Technical University of Crete
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DEVELOPMENT OF COHERENT AND INCOHERENT LIGHT SOURCES WITH COMPUTER CONTROL OF THEIR SPECTRAL EMISSION FOR BIOMEDICAL APPLICATIONS

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I dedicate this thesis to my parents for their understanding and support throughout my life.

ABSTRACT

The subject of this Master thesis is the design, prototyping and technical evaluations of advanced light sources offering distinct advantages over the conventional one.

Conventional black-body or gas discharge light sources are still very popular, they suffer however from a long list of shortcomings including but not limited to: ramp-like spectral emission, heating, uncontrolled sparks (short-peaks) in their emission spectra, limited ability to control their intensity distribution along their emission wavelength range etc.

This thesis addresses the demand for alternative light sources, free from the above mentioned limitations.

To this end, two kinds of compact solid state light sources were developed based on the optical multiplexing of distinct, narrow band LED and LASER light sources.

In the first case an array of LEDs was developed with members covering the spectral range from ultraviolet to near infrared. The LEDs were coupled with the multiple ending of a custom made polifurcated fiber optic bundle, thus achieving an excellent multiplexing. Specially developed hardware controllers were employed for controlling the intensity distribution across the entire wavelength range of the multi-LED light sources. The intensity distribution could, under computer control, take the 'flat' spectral profile corresponding to an 'absolute white' light source. Alternatively, it could take the form of spectrum with peaks and deeps in wavelength ranges defined by the user.

The second development corresponds to a multiple wavelength laser source with the option of controlling the relative intensity of LASER lines. All LASER lines are multiplexed in a liquid light-guide for achieving beam homogenization. A major challenge that was faced when the multilaser source was used for imaging was the so-called 'speckle' effect. This effect introduced fixed random pattern noise effects in imaging applications due to the local interference of the coherent LASER Light. This issue was effectively solved with the employment of a vibrating diffuser interposed in the beam's path. The vibrating diffuser destroyed partially the coherent nature of the laser beam, thus minimizing interference effects and reduce the speckle phenomena.

The developed light sources are currently used in a series of applications such as fluorescence microscopy, wavelength response calibrator, multispectral imaging, study of eye response to control optical stimuli etc.

Additional applications are currently on their development stage, while further improved designs are scheduled for the near future.

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INTRODUCTION

In this master thesis, two kinds of solid state light sources were developed based on the optical multiplexing of distinct, narrow band LED and LASER light sources. Conventional black-body or gas discharge light sources are still very popular but they have some drawbacks including ramp-like spectral emission, heating, uncontrolled sparks (short-peaks) in their emission spectra, limited ability to control their intensity distribution along their emission wavelength range.

So we need light sources that are free of the above shortcomings. The need of Light Sources with a controlled stable intensity distribution along its emission wavelength is immediate. Also, the feature of a flat line spectral emission is very important as well as custom emission curves with deeps and peaks that the user will pick. Moreover, the design of light source for exciting several fluorophores simultaneously or not is very important. Furthermore, the need of high power output combined with low working temperatures is very important feature of a light source. Nevertheless, the compact design of a Light source is an engineering challenge.

In Chapter 1, the characteristics and physics of various incoherent light source are presented. Specifically, black body radiation sources, incandescent lamps, gas-discharge light sources, lasers and LEDs.

Furthermore, in Chapter 2, the characteristics and physics of various coherent light sources, including gas lasers, solid-state lasers, semiconductor lasers as well as a series of tunable lasers.

In Chapter 3, various incoherent and coherent light sources that already are used in biomedical applications are presented.

In Chapter 4, the development of an innovative Incoherent Light Source, designed in our lab, is presented. The Incoherent Light Source is capable of emitting light wavelengths in the range of 380-810nm. All the electronics and mechanical parts as well as the software application are presented in detail. Finally, the technical evaluation of the source is presented. A series of laboratory tests have been taken place to evaluate the performance of the source. Also, several intended applications are listed.

