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FACULTY OF MECHANICAL ENGINEERING

Department of Information and Automation Technology

Bachelor Thesis

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CZECH TECHNICAL UNIVERSITY IN PRAGUE FACULTY
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Department of Information and Automation Technology

Laser Beam Shaping Technique

Study Branch: Mechanical Engineering

Study Program: Information and Automation Technology

Supervisor: Ing. Bc. Sarka Nemcova, Ph.D.

Written by: Yaman Sanajleh

Declaration

I hereby declare that I have completed this thesis entitled **Laser Beam Shaping Technique** independently with consultations with my supervisor, and I have attached a full list of used references and citations.

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II. Bachelor's thesis details

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Optical system for laser beam shaping

Bachelor's thesis title in Czech:

Optická soustava pro tvarování laserového svazku

Guidelines:

- Review of optical systems for laser beam shaping, with the focus on industrial applications (engraving, polishing).
- A design of an optical system reshaping the beam form a circular spot to a rectangular spot.
- Experimental validation of the initial design.
- Suggestion of a way how to make the ratio of the rectangular spot's sides variable.

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

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Abstract

The purpose of this work is to investigate the techniques with which we can shape a laser beam and test one of them. Using optics and mechanics together, we are able to create a method of shaping such an intense beam of light. The concentration of this thesis is to study a technique of shaping the laser beam spot on different surfaces in a way that benefits us most from the optics we have at our disposal. Turning the occurring circular laser spot to a rectangular one that we can control in height and width.

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Chapter I: Introduction

The fear of darkness vanished when man discovered fire. Until then, man knew only the natural sources of light. Later, light sources evolved into different artificial forms. Physicists had worked to create devices for producing powerful beams of light. This resulted in the invention of lasers. Lasers are an important milestone in the field of engineering and science. From a barcode scanner to intruder detection in high security areas. From optical tweezers to cutting off high strength materials. From removing body art to high-accuracy eye surgery, lasers are everywhere. That poses an important question, how can we shape this strong beam of light and use it for our needs? Laser technology is one of the results of our advances in optics and science. Its uses are becoming greatly diverse in manufacturing, laser technology is used for precision cutting, scanning, polishing, engraving, and many other uses. In order to use laser technology efficiently, it would be necessary to control the spot which the laser makes on different surfaces. Specifically, controlling the shape, dimensions, and intensity of the laser spot. This paper will investigate a technique of shaping the laser beam to produce the desired rectangular spot. This technique requires an arrangement of different optical elements to form a system where the laser light refracts and we achieve the required dimensions.

LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. A laser is not a typical source of light, it's unlike a flashlight or a light bulb. A laser is a device that stimulates atoms or molecules to emit light at unique wavelengths and amplifies it, resulting in a very narrow beam of radiation. It emits light through stimulated emissions of radiation which is a process that increases the intensity of light. The emission typically only occupies a small range of visible, infrared, and ultraviolet wavelengths. Which gives lasers their monochromatic nature. There have been several different types of lasers produced, each with its own set of characteristics. Laser light has four qualities that make it different from ordinary light, these characteristics are coherence, directionality, monochromatic, high optical intensity. Radiation is emitted when excited electrons jump to a lower energy level within the atom. Electron transition refers to the process of electrons moving from a higher energy level to a lower energy level or from a lower energy level to a higher energy level.

The electron transition occurs naturally in ordinary light sources and occurs randomly in time. One way to achieve this is stimulated emissions. Stimulated emissions are the process when a photon interacts with a high energy electron and forces it back to a lower energy level. This process results in the release of energy in the form of light. (1)

Laser engraving is a process that involves the evaporating of material. When the laser hits the surface of the material, Photons are absorbed by the material, and due to the high energy density in the laser beam there is no time for heat dissipation, which results in local melting and evaporating of the material. This leaves a permanently engraved spot which is required from laser engraving. This happens through an engraving machine. Laser engraving machines are usually made up of three crucial parts: a laser, controller, and a surface. The laser is the tool for drawing while the controller determines the speed of its movement and directionality. The surface is usually made of material which the laser beam can act on. For this, it would be optimal if we can alter the laser spot from a circular to a rectangular spot which we can change the width and height of depending on the application. Laser Engraving is a field where laser beam shaping techniques are required for optimal results.

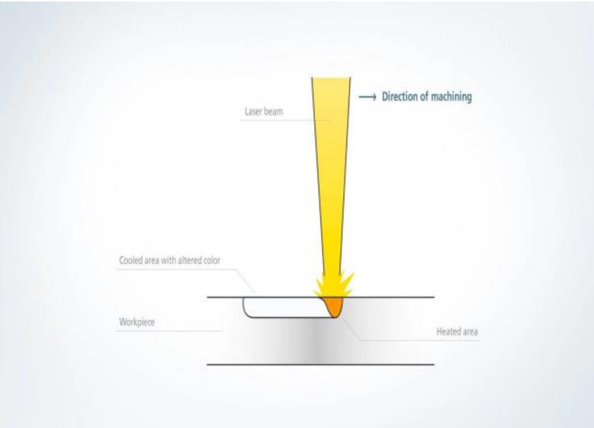


Figure 1, Laser Engraving Scheme (2)

Another field where laser beam shaping is needed is laser polishing. In theory, polishing happens in metals when a thin surface layer is melted by means of radiation (with a laser). In its molten phase the surface roughness is smoothened due to the material's surface tension. Then the material solidifies in a smoothed state. For optimal polishing results, its useful to be able to shape the laser beam spot for maximum accuracy. Laser cutting is a similar process in that it depends on the vaporizing of material using laser to cut the material. Usually, the materials cut by laser are metals like steel and aluminium. This happens simply by melting the excess materials, then high pressure nitrogen is used to blow the molten metal out of the new surface. Laser beam shaping technology can enhance the accuracy and quality of such operations.

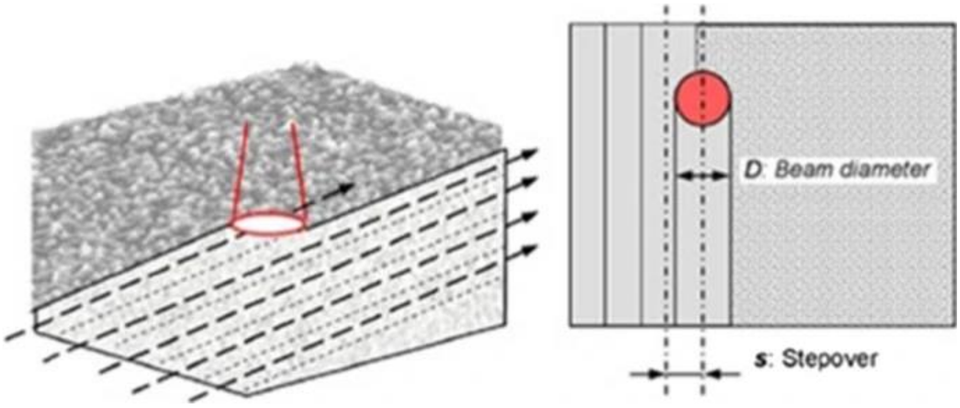


Figure 2, laser polishing illustration (3)

To achieve optimal results, the required laser spot on the surface of the material is preferably rectangular instead of the circular spot that it naturally occurs in which is due to the gaussian distribution of the beam of light. this paper will discuss a technique to achieve this with an arrangement of cylindric lens arrays and a focus lens (f-theta lens).

A Cylindrical lens is an optical component which has different radii in the x and y axis with one of them being infinite. This gives it a cylindrical shape which allows for image magnification along one axis only. Cylindrical lenses expand or condense light in one direction along one axis. This specific design enables light from a laser, or any other source, to be focused into a one-dimensional line instead of a single point. This quality is extremely crucial for this laser shaping technique. A lens array of these cylindrical lenses would allow the segmentation of the laser beam to then layer it segment by segment, until the desired dimensions and homogeneity of the spot are achieved.

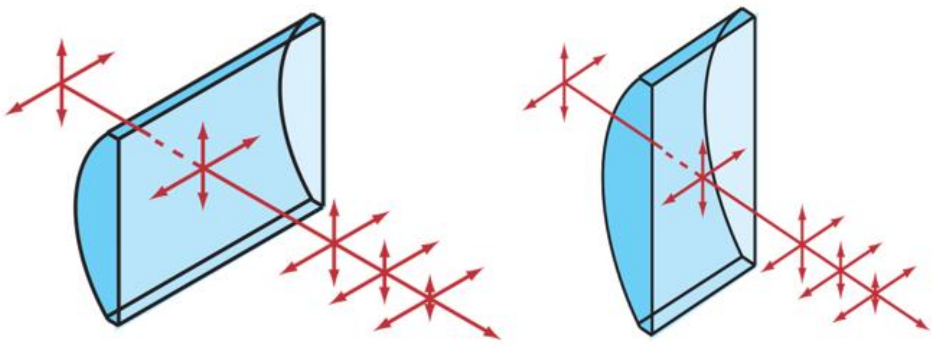


Figure 3, cylindrical lens illustrations (4)

By using two cylindrical lens arrays made up of small lenslets that divide the laser beam into smaller beamlets followed by a focus lens to recollect the beamlets and focus them onto its focus plane. By placing one horizontally so the optical power axis is parallel to the x-axis and the other vertically with its optical axis parallel to the y-axis, the laser beam will expand in both the vertical and horizontal directions. This will result in the change of the spot caused by the laser from a circular shape a rectangular one. To better align and focus the refracted segments of laser into a more coherent and intense square spot, a focus lens such as f-theta lens is used.

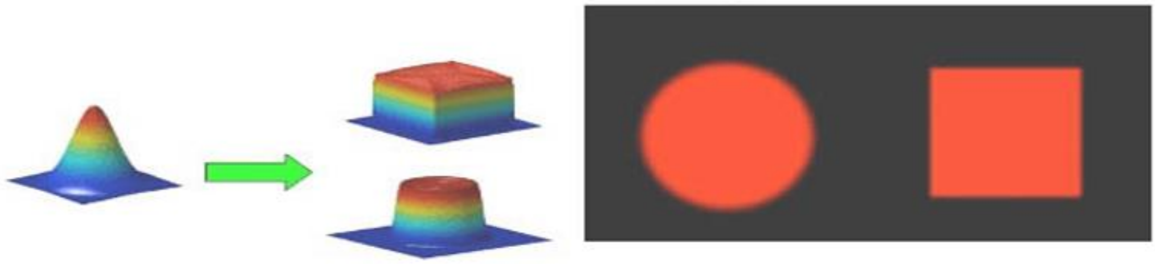


Figure 4, flat top beam profile illustration (5)

f-theta lens is a focus lens that is designed to focus a laser beam onto a planar image plane. It is regularly used in scanning systems. An f-theta lens will be placed at the focal point of the second lens array. The spot of the laser will then be at the focus plane of the f-theta lens. The focal length of the f-theta lens is related to spot size in the image plane. By using geometric and optical mathematical equations, the relationship between the spot size and the focal length can be formulated. This paper investigates this technique of laser beam shaping along with the related parameters and considerations.

Chapter II

Lasers Working Principle

Atoms release energy in the form of light. In an atom, electrons spin around the nucleus in different orbits, each with its own energy level. When electrons shift to a lower energy level than their initial one, they emit energy in the form of light. Meaning they release a photon. For any electron to jump from a lower energy level to a high energy level they need to be stimulated with a photon. As the figure below shows, a nucleus with electrons spinning around it with different energy orbits E1, E2, and E3. (6)

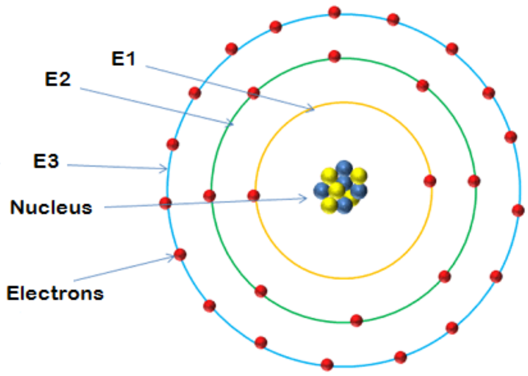


Figure 5, energy levels in an atom (6)

Electrons transition from one energy level to another by either absorbing or releasing radiation. In three ways as follows.

- Absorption of radiation
- Spontaneous emissions
- Stimulated emissions (6)

Absorption of radiation

The electrons spinning further away from the nucleus are at the higher energy levels, whereas the electrons orbiting close to the nucleus are at a low energy level and need additional energy to begin orbiting in a higher energy level. Light, heat, and electric fields are typical sources of that energy. Absorption of radiation is what happens when an electron in a lower energy level engages with a photon and absorbs energy which allows it to jump to a higher energy level.

