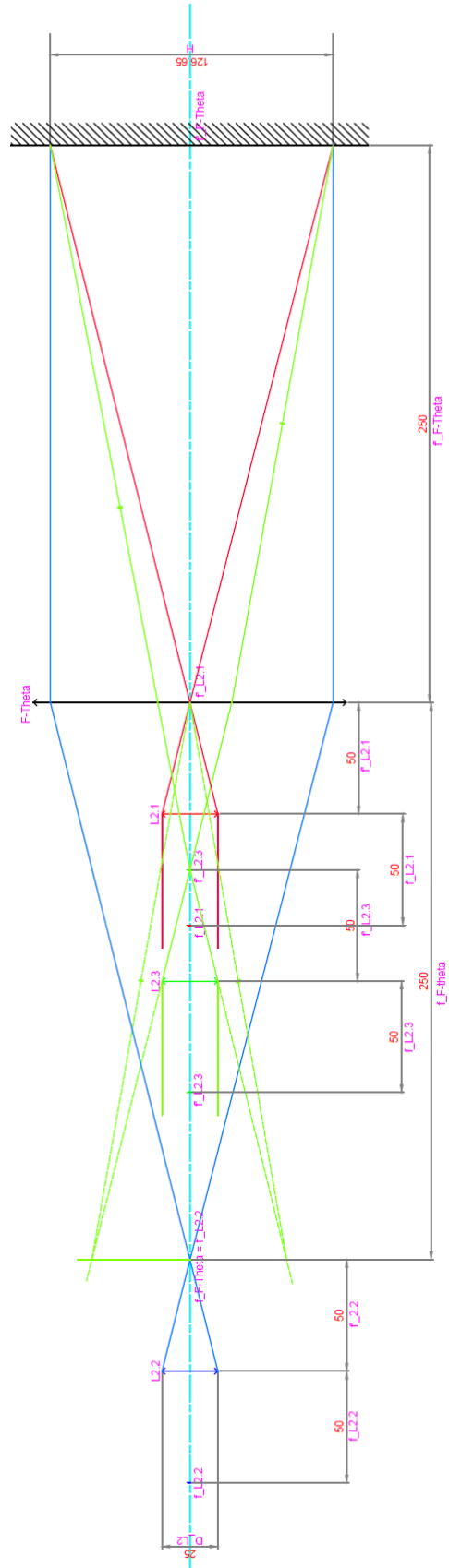
Appendix

From above:
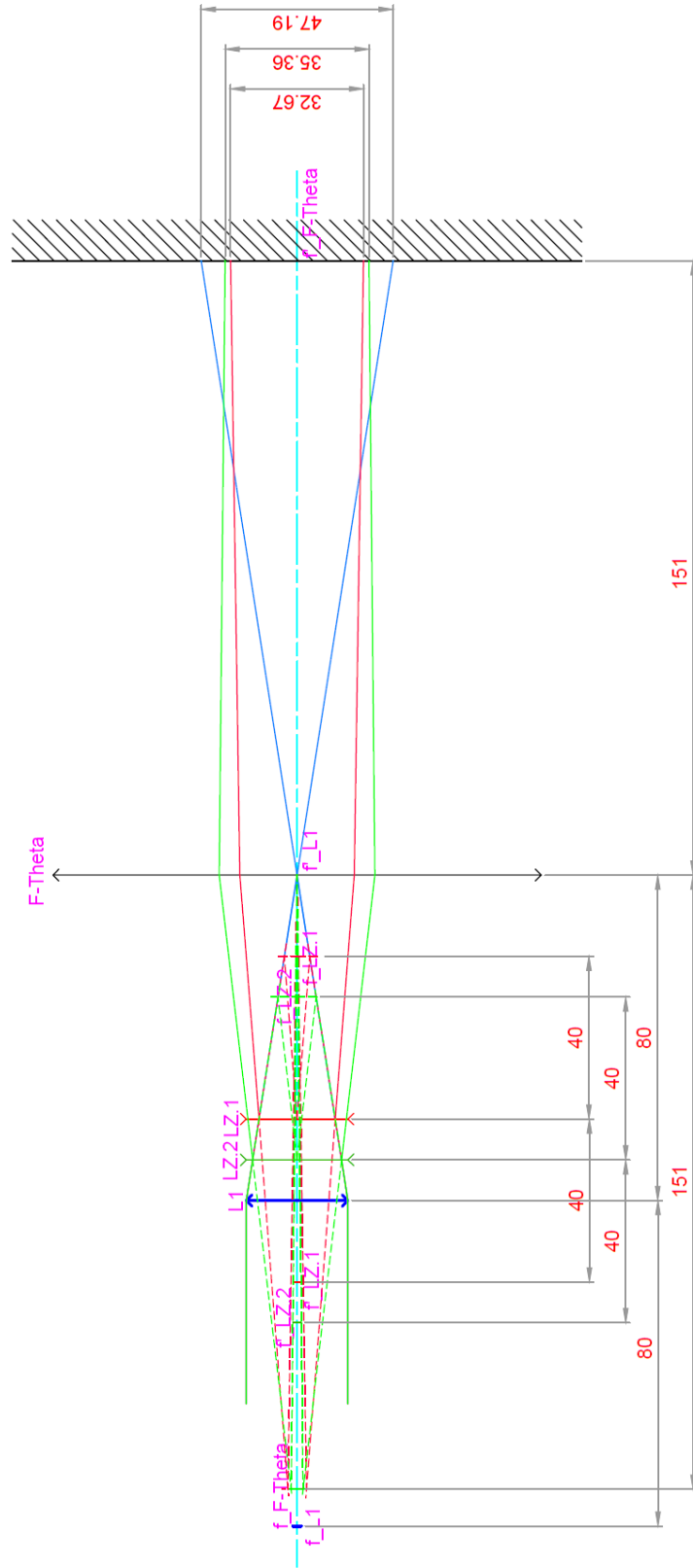
3 special positions of the lenslet:
Position 1 (L2.1): Back focal point of L2 is at the position of F-Theta
Position 2 (L2.2): Back focal point of L2 is at the front focal point of F-Theta
Position 3 (L2.3): Somewhere in between position 1 and 2

Side view:

b

From Above:

225

187.5

150

f_F-Theta

F-Theta

f_LZ2

LZ1

LZ2

f_LZ2

f_LZ1

L1

f_L1

f_F-Theta

150

150

40

40

40

40

40

40

c