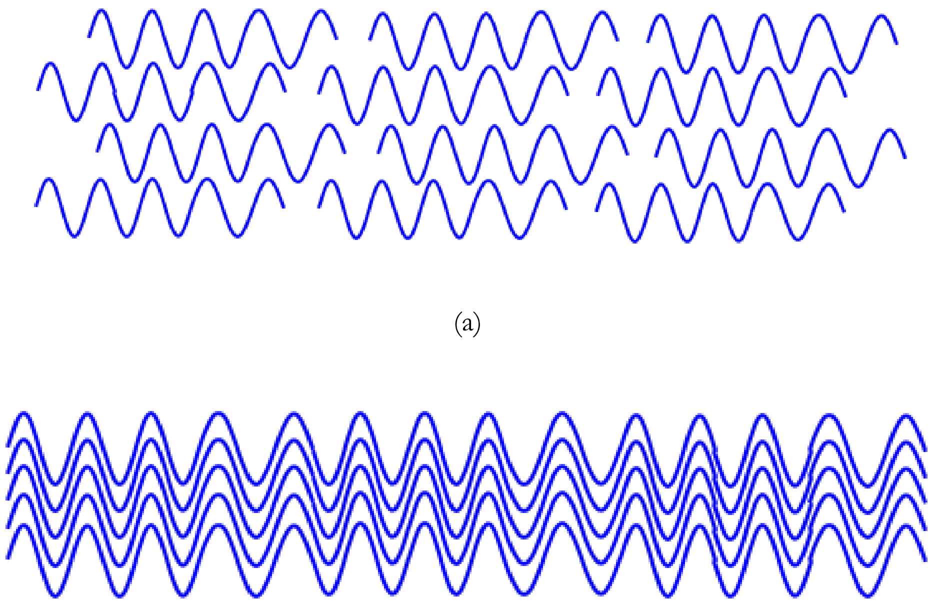
In Chapter 5, the development of an innovative Coherent Light Source, designed in our lab, is presented. The Coherent Light Source is designed for use in a wide range of applications including but not limited to fluorescence. All the electronics and mechanical parts are clearly presented and illustrated. Also, the Graphical User Interface application for controlling the source's emission is presented in detail. Finally, the technical evaluation of the source is presented including the emission spectra of the source a new method for speckle reduction.

1 INCOHERENT LIGHT SOURCES

Light source is a natural or artificial procedure that emits light. The most common natural light source is the sun. Sunlight is responsible for daylight vision. Also, there are other natural light sources like the moon, lightning flashes or bioluminescence, which provide ambient light.

Except from natural light source, there are artificial light sources. The first artificial light source that the humankind discovered is fire. In this chapter we will discuss several light sources, especially artificial, that can produce radiation in the visible region and in the invisible region.

Also, light sources can be distinguished in coherent and incoherent depending on the way the change of phase between the photons is done. In this chapter incoherent light sources are presented. As shown in Figure 1, incoherent light sources emit light with frequent and random changes of phase between the photons in contrast to coherent light sources where the photons are all in 'step' – other words the change of phase within the beam occurs for all the photons at the same time. In this chapter incoherent light sources are presented.



(a)

(b)

Figure 1 | Incoherent (a) and coherent (b) light waves

1.1 Physics [1]

1.1.1 Electromagnetic Waves / Wave model of light

Electricity can be static, like the energy that can make your hair stand on end. Magnetism can also be static, as it is in a refrigerator magnet. A changing magnetic field will induce a changing electric field and vice-versa—the two are linked. These changing fields form electromagnetic waves (Figure 2). Electromagnetic waves differ from mechanical waves in that they do not require a medium to propagate. This means that electromagnetic waves can travel not only through air and solid materials, but also through the vacuum of space.

James Clerk Maxwell first formally postulated electromagnetic waves. These were subsequently confirmed by Heinrich Hertz. Maxwell derived a wave form of the electric and magnetic equations, thus uncovering the wave-like nature of electric and magnetic fields, and their symmetry. Because the speed of electromagnetic waves predicted by the wave equation coincided with the measured speed of light, **Maxwell concluded that light itself is an electromagnetic wave**.

An important aspect of the nature of light is frequency. The frequency of a wave is its rate of oscillation and is measured in hertz, the SI unit of frequency, where one hertz is equal to one oscillation per second. Light usually has a spectrum of frequencies that sum to form the resultant wave. Different frequencies undergo different angles of refraction.

A wave consists of successive troughs and crests, and the distance between two adjacent crests or troughs is called the wavelength. Waves of the electromagnetic spectrum vary in size, from very long radio waves the size of buildings to very short gamma rays smaller than atom nuclei. Frequency is inversely proportional to wavelength.

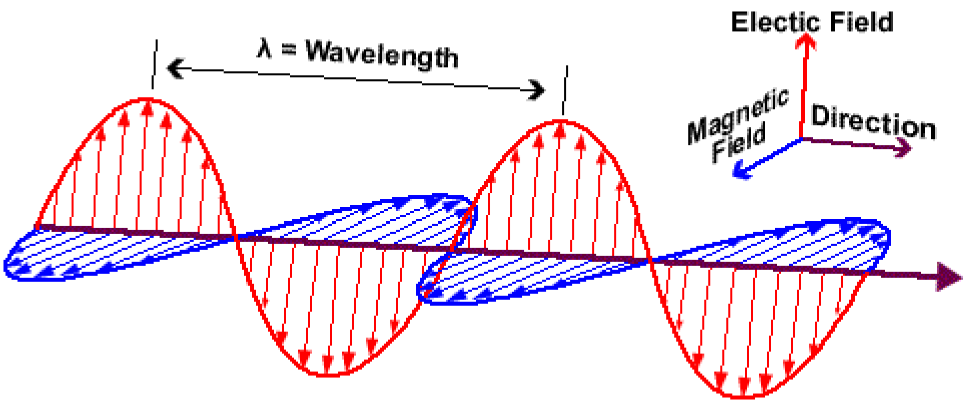


Figure 2 | Electromagnetic wave

1.1.2 Quantum Theory | Particle model of light

The wave picture of light is not the whole story, however. Several effects associated with emission and absorption of light reveal a particle aspect, in that the energy carried by light waves is packaged in discrete bundles called photons or quanta. A photon has an energy, E, proportional to its frequency, f, by

$$E = hf = \frac{hc}{\lambda} \quad (1.1.1)$$

where h is Planck's constant, λ is the wavelength and c is the speed of light in vacuum.