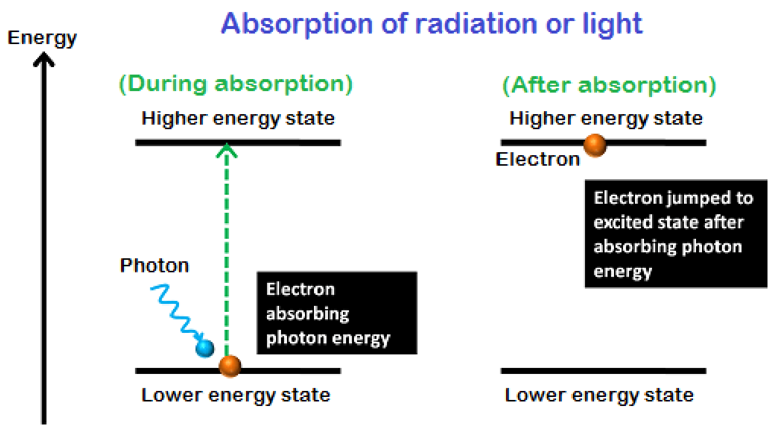


Figure 6, illustration of radiation absorption (6)

An electron in the low energy level requires sufficient energy to jump to a higher energy level. This energy must at least be equal to the difference of energy between the two levels. If the energy of the incoming photon is equal to the energy difference of the two levels, absorption of radiation occurs.

Spontaneous emissions

The excited electrons can only stay in the high energy level for a short period. The lifetime of an excited electron is the period an excited electron stays in the excited state, and it is about 10^{-8} seconds. After this period the electron returns to the lower energy level by discharging energy in the form of a photon. Spontaneous emissions occur when the electron emits photons to return to the lower energy state. This emission occurs naturally -or spontaneously- after the lifetime of the excited electron is over.

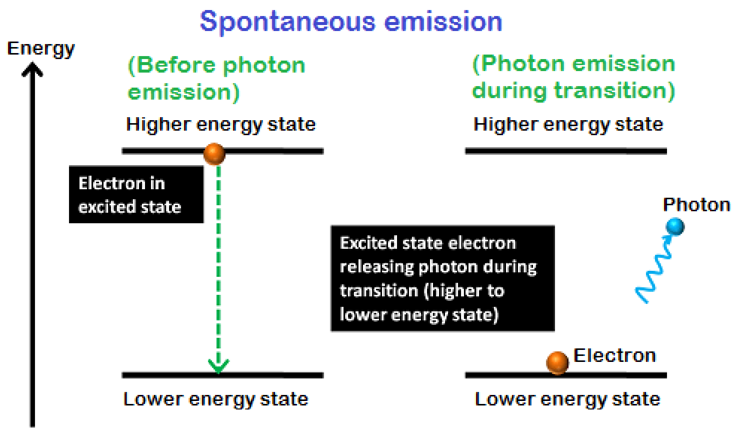


Figure 7, spontaneous emissions illustration (6)

With spontaneous emissions, the electrons return to the ground state without any photon interference. The emission of the photons occurs naturally. The photons emitted with spontaneous emissions have random changes of phase between them, which result in an incoherent beam of light. The photons emitted do not propagate in the same direction as the incident photons. (6)

Stimulated emissions

Instead of waiting for the excited electron's lifetime to end, an alternative technique can be used. Energy is supplied directly to the electrons in the excited state in stimulated emissions. Unlike spontaneous emission where the photon is supplied to the lower energy electrons, It is the procedure in which a photon incidents an excited electron and forces its return to the lower energy level. This causes the electron to release energy in the form of light as it falls down to the ground state.

The stimulated emissions process occurs much quicker when compared with spontaneous emissions. This is due to the fact that it doesn‘t occur naturally, it is rather induced and controlled. With this technique two photons are emitted, the incident on and the photon released due to the energy release of the electron in the high energy.

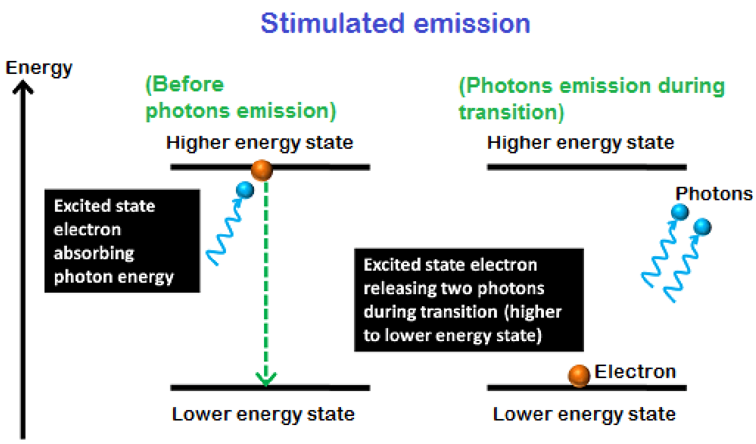


Figure 8, illustration of stimulated emissions (6)

Unlike spontaneous emissions, the photons emitted are all in phase and have the same frequency and energy, this means all the photons in the stimulated emission propagate in the same direction. Thus creating a uniform beam of light. The number of photons emitted is directly proportional to the number of excited electrons and the incoming light intensity. (6)

Laser Construction

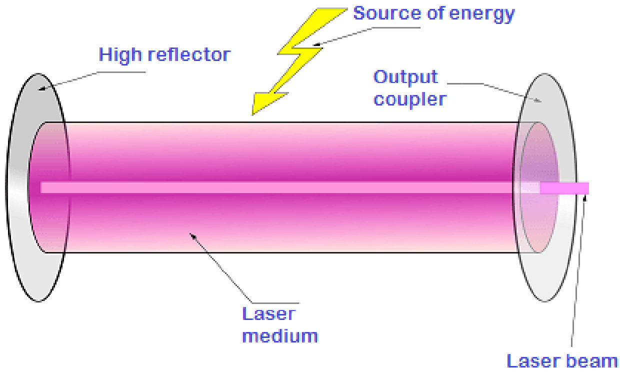


Figure 9, illustration of laser construction (7)

The main three components of a laser are:

- Energy Source
- Laser medium
- Optical Resonator

Energy source or pump source is what provides the system with the energy needed to achieve laser emissions. To achieve these emissions energy is needed to produce population inversion. Population inversion is the process of obtaining a higher number of electrons in the excited state compared with the low energy state. Once population inversion is achieved, we have an active medium and there are more electrons in the higher energy levels. The energy source for a laser medium can be electric discharge, chemical reactions, xenon flash lamps and light focused from a diode laser –which is widely used in helium lasers. The type of energy source varies depending on the laser medium. (7)

Laser mediums are what classifies a laser and determines its type and characteristics. The medium of a laser can be solid, gas, or liquid. Solid state mediums include certain crystals or glasses doped with rare-earth ions, for example neodymium, ytterbium, or erbium. One example of these lasers is ruby laser where a ruby crystal is used as a medium. Solid mediums can also be transition metal ions like titanium or chromium. Gaseous laser media include mixtures of helium and neon, nitrogen, argon, carbon monoxide and carbon dioxide, or metal vapours. A common gaseous laser is the helium-neon laser, their applications are vast; including barcode scanners, tool alignment, and non-contact measuring. Liquid media are typically made up of organic dyes, usually as a liquid solution. These dyes provide a much wide range of wavelengths. These lasers generate laser emission from the excited energy states of the organic dyes mixed in a liquid solvent. (7)

An **optical resonator** consists of two mirrors placed parallel to each other. One of the mirrors is fully reflective. the other is partially reflective. These mirrors are enhanced with different optical coatings that determine their reflectivity. The output coupler mirror allows some of the light in the laser medium to escape and form the laser beam. The beam created in the laser medium will bounce back and forth between the two mirrors which stimulates other electrons to release photons and fall back to the ground state, which in turn stimulates a large number of electrons to emit light achieving optical gain. The light is reflected hundreds of times prior to its escape through the output coupler mirror. (7)

Laser Properties

There are four laser properties that enable it to melt through a block of steel:

- **High optical power density**: The optical power density of a laser beam at some location is the optical power per unit area W/m^2 or W/cm^2. For a monochromatic gaussian beam the intensity I is equal to:

$$I = I_0 exp\left(\frac{-2r^2}{z^2 w_0}\right) = \left(\frac{2P}{z^2 w_0 \pi}\right) exp\left(\frac{-2r^2}{z^2 w_0}\right) \qquad (1)$$

Where I_0 is the maximum irradiance at the center of the beam, z is the distance from the beam waist – the position along propagation direction, w_0 is the waist radius, r is the radial distance away from the axis and P is the total power of the beam. (8)

- **Directionality:** laser propagates light in one direction because all the photons travel in the same direction. the narrow width of the laser beam enables it to travel long distances without losing density. The direction of a laser is perpendicular to the output coupler mirror's surface. Light spreads out uniformly and in all directions at ordinary light sources, whereas in laser, the light spreads in narrow solid angle. This is what gives laser a greater power density than ordinary light.

- **Coherence:** the wavelengths and frequencies of the laser light are all in phase with each other in space and time. This is because the electron transitions in a laser medium are controlled and happen artificially in comparison with ordinary light where the transitions happen spontaneously and at different time intervals producing photons that differ in energy, frequencies, and wavelengths.

- **Monochromatic**: In a laser medium the photons emitted have the same wavelength, energy, and frequency. Wavelengths of the laser depend on the laser medium. (9)

Characteristics describing the laser beam:

- **Beam divergence:** is the angular measure of how fast a beam expands away from the beam waist as explained in the figure 10. The beam divergence half angle is measured by the formula:

$$\theta = M^2 \frac{\lambda}{w_0} \qquad (2)$$

where M^2 is the beam quality factor – sometimes referred to as beam propagation factor, λ is the wavelength in the medium, and w_0 is the beam radius at the beam waist. The full divergence angle can be calculated by multiplying the equation by two. (9)

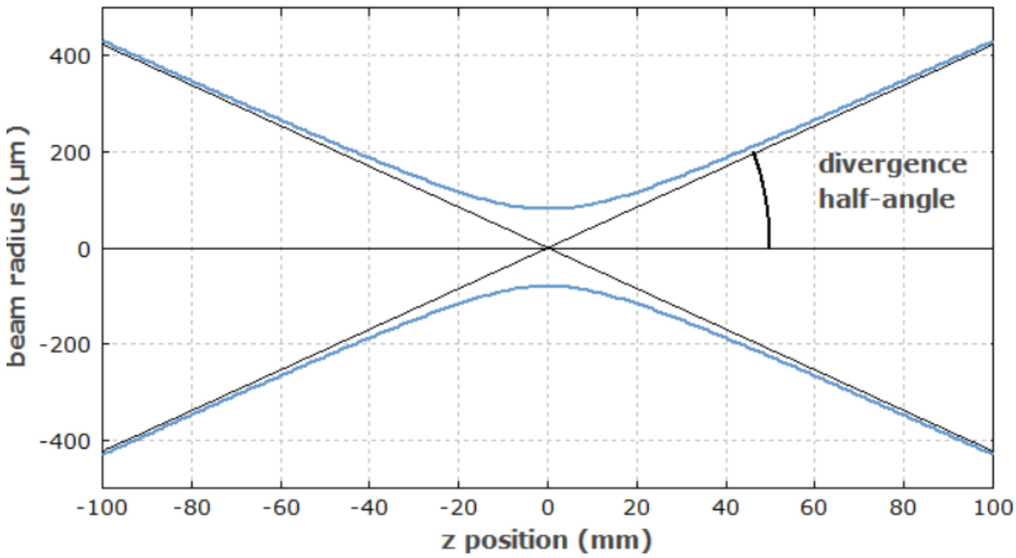


Figure 10, beam divergence figure, (9)

- **Beam waist**: also referred to as beam focus, is the location along the propagation of the laser beam where the beam radius is a minimum value. Respectively the waist diameter is the diameter of the beam at that location. The waist of a gaussian beam is defined as the location along propagation where the irradiance is $1/e^2$(13.5%) of its maximum value. This is an important parameter as it affects the beam divergence angle and thus the beam quality. (10)
- **Beam quality:** is understood as a measure of how tightly a beam can be focused with limited beam divergence. It is quantified in two ways. With the beam parameter product (BPP) which is the product of the beam divergence angle with the waist radius of the beam. Or with the M^2 factor, defined as the beam parameter product divided by λ/π. It compares the performance of a real laser with a diffraction-limited gaussian beam. Low values of BPP or M^2 indicate a high-quality laser beam. $M^2 = 1$ for a perfect gaussian beam. (11)

Lasers Beam Machining

The previous section discussed the properties of the laser light that enable it to cut through dense metals. The high optical power density, and its extreme directionality. This section will go into details of how laser light machining works and what the components of a typical laser machining system are.