These apparently contradictory wave and particle properties have been reconciled since 1930 with the development of quantum electrodynamics, a comprehensive theory that includes both wave and particle properties. **The propagation of light is best described by a wave model, but understanding emission and absorption requires a particle approach.**

The Electromagnetic Spectrum

The electromagnetic spectrum encompasses electromagnetic waves of all frequencies and wavelengths. Figure 3 shows approximate wavelength and frequency ranges for the most commonly encountered portion of the spectrum. Despite vast differences in their uses and means of production, these are all electromagnetic waves with the same propagation speed (in vacuum) Electromagnetic waves may differ in frequency and wavelength by the relation described above.

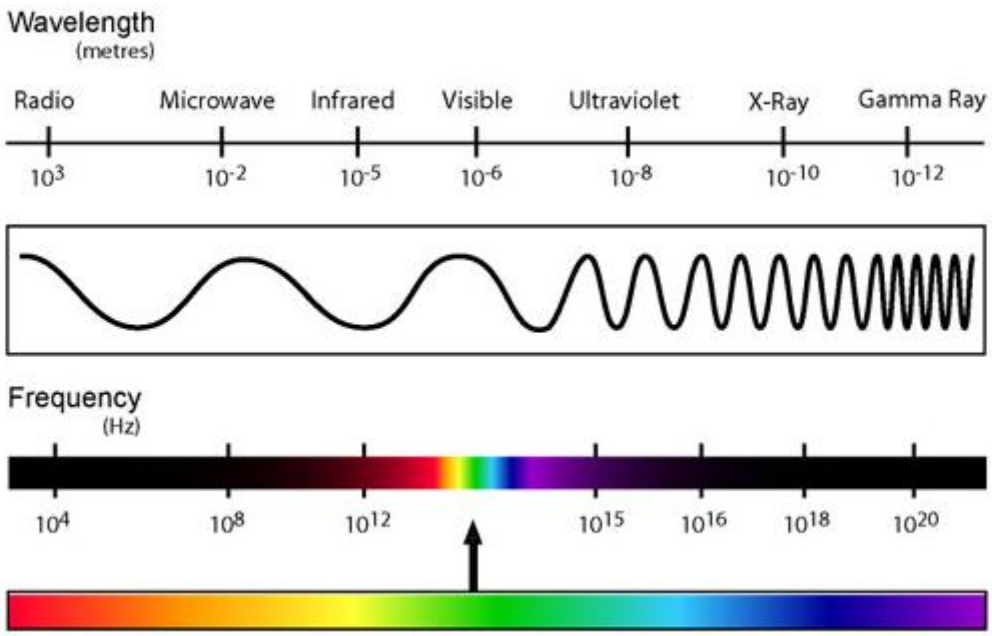


Figure 3 | Electromagnetic Spectrum

In general, EM radiation (the designation 'radiation' excludes static electric and magnetic and near fields) is classified by wavelength into radio, microwave, infrared, the visible spectrum we perceive as visible light, ultraviolet, X-rays, and gamma rays.

The behavior of EM radiation depends on its frequency. Lower frequencies have longer wavelengths, and higher frequencies have shorter wavelengths, and are associated with photons of higher energy. There is no fundamental limit known to these wavelengths or energies, at either end of the spectrum, although photons with energies near the Planck energy or exceeding it (far too high to have ever been observed) will require new physical theories to describe.

Ordinary white light includes all visible wavelengths. However, by using special sources or filters, we can select a narrow band of wavelengths within a range of a few nm. Such light is approximately monochromatic (single-color) light. Absolutely monochromatic light with only a single wavelength is an unattainable idealization. When we use the expression "monochromatic light with band 550 nm" with reference to a laboratory experiment, we really mean a small of wavelengths around 550 nm. Light from a laser is much more nearly monochromatic than is light obtainable in any other way.

We can detect only a very small segment of this spectrum directly through our sense of sight. We call this range visible light. Its wavelengths range from about 380 to 750 nm, with corresponding frequencies from about 790 to 400 THz.