Laser beam machining is a thermal non-contact machining process. It‘s a mechanism for material removal using the heat generated by the high-power density laser light focused on the material surface through a focus lens. The focused laser light melts, evaporates and chemically degrades the material.

Principle elements of laser machining system:

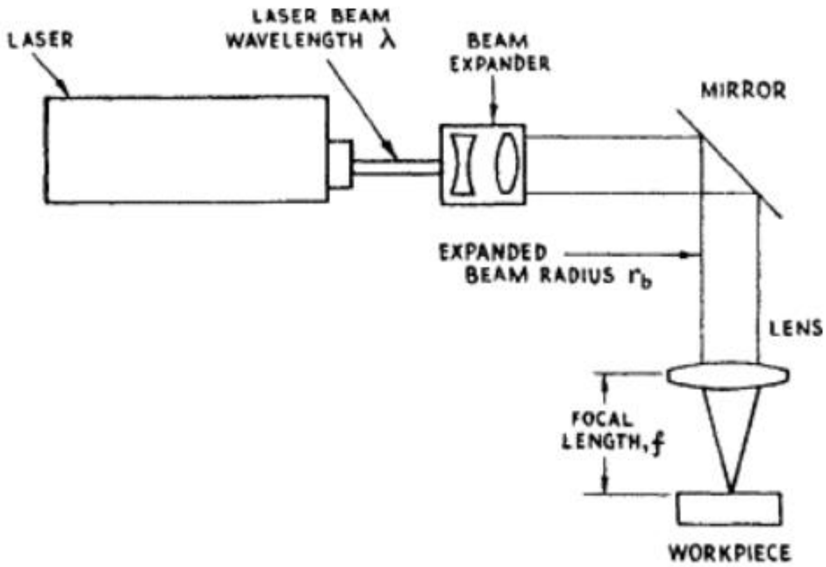


Figure 11, LBM illustration of elements involved (12)

Laser this is where the laser light is emitted through stimulated and spontaneous emissions. The lasing medium attributes to the wavelengths, optical power and type of laser beam formed. Typical types of laser media used for metal processing are gas media, specifically CO_2 gas is most used due to its long emission wavelength (10.6μm) which leads to better absorption by the machined material. Another advantage is their high output power. Helium neon lasers and fibre lasers are also used commonly when machining metal sheets. After the laser beam is formed it goes through a beam expander**. Beam expander** is a telescope that increases the diameter of the input beam from the laser to a larger output beam. It consists of two lenses separated by a sum of their focal lengths. Galilean telescopes are used as beam expanders, and they are made up of a positive and a negative lens. The output beam from the beam expander then is reflected by **mirror** which reflects the beam directly to a focusing optic (lens). the mirror acts as a guidance element to the laser beam and it’s a part of the optical system that shapes the laser beam. The last optical element that the beam goes through before interacting with the workpiece is the lens. The **lens** acts as a transmissive focusing optic. It's a positive lens and its purpose is to focus the incoming laser beam into a point on the workpiece surface. (13) (12)

Chapter III: Important concepts

Gaussian beam distribution

Laser beams are assumed to be gaussian with an irradiance profile that follows an ideal gaussian distribution. **Irradiance** is the radiant flux received by a surface per unit area [W/m^2]. Real laser beams deviate slightly from the ideal gaussian behaviour. The gaussian distribution is a radially symmetric distribution where the irradiance profile decreases as the distance from the centre of the beam perpendicular to the direction of propagation increases. It is the fundamental mode for laser beams. The transverse optical intensity distribution of a beam is described with the gaussian function in equation (1) described in the previous chapter.

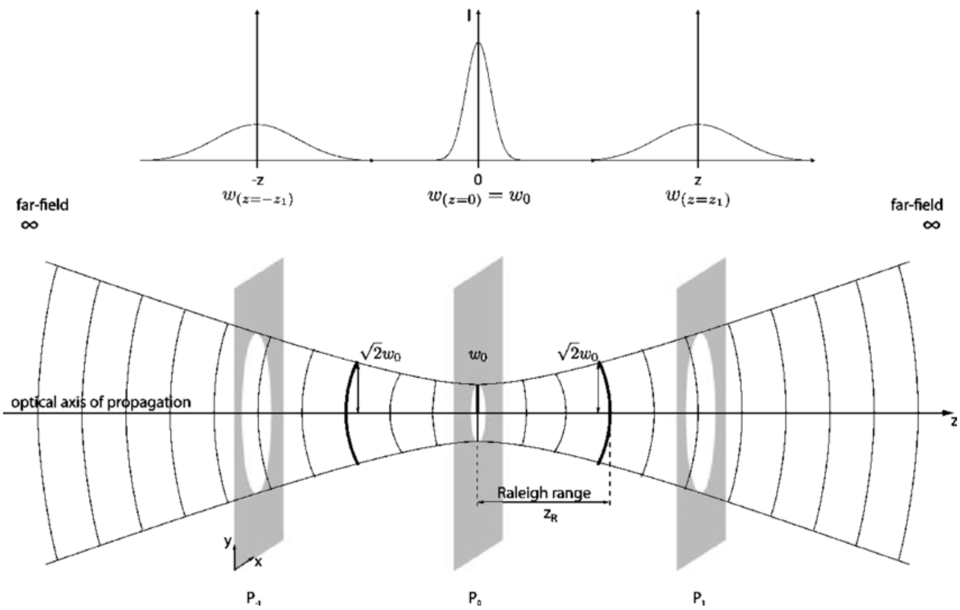


Figure 12, gaussian beams intensity distribution (14)

The Rayleigh range – also called the Rayleigh distance, is the distance from the beam waist where the beam radius increases by a factor of the square root of two. In other words, where the spot area exactly doubles. This is an important quantity for determining the field of focus of a laser beam. (8)

While most laser beams are gaussian, for many applications it is desirable to have a non-gaussian irradiance profile as gaussian beams have a decrease in their symmetric irradiance profiles when the distance from the beam waist increases. Applications related to laser beam machining such as laser polishing and engraving benefit more from a uniform irradiance profile along the cross section of the laser beam waist; which corresponds to the focused spot. Laser beams with such a constant irradiance are called **Flat top** beams – sometimes referred to as Top Hat beams. (15)

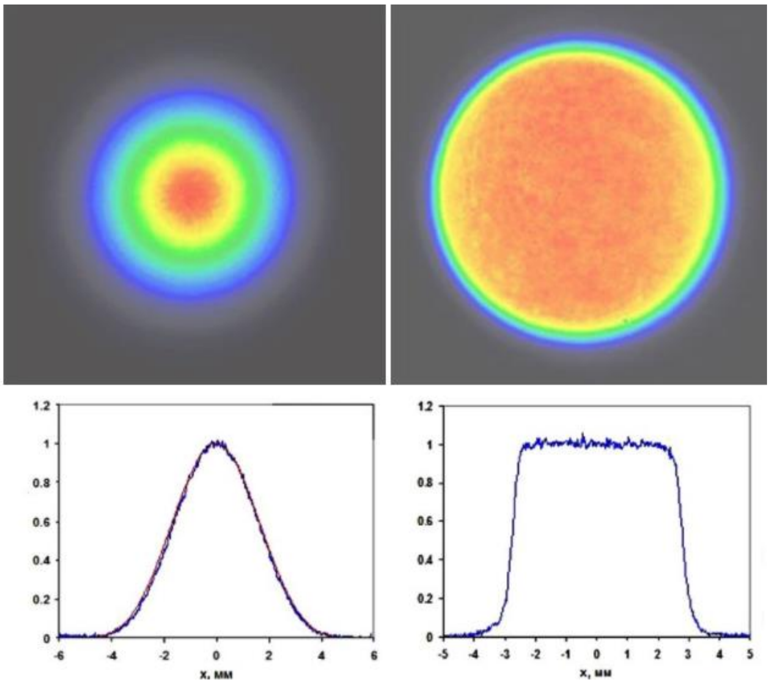


Figure 13, example of the difference in irradiance profile between a gaussian and flat top laser beam (15)

Gaussian beam lasers are cost efficient and more common, but their disadvantage to flat top beams is having low irradiance regions around the focused spot. This leads to wasted energy if the optical intensity in these regions is lower than the required threshold. Flat top beams offer more predictable and accurate results when used in laser beam machining. Flat top laser beams provide cleaner more precise cuts in contrast to gaussian beams. The proximity of a real beam to an ideal flat top beam can be evaluated with the flatness factor F_n. It is calculated as so:

$$F_n = \frac{Average\ irradiance\ [\frac{W}{m^2}]}{Maximum\ irradiance\ [\frac{W}{m^2}]} \qquad (2)$$

Laser beams with gaussian intensity distribution are converted to flat top beams through different beam shapers using different techniques. (16)

Overview of Beam Shaping used techniques

Beam shaping is the procedure of redistributing the irradiance and phase of a beam of light. The beam shape is determined by the irradiance distribution. Beam shaping is required in many laser processing applications such as laser cutting, engraving, and industrial and medical applications as well. There are two major ways for laser beam shaping based on the methods and elements used; the first is through diffractive optical elements (DOEs), such as beamsplitters. The second is through refractive optical elements. Such as Beam Homogenizers. The required technique for shaping a laser beam depends on the application it is used for, type of processes and laser power, and on cost limitations of a specific application. (17)

Diffractive beam shaping

Diffraction of light is the change in direction of waves as they pass through an opening or a slit, or around a barrier in their path. Diffractive optical elements do not change the speed or wavelength of the light waves coming through. A simple beam shaping method using DOEs is achieved through aperturing of the beam as shown in figure 14. In this technique the beam is first expanded and collimated then an aperture is used to select a suitably flat portion of the beam with relatively homogeneous irradiance. The disadvantage of this technique is that it is not lossless. It is optimal, for obvious reasons, that the beam shaping operation conserve energy. Furthermore, if the irradiance of the input beam is not suitable, it might not be possible to find an aperture size and position that would yield a desirable result. (18)

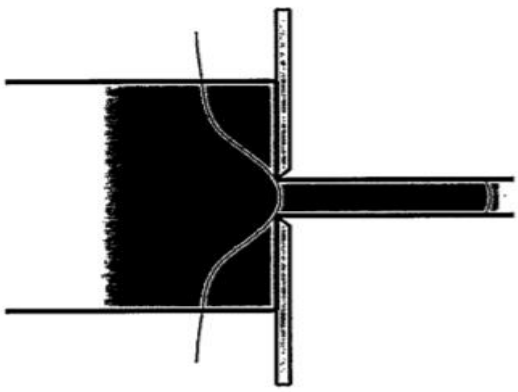


Figure 14, illustration of a uniform flat beam obtained through an aperture (18)

Diffractive elements typically operate collimated coherent beams with an optional focus lens. A typical use of diffractive elements is splitting the laser beam into an array of spot. A collimated beam incidents the diffractive element - commonly made with multiple holes but can also be patterned depending on the application - and is then split into different spots depending on the geometry of the diffractive element as the figure shows below.

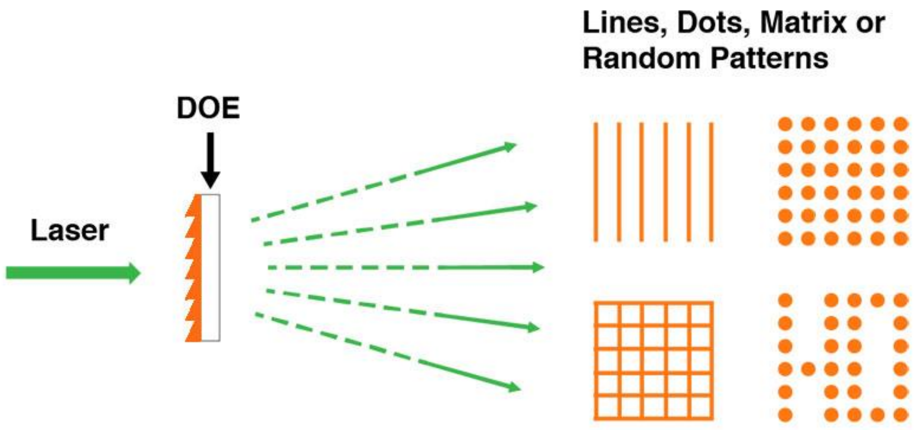


Figure 15, beam splitting illustration (19)

Refractive beam shaping

Refractive beam shapers utilize lenses that bend light waves to achieve a flat-top uniform beam from a gaussian beam input. Field mapping refractive beam shapers are well-known and used often. They are commonly implemented as telescopic systems of two lenses with collimated beams at the input and output. The change of irradiance profile from gaussian to uniform is realized by accurate introducing of wave aberration by the first component to redistribute the energy, and further its compensation by the second one. The resulting collimated output beam has uniform irradiance, flat wave front and is free of aberrations. (18)

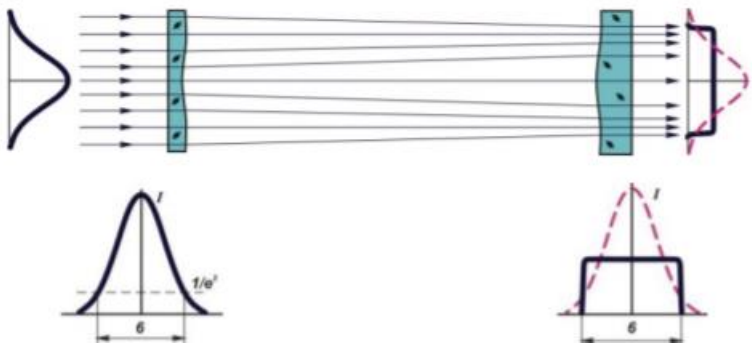


Figure 16, illustration of the basic principle of refractive beam shaping (18)

Refractive beam shapers are often accompanied with a telescopic system to expand the collimated beam. An objective lens and an image lens are placed before the beam shaping combination of lenses for the expansion of the beam. Figure 17 illustrates the optical layout of these systems. (18)

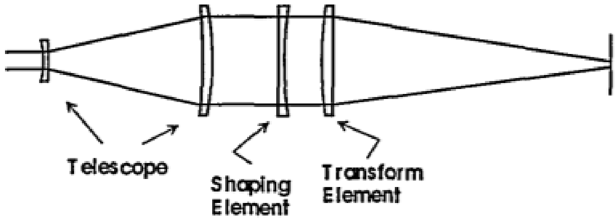


Figure 17, refractive beam shaping principle with expander telescope (18)

Beam homogenizers

Also called beam integrators, consist of two basic components; first is the sub-aperture array which is made up of two lenslet arrays which segment the input collimated beam into an array of beamlets. Followed by a focusing lens that superimposes the beamlets on its focus plane to form a laser spot with a uniform irradiance profile. The beamlets are overlapped and focused on the target plane. An example of a system with this construction is illustrated below. Preceding the first lens array is another lens array placed with its optical power axis perpendicular to the first lens array. The second lens array in the figure is acts as a field lens which increases the field of view. The incident beam is of course collimated, and homogenization is achieved by dividing the wave front into separate beams with each lens element and then focusing those beams with the focusing lens onto the target area. The quality of the uniformity is based on the number of lens elements within the lens arrays. This is the limiting factor of this system. (18)

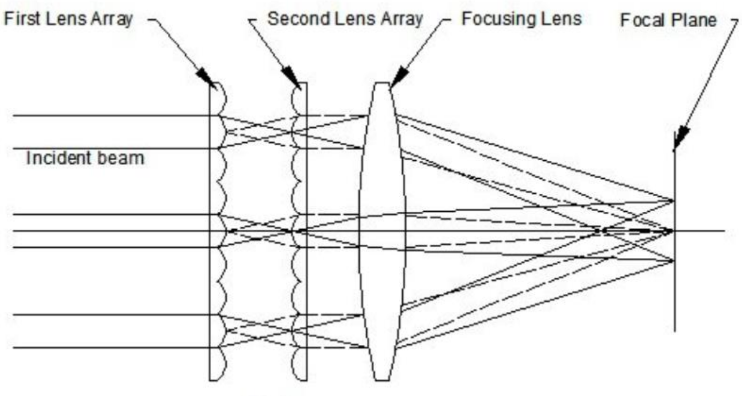


Figure 18, laser beam homogenizers (18)

F-theta lens

f-theta lenses have been designed to provide a high performance in laser applications such as engraving and scanning systems as well as material processing. For laser engraving and scanning, a planar imaging field is desired for the best results. A spherical lens can only image along a sphere. The flat-field scanning lens is a solution to this problem. However, the displacement of the beam depends on the product of the effective focal length and tangent of the deflection angle [f * tan (ɵ)]. (20)

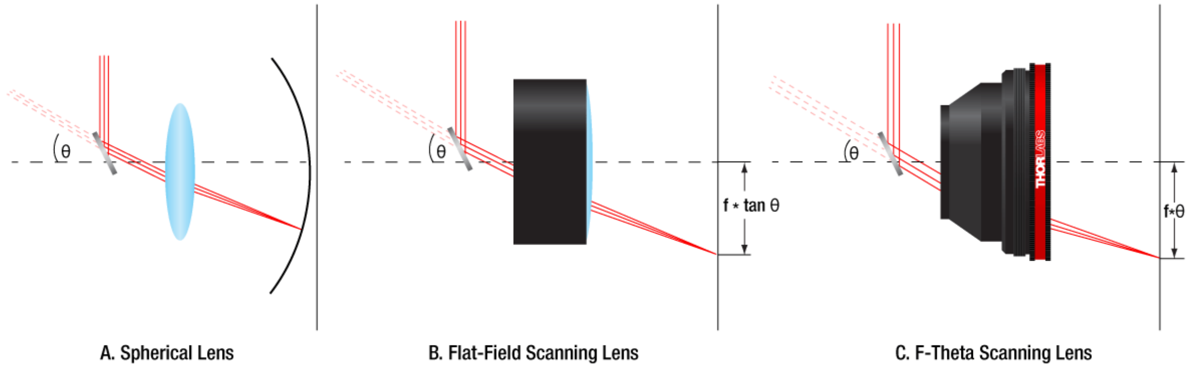


Figure 19, comparison illustration (20)

The ideal solution is to produce a linear displacement which would result in a constant scan rate. F-theta lenses are constructed with a barrel distortion that gives a displacement that is linear with ɵ. This response removes the need for complicated electronic correction and provides a fast, compact, and reliable scanning system. The compact design of the f-theta lens allows the user to reduce the number of optical components required to provide a flat image plane. The ability of these lenses to realize tighter spot sizes means that the resolution for scanning and printing is better. This also means higher intensity for engraving or material processing and most importantly the spot size is constant in resolution and intensity across the entire image plane. F-theta lenses are easier to control because by controlling the angle of deflection [ɵ] we will know how far from the optical axis the spot will be. (20)

Cylindrical lenses

Cylindrical lenses can be plano-convex (focuses light) or plano-concave (expands light). Cylindric lenses focus light to a **line** in only one axis. The line generated is parallel to the cylindrical lens’s axis of optical power as is shown in figure 20. (4)

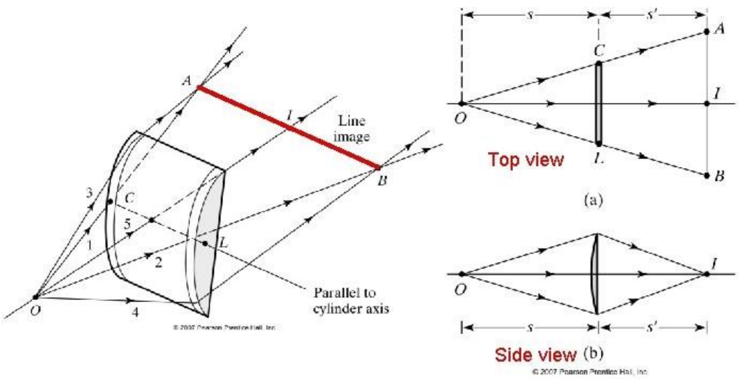


Figure 20, cylindrical lenses (21)

Cylindric vs spherical lenses (in terms of geometry):

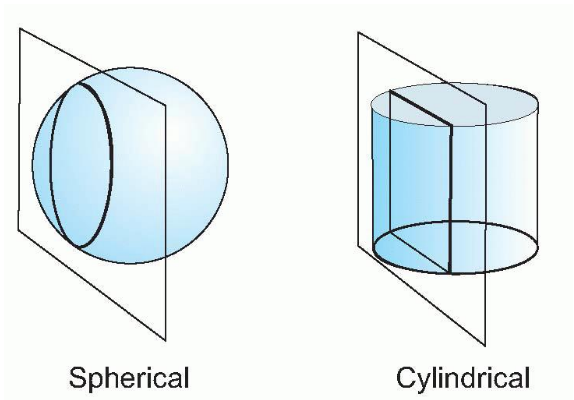


Figure 21, geometry of cylindrical lenses (22)

Cylindrical lenses are used to expand, focus, or condense incoming light. They can be used to expand the output of a laser diode into a symmetrical beam. Spherical lenses focus light into a point. (4)

Considering a ray from infinity, the focal point of a cylindrical lens is equal to:

$$\frac{1}{f'} = \frac{1}{p'} - \frac{1}{p}, \quad \textit{lens equation} \tag{3}$$

$$p = -\infty,\ p' = f'$$

Cylindrical lenses as thick lenses:

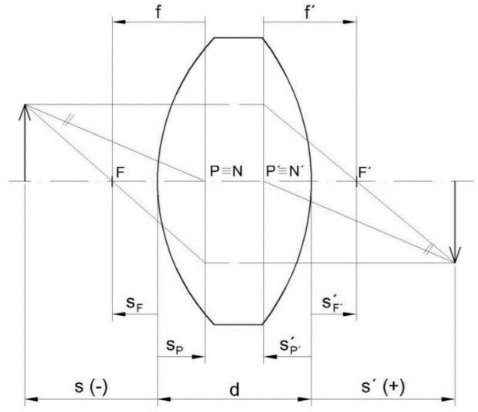


Figure 22, thick lens illustration of parameters (23)

Transfer equations:

$$\frac{n'}{s'} - \frac{n}{s} = \frac{n'-n}{r} \tag{4}$$

Effective focal length:

$$f' = \frac{s1'.s2'.s3'....}{s1.s2.s3....} \tag{5}$$

holds for the paraxial space, where sinα = α. (23)

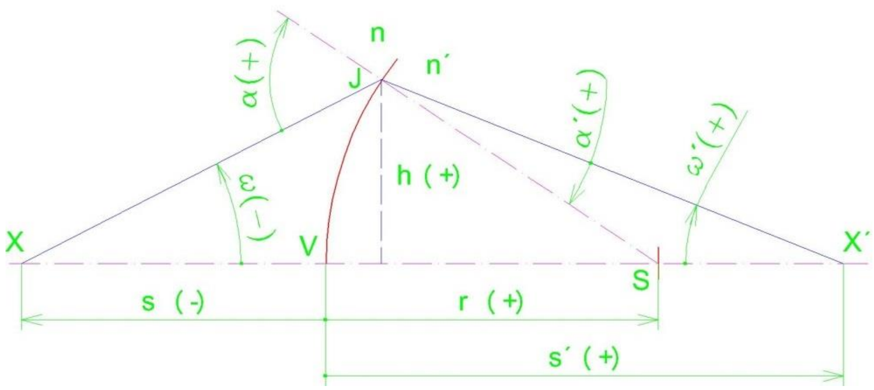


Figure 23, thick lens parameters. (23)

For a centered system of spherical surfaces (or cylindric surfaces, calculated in the meridional plane), i.e. a lens or lens combinations.

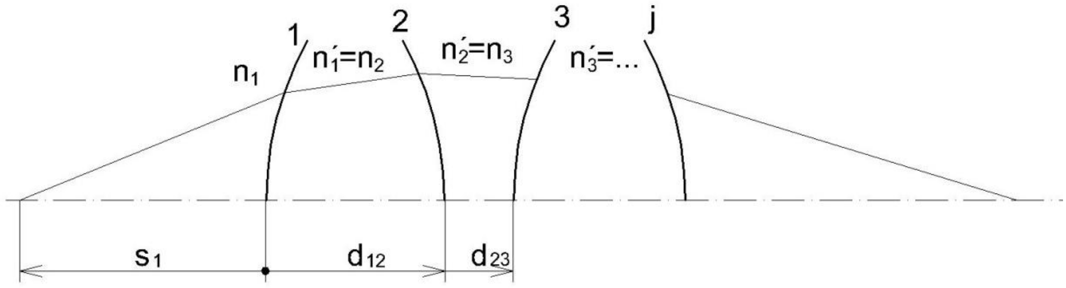


Figure 24, thick lens illustration. (23)

most common applications of cylindrical lenses include astigmatism correction and laser line generation.