Invisible forms of electromagnetic radiation are no less important than visible light. Our system of global communication, for example, depends on radio waves: AM radio uses waves with frequencies from 5.4×10^5 Hz to 1.6×10^6 Hz while FM radio broadcasts are at frequencies from 8.8×10^7 Hz to 1.08×10^8 Hz (Television broadcasts use frequencies that bracket the FM band.) Microwaves are also used for communication (for example, by cellular phones and wireless networks) and for weather radar (at frequencies near 3×10^9 Hz). Many cameras have a device that emits a beam of infrared radiation; by analyzing the properties of the infrared radiation reflected from the subject, the camera determines the distance to the subject and automatically adjusts the focus. X rays are able to penetrate through flesh, which makes them invaluable in dentistry and medicine. Gamma rays, the shortest-wavelength type of electromagnetic radiation, are used in medicine to destroy cancer cells. Modern imaging detectors can take images of an object in different wavelengths as a way to probe the internal structure of it in different depths.

1.2 Blackbody Radiation [2]

All bodies above a temperature of absolute zero emit radiation. The hotter they are, the more they emit. The constant agitation of the atoms and molecules that make up all objects involves accelerated motion of electrical charges (electrons and protons). The fundamental laws of electricity and magnetism, as embodied in Maxwell's equations, predict that any accelerated motion of charges will produce radiation. The constant jostling od atoms and molecules in material substances above a temperature of absolute zero produces electromagnetic radiation over a broad range of wavelengths and frequencies. The total radiant flux emitted from the surface of an object at temperature T is expressed by the Stefan-Boltzmann law, in the form

$$M_{bb} = \sigma T^4 \quad (1.2.1)$$

where M_{bb} is the exitance of (irradiance leaving) the surface in a vacuum, σ is the Stefan-Boltzmann constant and T is the temperature in degrees Kelvin.

The above equation is for a perfect or full emitter which is called a blackbody. A blackbody is defined as an ideal body that allows all incident radiation to pass into it (zero reflectance) and that absorbs internally all the incident radiation (zero transmittance). This must be true for all wavelengths and all angles of incidence. According to the definition of a blackbody, it is a perfect absorber, with absorptance of 1.0 at all wavelengths and directions. Due to the law of the conservation of energy, the sum of the reflectance R and absorptance A of an opaque surface must be unity, A+R=1.0. Thus, if a blackbody has an absorptance A of an opaque 1.0, its reflectance must be zero. Accordingly, a perfect blackbody at room temperature would appear totally black to the eye, hence the origin of the name.

Only a few surfaces, such as carbon black, carborundum and gold black, approach a blackbody in these optical properties. Most surfaces are not perfect absorbers many have reflectances that are different for different wavelengths. They are therefore called spectrally selective surfaces, because their optical properties are selectively different for different portions of the spectrum.

(a) (b) (c)

Figure 4 | Surfaces that approach a blackbody. (a) Carborundum, (b) Carbon black, (c) Gold black

The radiation emitted by a surface is in general distributed over a range of angles filling the hemisphere and over a range of wavelength. As shown by Grum, the angular distribution of radiance from a blackbody is constant; that is, the radiance is independent of direction; it is a Lambertian surface. Specifically, this means that $L_\lambda(\theta,\varphi) = L_\lambda(0,0) = L_\lambda$. Thus, the relationship between the spectral radiance $L_{bb\lambda}$ and spectral $M_{bb\lambda}$ of a blackbody is given bellow

$$M_{bb\lambda} = \pi L_{bb\lambda} \quad (1.2.2)$$

If $L_{bb\lambda}$ is in $W \cdot m^{-2} \cdot nm^{-1} \cdot sr^{-1}$, then the units of $M_{bb\lambda}$ will be $W \cdot m^{-2} \cdot nm^{-1}$.

1.2.1 Planck's Law

As the temperature changes, the spectral distribution of the radiation emitted by a blackbody shifts. In 1901, Max Planck made a radical new assumption – that radiant energy is quantized – and used this assumption to derive an equation for the spectral radiant energy density in a cavity at thermal equilibrium (a good theoretical approximation of a blackbody). By assuming a small opening in the side of the cavity and examining the spectral distribution of the emerging radiation, one can derive an equation for the spectral distribution of radiation emitted by a blackbody. The equation, now called Planck's blackbody spectral radiation law, accurately predicts the spectral radiance of blackbodies in a vacuum at any temperature. Using the notation of this text the equation is:

$$L_{bb\lambda} = \frac{2hc^2}{\lambda^5 (e^{hc/\lambda kT} - 1)} \quad (1.2.3)$$

Substituting in values for wavelength and temperature in the above equation blackbody spectral exitance values could be determined.

where h is Planck's constant, c is the speed of light in vacuum and k is Boltzmann's constant. Using these values of the constants, the units of $L_{bb\lambda}$ will be $W \cdot m^{-2} \cdot \mu m^{-1} \cdot sr^{-1}$.