- An abnormality in the curvature of the cornea causes light to focus at different point in the cornea. This is called astigmatism and it is corrected using a cylindrical lens placed in front of the eye to focus the incoming light.
- Laser line generator: Cylindric lenses can also be used as laser line generators, the incoming laser from the laser cavity will be focused to a line after passing through a cylindrical lens. So, a laser line will be generated. This is important for engineering applications like laser cutting and laser polishing. An aspherical cylindrical lens with a protective coating is usually used. (4)

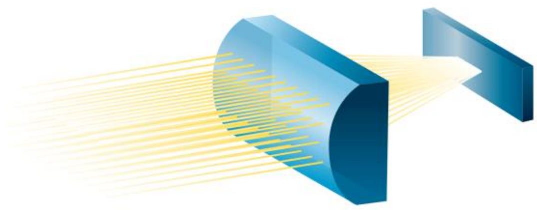


Figure 25, cylindrical lens as a laser ling generator (4)

Chapter IV: Practical Work

The goal of this work is to reshape the gaussian laser beam with a circular spot to a rectangular spot of WidthxHeight dimensions and to control the width of the rectangular spot.

Numerical analysis of the situation:

Two parameters are crucial to the construction of this system, provided that it is treated as thin lens system. One of them is the ratio of focal lengths of the lens arrays, the focal length of the lens arrays, and the height of the lens elements in the lens arrays.

The situation is illustrated below:

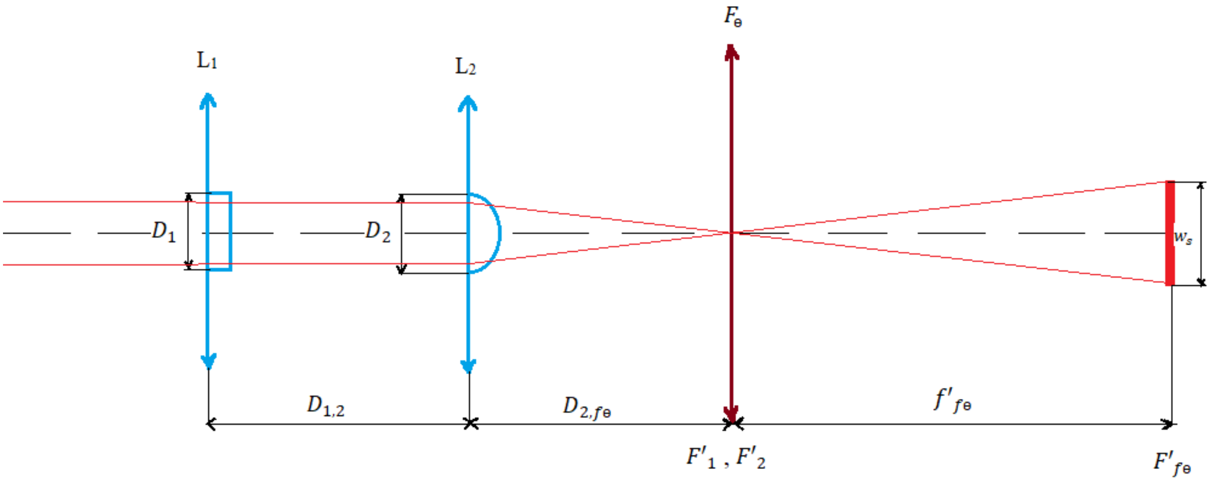


Figure 26, illustration of optical elements in the x-y plane

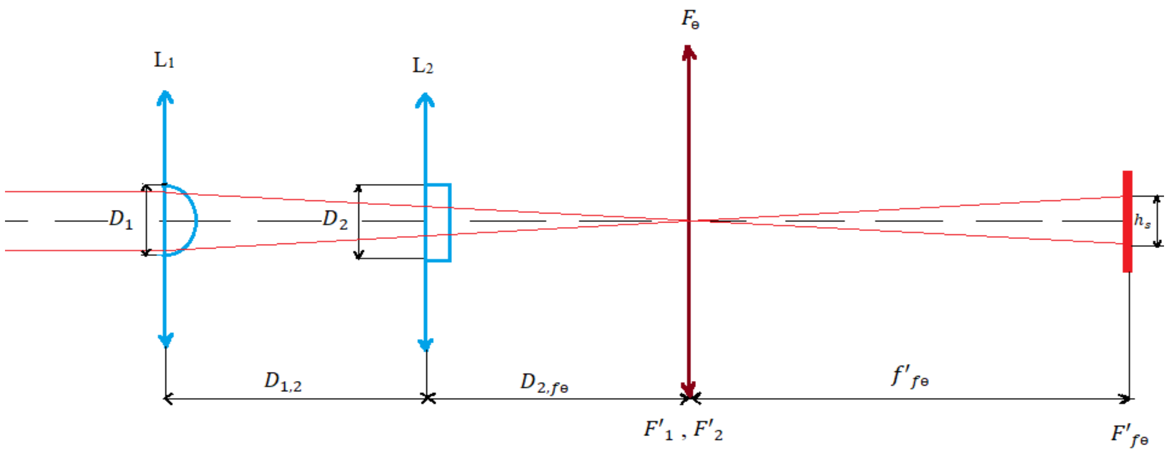


Figure 27, illustration of optical elements in the x-z plane

L1 and L2 are cylindrical lens arrays, both placed at a distance from f-theta lens chosen to be equal to their focal lengths to obtain the initial spot size and maintain the similar triangle ratios. They are placed in a crossed manner with their optical axis perpendicular to each other. The rectangular resultant spot will therefore be at the focus plane of the f-theta lens. Let h_s be the height of the spot and in its perpendicular direction w_s as the width. While both lens arrays are equal in size and diameter of their cylindric lens elements, their focal lengths must be different to obtain a rectangular spot shape. Assuming that L_1 contributes the height of spot. and L_2 contributes the width, then the ratios of their parameter will be as following:

$$\frac{D_1}{f'_1} = \frac{h_s}{f'_{f\theta}} \tag{6}$$

$$\frac{D_2}{F_2} = \frac{w_s}{f'_{f\theta}} \tag{7}$$

$$\frac{w_s}{h_s} = \frac{f'_1}{f'_2} \tag{8}$$

The ratios above are obtained by the similarity of the triangles formed when two laser rays parallel to the optical axis refract through the system. Based on the formulas, the ratio of width to height of spot must be equal to the ratio of the focal lengths of L_1 and L_2.

If the width is three times the height, the focal length of the first lens array L_1 must be three times the focal length of lens array L_2.

The focal length of the f-theta lens $f'_{f\theta}$ - or the focus lens - is crucial to the structure of the system. It corresponds distance at which a specimen is placed for machining (polishing, cutting). The focal plane of f-theta is where the optimum size and intensity of the spot will be. One of the lens arrays will be responsible for the height and the other for the width. In the experiment two cylindrical lenses were used instead of two lens arrays. The equations that relate the parameters of the lenses with the spot size are derived as follows:

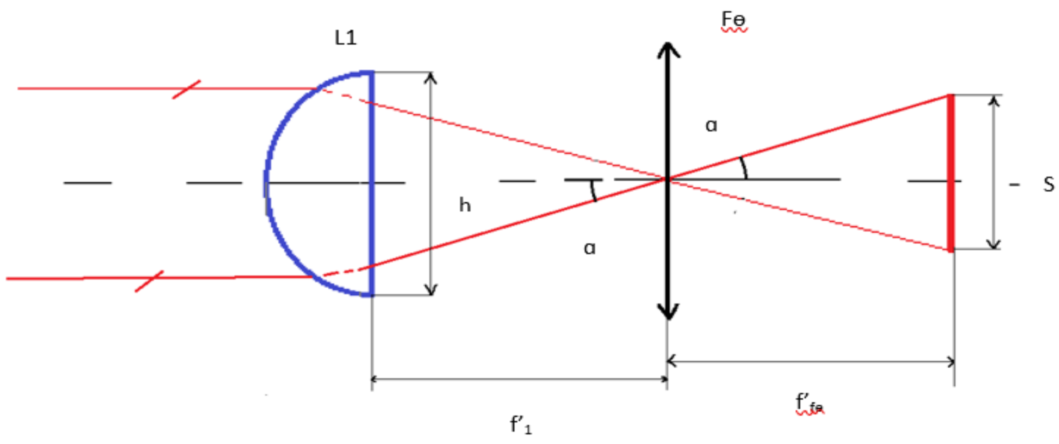


Figure 28, schematic of cylindric lens and f-theta lens for ratio calculation

$$\frac{\frac{1}{2}h}{f'_1} = \frac{\frac{1}{2}S}{f'_{f\theta}} \tag{9}$$

$$\tan \alpha = \frac{opposite}{adjacent} \tag{10}$$

$$\frac{\frac{1}{2}h}{f'_1} = \frac{\frac{1}{2}S}{f'_{f\theta}} = \tan \alpha \tag{11}$$

$$S = \frac{hf'_{f\theta}}{f'_1} \tag{12}$$

Equation 12 is a very important relation. It describes the relationship between the spot size and some of the crucial parameters of the lenses. The spot size in one axis, either x or y axis depending on the lens array involved (whether width or height) is determined by the height of the cylindric lens – the diameter, the focal lengths of the f-theta lens and of the cylindric lens itself. This holds true for both lenses – or lens arrays, with either the horizontal or the vertical axis.

This relation also indicates that the only parameters that affect the spot size are the height and focal lengths of the lenses. The spot size does not depend on the lenslets distances from f-theta lens nor from each other. This means that to change the size of the laser spot, the height or the focal lengths must be manipulated accordingly.

Note that the focal lengths of L_1 and L_2 are crucial to the system, but not the distances between them. Let's trace the lower rim ray, which determines the top point of the spot in the f-theta focal plane, i.e. the spot size. Sliding the lens along the optical axis, we see that the lower rim rays are all parallel for any lens position. Any set of parallel rays will be focused at a point in the focal plane as the figure illustrate below. Rays coming from infinity will first be focused at the focal point of the lens L_1, then in the focal plane of f-theta lens. This illustrates that the distance L_1 is placed doesn't play a part in deciding the spot as the angle will be the same. The mathematical proof is that the lenslet distance does not appear in equation (12).

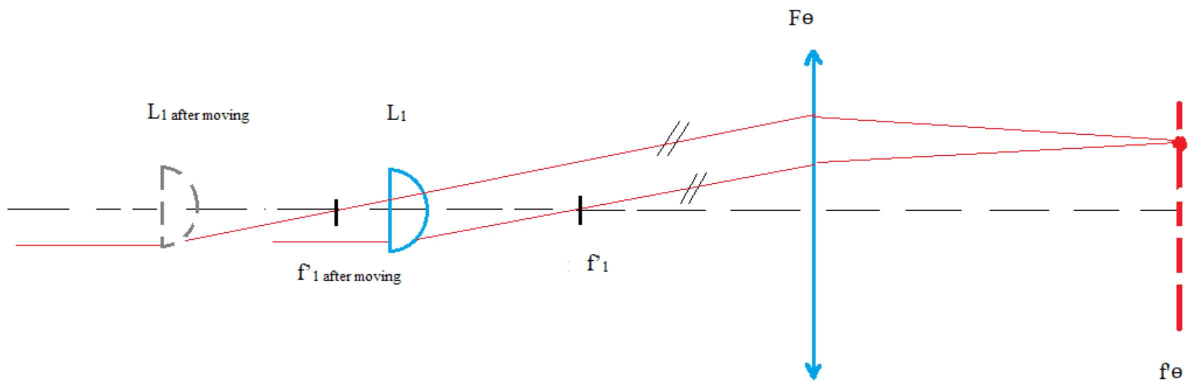


Figure 29, illustration of moving the cylindrical lens and its consquence

Changing the spot size

To make the spot size bigger or smaller one technique is to change the focal length of the lens by adding another lens with its own focal length. A concave cylindrical lens can be added and used as a zoom lens in one axis. A change in the distance between the cylindrical lens and the concave cylindrical lens will result in a change of their effective focal length, which will result in the change of the size of the spot in one axis depending on the axis of the first cylindric lens. The mathematical relation for obtaining the effective focal length of the second lens array [f'_2] and the focal length of the zoom lens [f'_z] is as follows:

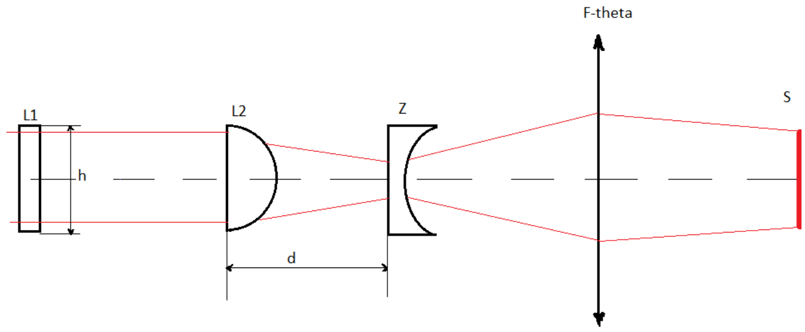


Figure 30, schematic of optical system with concave lens

$$f'_{2,z} = \frac{f'_2 f'_z}{f'_2 + f'_z - d} \tag{13}$$

Where *d* is the distance between the two lenses. This is the variable to control in the system by moving the zoom lens, which would affect the focal length and thereby change the spot size in one direction. The joined equation for obtaining the spot size will then be:

$$S = \frac{hf'_{f\theta}}{f'_{2,z}} = S = \frac{hf'_{f\theta}}{\frac{f'_2 f'_z}{f'_2 + f'_z - d}} \tag{14}$$

Where S is the spot size in one axis. The zoom lens only allows the change in spot size in one axis. Either width or height depending on its axis of optical power. To change the size in both axis x and y, another concave cylindrical lens must be placed. This won't be needed for applications such as laser polishing and engraving which don't require such a modification. Changing the spot size in one axis is efficient enough.