From (1.2.2), the spectral exitance $M_{bb\lambda}$ of a blackbody at temperature T is just the spectral radiance $L_{bb\lambda}$ (1.2.3) multiplied by π:

$$M_{bb\lambda} = \frac{2\pi hc^2}{\lambda^5 (e^{hc/\lambda kT} - 1)} \quad (1.2.3)$$

Substituting constants and rearranging terms yields the following form of this equation, when the wavelength is given μm and the temperature in degrees Kelvin:

$$M_{bb\lambda} = \frac{3.741 \cdot 10^8}{\lambda^5 (e^{14388/\lambda T} - 1)} \quad (1.2.4)$$

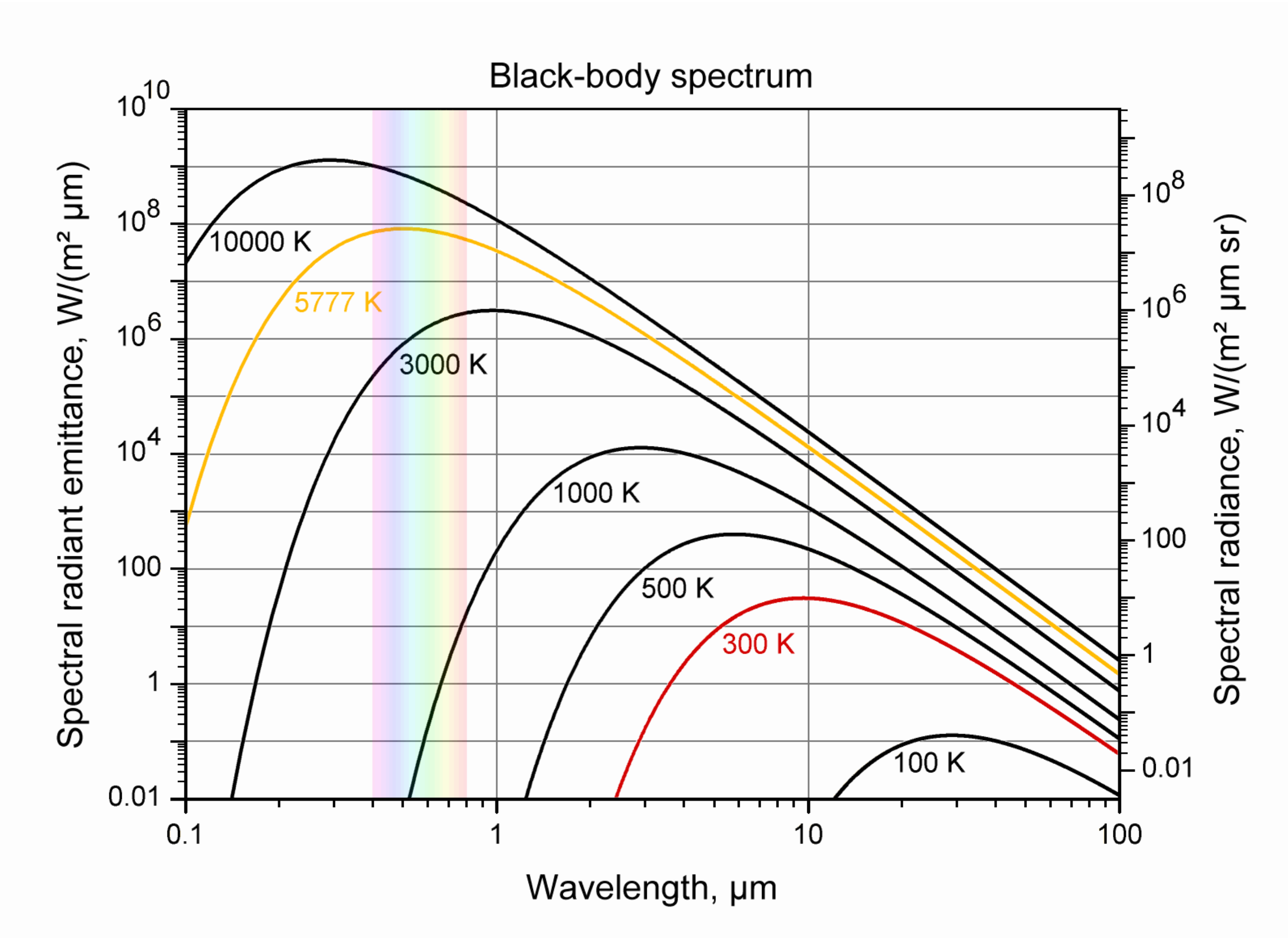


Figure 5 | Spectral radiant emittance spectra for blackbodies at various temperatures from 100 to 10000K

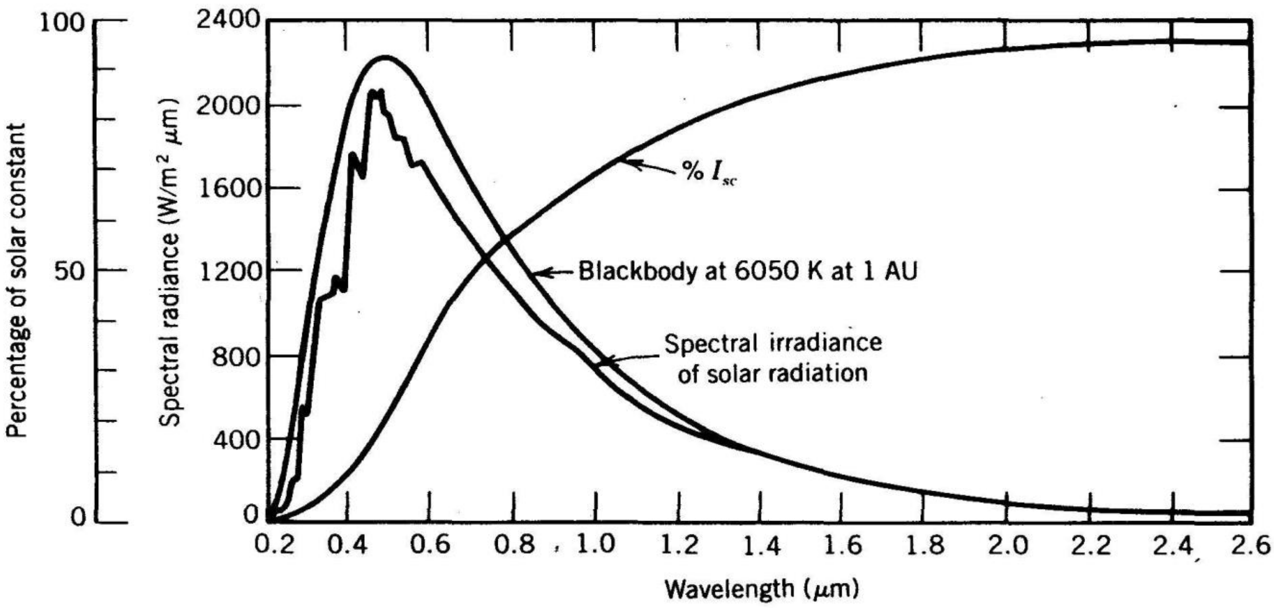


Figure 6 | Extraterrestrial solar spectral irradiance curve and scaled 6050K blackbody spectrum.

1.2.2 Wien displacement law

Differentiating Planck's formula (1.2.3) and setting the result equal to zero, a solution of the resulting equation for wavelength yields for a simple relationship between the wavelength λ_m where the Planck radiation formula has its maximum value $M_{\lambda m}$ (or $L_{\lambda m}$) and the temperature T of the blackbody. The resulting relationship is called Wien's displacement law and is given by

$$\lambda_m T = 2897.8\mu m \cdot K \quad (1.2.5)$$

1.2.3 Luminous efficacy of blackbody radiation

Substituting $M_{bb\lambda} = \frac{2\pi hc^2}{\lambda^5(e^{hc/\lambda kT}-1)}$ for the hemispherical spectral exitance of a blackbody into $E_V = 683\int_{380}^{770} E_\lambda V_\lambda d\lambda$ and $E_e = \int_0^\infty E_\lambda d\lambda$, and using the results in irradiance version of $K_r = \frac{Q_v}{Q_e}$ (replacing each Q with E), for each of several different temperatures T, one can calculate the radiation luminous efficacy K_{rbb} of blackbody radiation as a function of temperature. Figure 7 shows the plot of the luminous efficacy of a blackbody radiatior as a function of temperature, where it can be seen that, as expected, the luminous efficacy drops very rapidly as the body cools down from white hot temperatures.

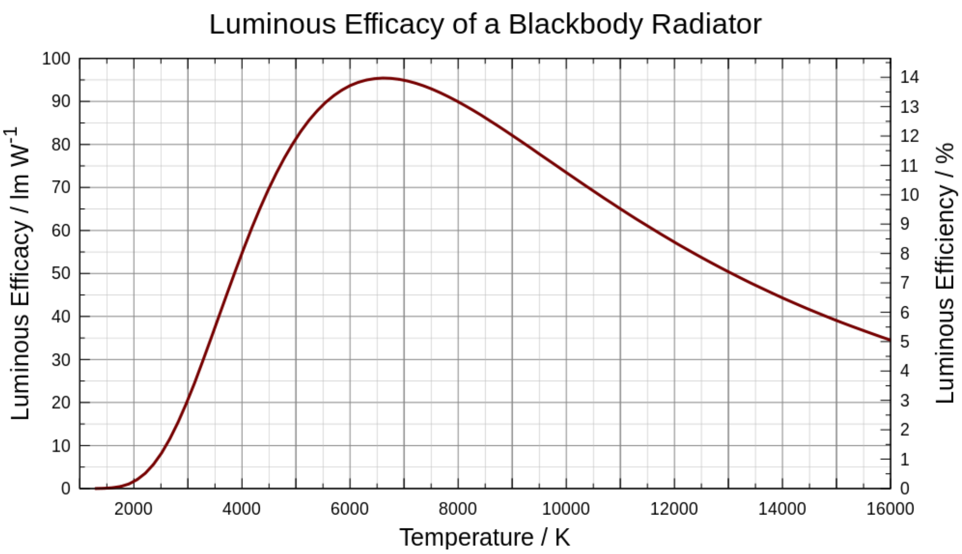


Figure 7 | The luminous efficacy of blackbody radiation on a linear scale as a function of temperature.