Experiment

To test the formulated relations of the beam shaping optical system, an experiment was conducted using lenses and equipment available in the optical lab of the department of Automatization and Control Engineering. The goal of the experiment is to verify the relations obtained in the previous section.

Equipment and elements used:

1. He-Ne laser: this is the source of the laser beam
2. Space filter: made up of a microscope objective and a pinhole. This element is used to expand the laser light to a divergent beam.
3. Collimator: a collimator is a positive lens used here to change the diverging light rays to a parallel rays. f‘=500mm
4. Two convex cylindric lenses: two positive cylindric lenses. One with f'_1= 50mm, the other f'_2=110mm. These two lenses together with focus lens and zoom lens form the optical system for this beam shaping technique.
5. One concave cylindric lens: the zoom lens, a negative concave cylindric lens which is responsible for changing the size of the produced spot in one direction. f'_z=-30mm
6. Focus lens: a positive lens, with a relatively high focal length. this will come in f-theta lens‘ stead for the experiment; focal length f‘=250mm
7. Lens holders: instruments that hold the lenses in proper place.
8. Caliper and ruler: used for measurement of dimensions and spaces between the elements of the system.
9. Two mirrors: they‘re used here to reflect and change the direction of the laser light into the system of lenses.
10. Diaphragm: used to stop down the beam. Diameter is variable, for the experiment set to 20mm.

Creating a beam of parallel rays:

For our application the laser beam must be collimated. To generate collimated light from a divergent beam, we use a collimator lens with its focus coinciding with the divergent beam's focus. The figure below illustrates the components of the system.

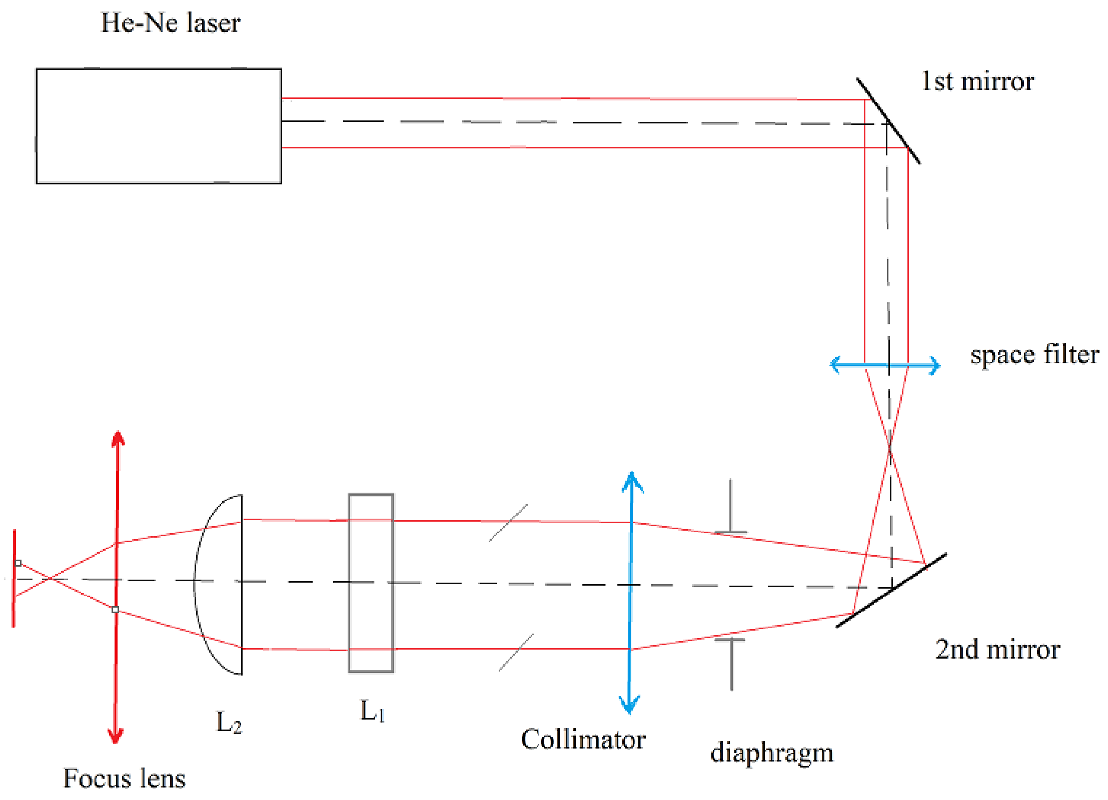


Figure 31, illustration of entire system of components

Steps:

1. Firstly, the adjustment of the space filter was made. A mirror was placed against the front mechanical face of the space filter. The back-reflected beam was observed. The space filter was rotated until a spot from the reflected beam was seen at the laser.

At this setting the space filter’s optical axis is parallel to the laser beam. The height and side adjustment were made to make the laser beam and space filter’s optical axes colinear. Lastly, we focused the pinhole until the most perfectly circular spot was achieved without any rings around the spot as shown in the pictures below.

Figure 32, pictures of the spot before and after focusing the pinhole

2. Then the diameter of the beam was checked first before the collimator where a mirror was placed to reflect and adjust the direction of the beam into the collimator. After the beam enters the collimator, the collimator’s position is adjusted and the output beam’s diameter was observed, if the diameter of the beam got increasingly bigger after the collimator, then the collimator is placed too close to the pinhole. If the beam’s diameter got smaller and then bigger, meaning the beam converged to a certain point then began diverging before the collimator, meaning the collimator is too far from the focused pinhole.

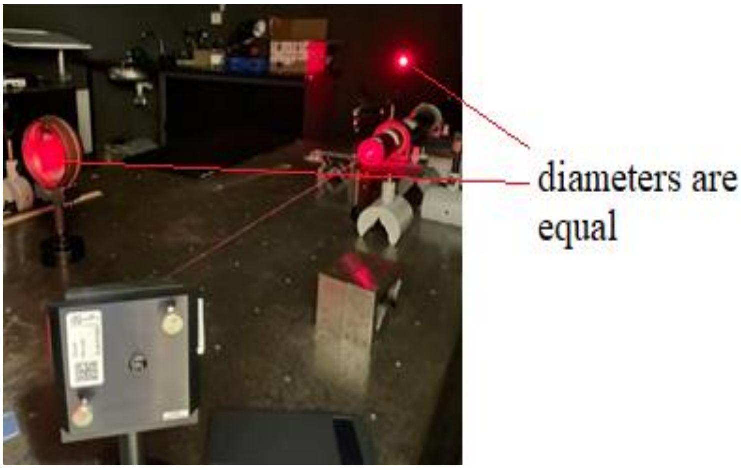


Figure 33, picture illustrating the collimated beam with equal diameters at the collimator and at projection on the wall

3. After this, a mirror was placed in front of the collimator and the collimator’s position was shifted lightly and tilted until the smallest spot size was observed in the back reflection from the second mirror on the pinhole. If the pinhole was exactly at the focal point of the beam, the beam will diverge beyond the pinhole into the collimator, then a beam of parallel rays would propagate from the collimator.
4. To further verify the collimation of the beam, a parallel plate was placed after the collimator to observe the spot. If the beam was of parallel rays, a uniformly illuminated spot will be observed on the surface of the plate. If the beam was not of parallel rays, interference fringes would appear on a screen behind the plate and the collimator’s position will be shifted until the interference fringes become wider and wider so as to realize one interference fringe wide enough to form an equally illuminated spot.

Procedure of expirement

The experiment is divided into two tasks. Firstly, changing the laser spot **shape** from circular to rectangular and checking functionality of system. The second task is adding the negative concave cylindric lens to change the spot **size**.

Task 1: Changing the spot shape

Preparation began with emitting the laser light onto a mirror, which then is reflected into the beam expander. The beam from here is reflected by the second mirror followed by an aperture stop of 20mm in diameter then the beam propagates through the collimator which turns the laser light into a beam of parralel rays. Then the laser beam enters the beam shaping system comprised of two positive cylindrical lenses and a focus lens. The first is placed horizontally and the second vertically. Both the cylindrical lenses have been stopped down with slits of 5mm height. Finally, the laser is focused with the focus lens onto the focus plane of the focus lens with f‘=250mm. The placement of the elements is shown below.

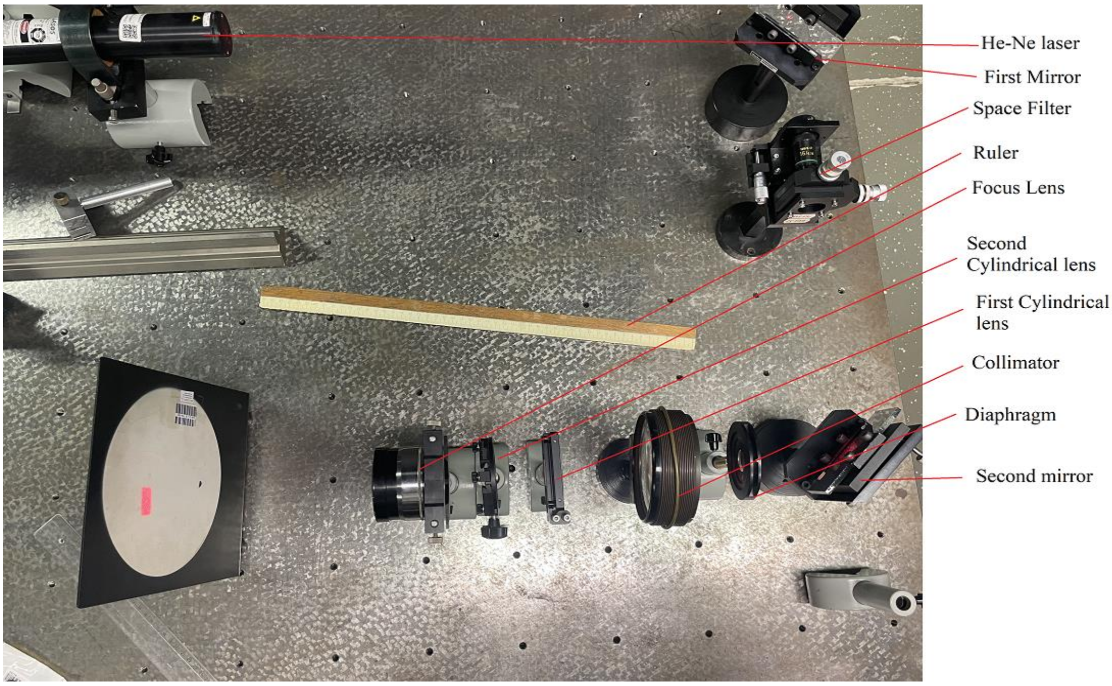


Figure 34, picture of elements of the system

Both cylindrical lenses are placed so that their focal points are on the focus lens’s surface. This is done to keep in line with the formulas as the position of the cylindrical lenses relative to each other is not a factor in determining the spot size.

calculated values:

for h_1=5mm= h_2, f'_1=110mm, f'_2=50mm, f'_f=250mm

the calculated height of the spot is:

$$S_H = \frac{hF'_f}{F'_1} = \frac{5 * 250}{110} = 11.363mm$$

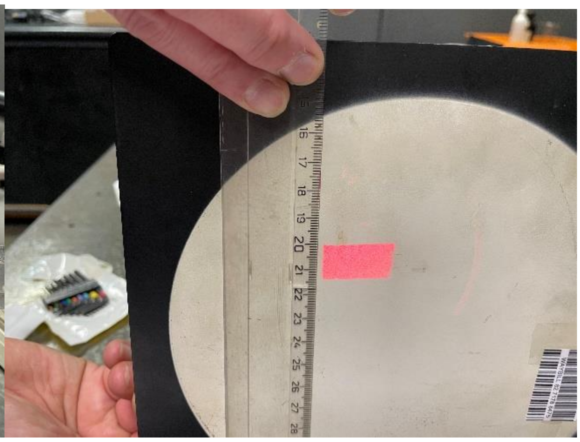
Width:

$$S_W = \frac{hF'_f}{F'_1} = \frac{5 * 250}{50} = 25mm$$

S_H and S_W are the calculated values for the spot size. In theory, these dimensions result in a rectangular spot of size 11.36x25mm.