1.2.4 Radiation exchange

The emission of blackbody radiation into a medium brings up a host of important additional topics. For example, the optical properties of the medium into which the radiation is emitted are very important to the subsequent fate of the radiation. Also, the presence of another medium adjacent to or in contact with the emitting source can affect the properties of the source and can therefore alter the amount and spectral distribution of the emission. For example, if an ideal blackbody is in contact with another blackbody (or nonblackbody) at a temperature that is different from that of the first blackbody, heat will tend to flow by conduction from the hotter to the colder body, possibly altering the temperature of the original blackbody and hence its emission characteristics. Even if the bodies are not in contact, radiant heat can flow between them, again altering their temperatures under transient conditions and changing the nature of the emissions.

1.2.5 Experimental approximations of a blackbody

Several researchers developed black body simulators which are absorbent cavities of various shapes with small holes to control the emitted radiation. Thus, angular and spectral characteristics of a blackbody can be approximated with these arrangements like this shown in Figure 8.

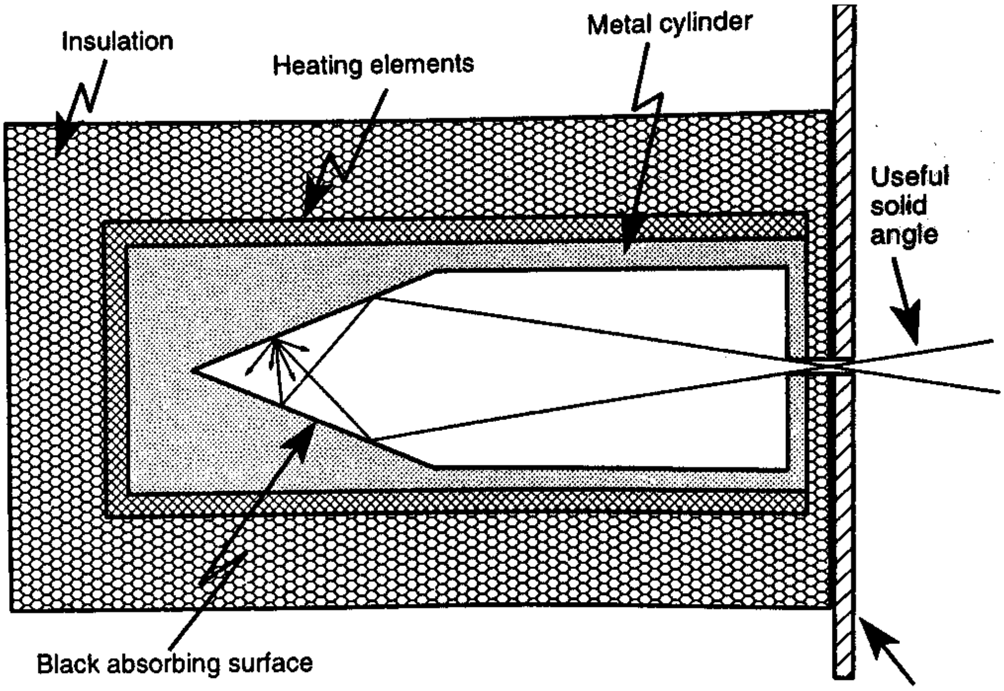


Figure 8 | Schematic diagram of an experimental realization of a blackbody radiator.

A metal cylinder is hollowed out to form a cavity with a small opening in one end. At the opposite end is placed a conical shaped “light trap”, whose purpose is to multiply reflect incoming rays, with maximum absorption at each reflection, in such a manner that a very large number of reflections must take place before any incident ray can emerge back out the opening. With the absorption high on each reflection, a vanishingly small fraction of incident flux, after being multiply reflected and scattered, would emerge from the opening. In consequence, only a very tiny portion of the radiation passing into the cavity through the opening can be reflected back out the cavity.

The temperature of the entire cavity is controlled by heating elements and thick outside insulation so that all surfaces of the interior are at precisely the same temperature and any radiation escaping from the cavity will be that emitted from the surfaces within the cavity.

1.3 Real Artificial Incoherent Light Sources

1.3.1 Incandescent lamp [2, 3, 4]

Figure 9 | A 200 Watt incandescent lightbulb filament.