Measured spot:

The spot size produced by this system resulted to be indeed rectangular with size 12.5x26mm. As shown in the pictures below.



The offset of 1mm in between the measured and calculated values may be due to;

1) the lenses having a slightly different focal length. This is normal as there are tolerences to focal lengths.

2) Measuring the spot at a location slightly off the focal plane of the focus lens.

3) The laser beam not consisting of perfectly parallel rays. The focal plane position of the focus lens was determined during the experiment by finding the smallest spot after taking out the cylindric lenses.

4) The paper slit stopping the cylindric lenses down being not precisely 5mm high.

The result in the images above verify the relations calculated and validate the functionality of this beam shaping technique. The spot height or width depends on the focal lengths of the lenses and the height of the cylindrical lenses – or the height of the slit used to stop them down.

Testing focal length ratio relation to spot dimensions:

Calculated:

$$\frac{w_s}{h_s} = \frac{f'_1}{f'_2} = \frac{110}{50} = \frac{25}{11.36} = 2.20$$

Measured:

$$\frac{w_s}{h_s} = \frac{26}{12.5} = 2.08 \approx \frac{f'_1}{f'_2} \equiv 2.2$$

This indicates that the equation of the ratios of focal length to spot width and height holds true. During the expirement both cylindrical lenses were moved and no changes in the spot dimensions were observed. This is an experimental proof of the independence of the spot size to the lenses‘ distances from the f-theta lens as formula (12) concluded.

Task 2: Changing the spot size

Procedure:

Changing the spot size can be achieved in three ways; by changing the focal lengths of either the cylindrical lenses or both, changing the f-theta lens focal length – this could be done by swapping the lens itself or adding additional optical elements. Or by changing the height of cylindric lenses. The most applicable way is to change the focal length of the lens directly before the f-theta lens (lens 2) by adding a concave cylindrical lens. Call it a zoom lens with f'_z=-30mm. This will change the effective focal length of lens 2 and enable the control of their focal lengths by manipulating the distance between the two lenses as in formula (15):

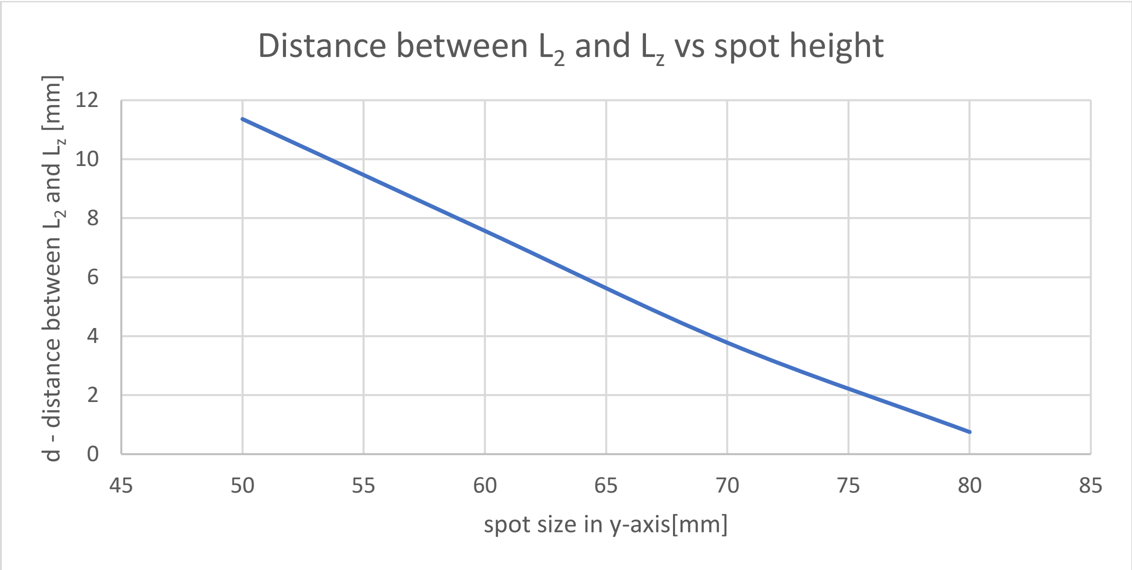
$$f'_{2,z} = \frac{f'_2 f'_z}{f'_2 + f'_z - d} \tag{15}$$

This will in turn change the spot size in one axis -the axis of optical power of both cylindrical lenses, as so:

$$S = \frac{hf'_{f\theta}}{f'_{2,z}} = S = \frac{hf'_{f\theta}}{\frac{f'_2 f'_z}{f'_2 + f'_z - d}} \tag{16}$$

Calculated values:

f'_2[mm]	f'_z[mm]	d[mm]	$f'_{2,z}$[mm]	S_y[mm]
110	-30	50	-110	11.36
110	-30	60	-165	7.57
110	-30	70	330	3.78
110	-30	81	3300	0.37

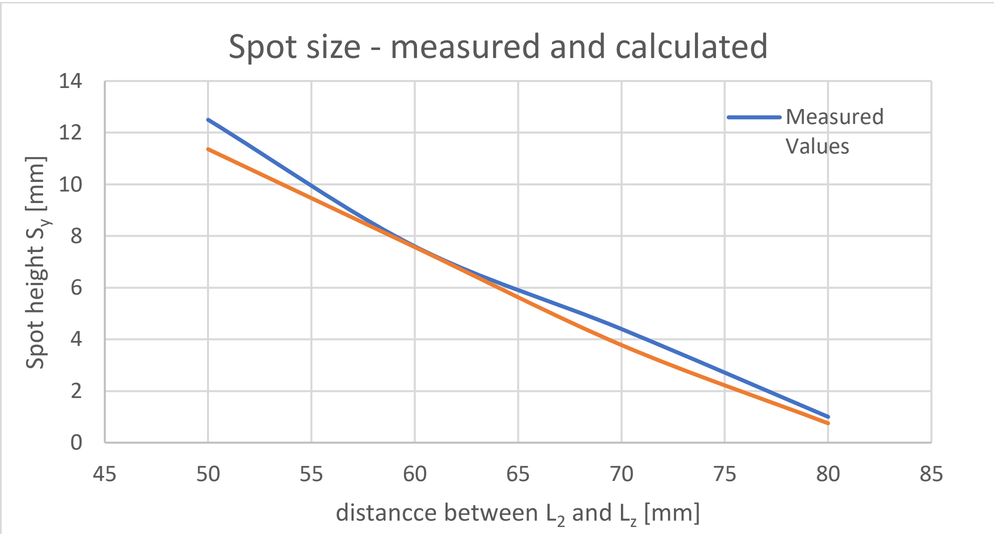


Measured values:

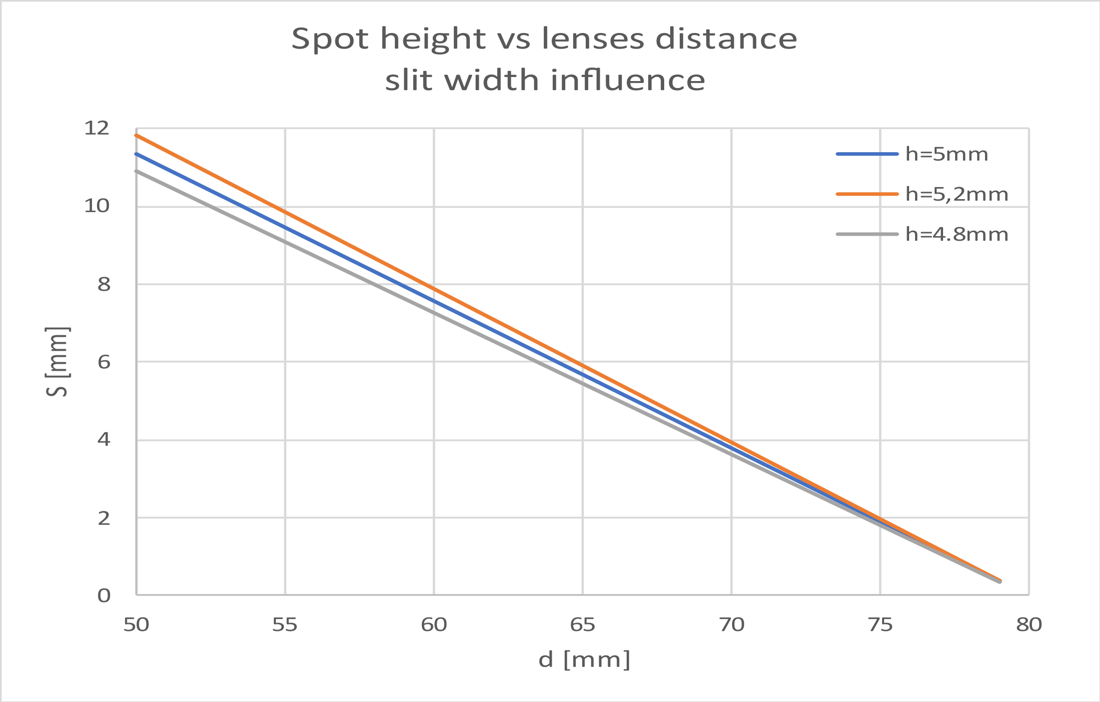
With increasing the distance between L_z and L_2 incrementally by 10mm, except for the last increament was 11mm to keep getting real results as d=80mm yields a $f'_{2,z}$ = infinity, so

81mm was used to keep the denominator in equation (16) a real value. the following S_y values were measured:

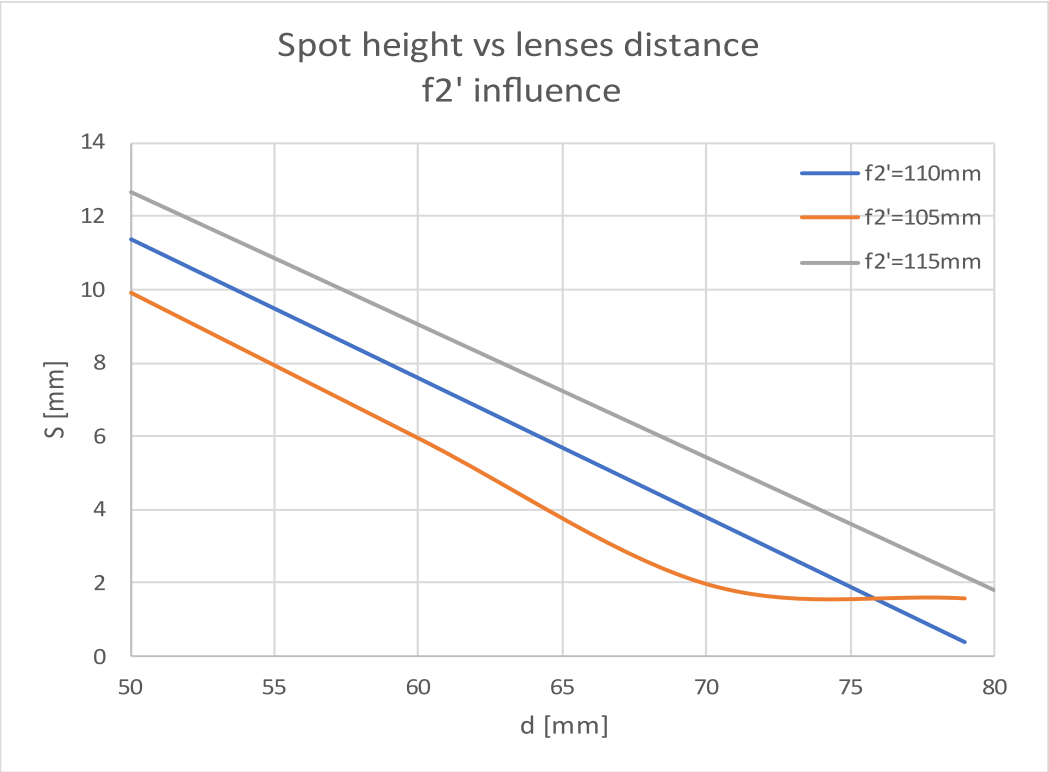
d[mm]	S_y[mm]
50	12.5
60	7.6
70	4.4
81	1



The spot size values are very sensitive to the focal lengths and to the stop size used to stop the cylindrical lenses i.e., the used height of the lenses, as well as the lenses' separation.



The plot relating the spot height with lense' distance and relating f'$_2$ influence is as follows::



Conclusion

The goal of this thesis was to investigate a laser beam shaping technique that controls the shape and size of the laser spot. With two positive lens arrays of cylindrical lens elements to divide the input collimated laser beam into beamlets for them to later be superimposed onto the focal plane of the f-theta lens, and a negative lens array for controlling the spot size in one dimension. During the experiment the offset between the measured and calculated values was 0.5 mm on average and it may be due to the following reasons as mentioned above in this chapter; 1) the lenses having a slightly different focal length due to different focal length tolerances 2) Measuring the spot at a location slightly off the focal plane of the focus lens. 3) The laser beam not consisting of perfectly parallel rays. 4) The size of the slit used to stop down the cylindrical lenses. However, the results of the experiment confirm that the beam shaping technique is indeed functional and controllable. an optical system with the components in this experiment was simulated using Zemax software by the thesis supervisor Ing. Bc. Sarka Nemcova, Ph.D. With L_1 focal length being 110mm, L_2=50mm, L_3 as the zoom lens with f‘=-30mm and the f-theta lens with focal length of 250mm. the height of the lenslets of L_1 and L_2 was 5mm. The distance d between L_2 and L_3 was increased increamentally as in the experiment from 50mm to 60mm to 70mm to 80mm. The layout is as follows:

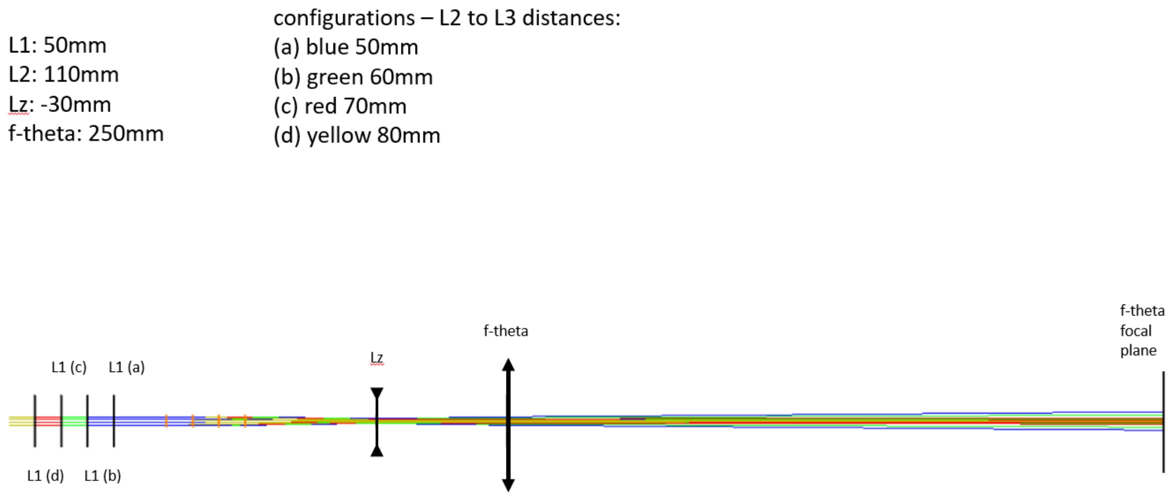


Figure 35, Screenshot of system in Zemax software

The spots obtained at each position of L_z were the following:

At d=50mm, the spot width was w_s= 11.14 mm

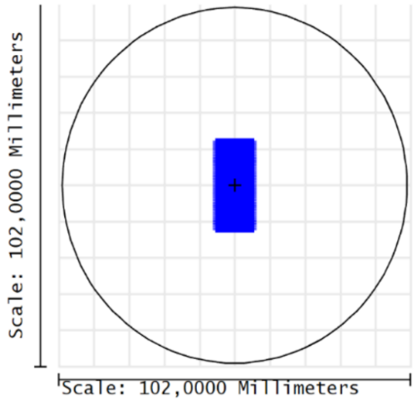


Figure 36, spot size with d=50mm

At d=60mm, the spot width was w_s= 7.4 mm

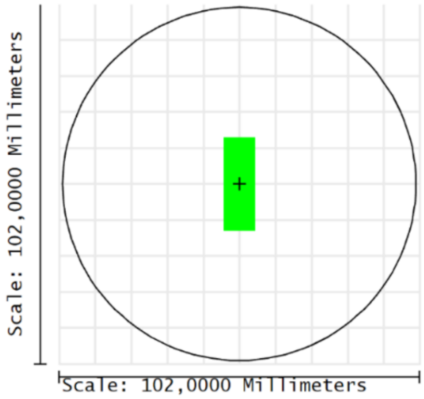


Figure 37, spot size with d=60mm

At d=70mm, the spot width was w_s= 3.64 mm

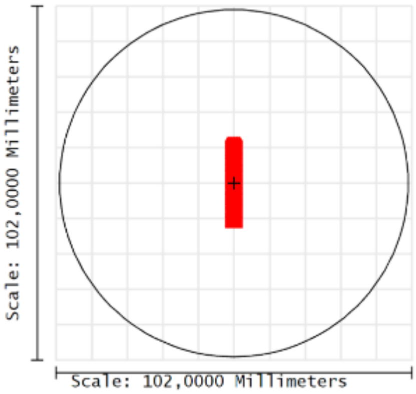


Figure 38, spot size with d=70mm

At d=80mm, the spot width was w_s= 0.1 mm

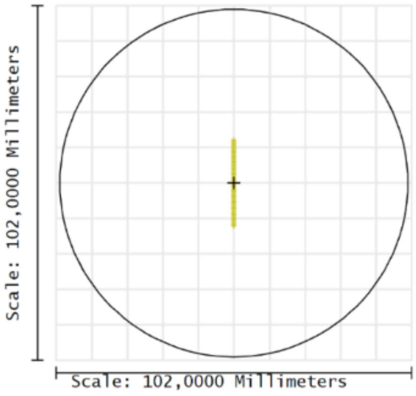


Figure 39, spot size at d=80mm

Results of the zemax simulation verify the ability of the technique to form a rectangular spot of the laser beam and verifies its controlability. In addition to the reasons mentioned above, The slight offset between the values obtained from the Zemax simulation and values measured during the experiment may be due to the extreme sensitivity of the spot size to the size of the slit used to stop down the cylindrical lenses during the experiment.

References

1. Shaik, Muskan. laser. *physics-and-radio-electronics.com.* [Online] [Citace: 20. october 2021.] https://www.physics-and-radio-electronics.com/physics/laser/laserintroduction.html.

2. laser marking. *www.trumpf.com.* [Online] [Citace: 23. october 2021.] https://www.trumpf.com/en_GB/solutions/applications/laser-marking/annealing-laser-marking-procedure/.

3. *Review on Surface Quality Improvement of Additively Manufactured Metals by Laser Polishing.* Ermergen, T., Taylan, F. místo neznámé : Arabian journal for science and engineering, 2021.

4. edmundoptics. WHAT ARE CYLINDER LENSES? *https://www.edmundoptics.eu.* [Online] [Citace: 15. 10 2021.] https://www.edmundoptics.eu/knowledge-center/application-notes/optics/what-are-cylinder-lenses/#:~:text=Cylinder%20lenses%20are%20a%20type,in%20only%20a%20single%20axis..

5. Grossinger, Israel. beam shaper. *holoor.co.il.* [Online] [Citace: 11. january 2022.] https://www.holoor.co.il/product/beam-shaper/.

6. Shaik, Muskan. principles of a working laser. *https://www.physics-and-radio-electronics.com.* [Online] [Citace: 20. october 2021.] https://www.physics-and-radio-electronics.com/physics/laser/principlesofworkingofalaser.html.

7. —. laser construction. *https://www.physics-and-radio-electronics.com.* [Online] [Citace: 21. october 2021.] https://www.physics-and-radio-electronics.com/physics/laser/laserconstruction.html.

8. Paschotta, Dr. Rudiger. Gaussian beams. *rp-photonics.com.* [Online] april 2020. https://www.rp-photonics.com/gaussian_beams.html.

9. —. rp-phonetics.com. *rp-phonetics.com.* [Online] september 2020. https://www.rp-photonics.com/beam_divergence.html.

10. Paschotta, Dr. Rüdiger. beam divergence. *https://www.rp-photonics.com/beam_divergence.html.* [Online] [Citace: 21. october 2021.] https://www.rp-photonics.com/beam_divergence.html.

11. —. beam quality. *rp-photonics.com.* [Online] [Citace: 21. october 2021.] https://www.rp-photonics.com/beam_quality.html.

12. Stewart C. Black, Vic Chiles, A.J. Lissaman, S.J. Martin. Principles of machning - non traditional methods . [autor knihy] MSc, CEng, FIEE, FIMechEVicChilesCEng, PhD, BSc, MIEEA.J.LissamanCEng, MIMechE, FIProdES.J.MartinCEng, FIMech, FIProdE Stewart C.BlackBSc. *Principles of machning - non traditional methods .* gloucestershire : autor neznámý, 1996.

13. Kuman, Amrit. learnmechanical. *learnmechanical.com.* [Online] [Citace: 21. october 2021.] https://learnmechanical.com/laser-beam-machining/.

14. Jahrling, Nina. *researchgate.net.* [Online] october 2011. [Citace: 21st. december 2021.] https://www.researchgate.net/figure/Free-Gaussian-beam-propagation-along-the-z-axis-w-G-z-beam-width-z-axial-distance_fig1_220514305.

15. edmundoptics. why use lat top laser beams. *edmundoptics.eu.* [Online] january 2021. https://www.edmundoptics.eu/knowledge-center/application-notes/optics/why-use-a-flat-top-laser-beam/.

16. Kristina Kaszei, Cory Boone. Flat-top laser beams: Their uses and benefits. *https://www.laserfocusworld.com.* [Online] 24. March 2021. [Citace: 15th. december 2021.] https://www.laserfocusworld.com/optics/article/14197298/flattop-laser-beams-their-uses-and-benefits.

17. diffractive-optical-element-basics/. *https://www.holoor.co.il.* [Online] 19. November 2020. [Citace: 2nd. january 2022.] https://www.holoor.co.il/diffractive-optical-element-basics/.

18. *Laser Beam Shaping techniques.* Fred M. Dickey, Louis S. Weichman, Richard N. Shagam. Albuquerque USA : Sandia National Labratories, 2000.

19. HoloGraphix. Custom Diffractive Optical Elements. *https://holographix.com.* [Online] [Citace: 23rd. december 2021.] https://holographix.com/custom-diffractive-optical-elements/.

20. thorlabs. *https://www.thorlabs.com/.* [Online] [Citace: 6th. january 2022.] https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=10766.

21. slidetodoc.com. chapter1 ray optics postulates of ray optics. *https://slidetodoc.com/.* [Online] [Citace: 11. january 2022.] https://slidetodoc.com/chapter-1-ray-optics-postulates-of-ray-optics/.

22. Argueta, Victor. 5 applications of cylindrical lenses. *opticsforhire.com.* [Online] optics for hire. [Citace: 11. january 2022.] https://www.opticsforhire.com/blog/5-applications-of-cylindrical-lenses-design.

23. Nemcova, Sarka. Lecture 4 - curved optical surfaces. *moodle-vyuka.cvut.cz.* [Online] [Citace: 11. december 2021.] https://moodle-vyuka.cvut.cz/pluginfile.php/88642/mod_resource/content/0/TOP-lecture4.pdf.

24. *youtube.com.* [Online] 25. february 2020. [Citace: 13. january 2022.] https://www.youtube.com/watch?v=Z7Q17-ctQVQ.

25. Dr, Rudiger paschotta. https://www.rp-photonics.com. *https://www.rp-photonics.com.* [Online] january 2021. https://www.rp-photonics.com/beam_quality.html.