The incandescent light bulb or lamp is a source of electric light that works by incandescence, which is the emission of light caused by heating the filament. They are made in an extremely wide range of sizes, wattages, and voltages. Incandescent bulbs are the original form of electric lighting and have been in use for over 100 years. While Thomas Edison is widely considered to be the inventor of the incandescent bulb, there are a number of people who invented components and prototypes of the light bulb well before Edison did. One of those people was British physicist Joseph Wilson Swan, who actually received the first patent for a complete incandescent light bulb with a carbon filament in 1879. Swan's house was the first in the world to be lit by a light bulb. Edison and Swan merged their companies and together they were the first to design a bulb that was commercially viable.

Working principle

Filament

An incandescent bulb typically consists of a glass enclosure containing a filament wire. An electric current passes through the filament, heating it to a temperature that produces light. The first successful light bulb filaments were made of carbon. Early carbon filaments had a negative temperature coefficient of resistance — as they got hotter, their electrical resistance decreased. This made the lamp sensitive to fluctuations in the power supply, since a small increase of voltage would cause the filament to heat up, reducing its resistance and causing it to draw even more power and heat even further.

Figure 10 | A 200 Watt incandescent lightbulb filament.

In 1902, the Siemens company developed a tantalum lamp filament. These lamps were more efficient than even graphitized carbon filaments and could operate at higher temperatures. Since tantalum metal has a lower resistivity than carbon, the tantalum lamp filament was quite long and required multiple internal supports. The metal filament had the property of gradually shortening in use; the filaments were installed with large loops that tightened in use. This made lamps in use for several hundred hours quite fragile. Metal filaments had the property of breaking and re-welding, though this would usually decrease resistance and shorten the life of the filament.

Around 1900, osmium was also used as a lamp filament in Europe, and the metal was so expensive that used broken lamps could be returned for partial credit. It could not be made for 110 V or 220 V so several lamps were wired in series for use on standard voltage circuits.

Finally, in 1906, the tungsten filament was introduced. Despite the fact that the tungsten metal was initially not available in a form that allowed it to be drawn into fine wires, a process was developed at General Electric for production of a ductile form of tungsten. So tungsten became the material of choice for filaments because they produce twice as much light and lasted much longer than the other filaments.

Enclosure glass

Incandescent light bulbs usually contain a stem or glass mount attached to the bulb's base which allows the electrical contacts to run through the envelope without gas/air leaks. Small wires embedded in the stem support the filament and/or its lead wires.

Gas fill

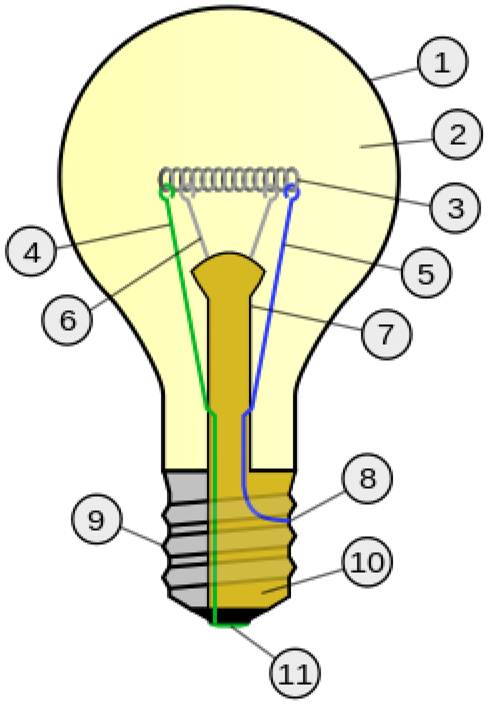
The enclosing glass enclosure contains either a vacuum or an **inert gas** to preserve and protect the filament from evaporating. The role of the gas is to prevent evaporation of the filament, without introducing significant heat losses. For these properties, chemical inertness and high atomic or molecular weight is desirable. The presence of gas molecules knocks the liberated tungsten atoms back to the filament, reducing its evaporation and allowing it to be operated at higher temperature without reducing its life. It however introduces heat losses from the filament, by heat conduction and heat convection.

Early lamps, and some small modern lamps used only a vacuum to protect the filament from oxygen. This however increases evaporation of the filament, albeit it eliminates the heat losses.

The most common fills are:

1. Vacuum, used in small lamps. Provides best thermal insulation of the filament but does not protect against its evaporation. Used also in larger lamps where the outer bulb surface temperature has to be limited.
2. Argon (93%) and nitrogen (7%), where argon is used for its inertness, low thermal conductivity and low cost, and the nitrogen is added to increase the breakdown voltage and prevent arcing between parts of the filament.

3. Nitrogen, used in some higher-power lamps, e.g. projection lamps, and where higher breakdown voltage is needed due to proximity of filament parts or lead-in wires.
4. Krypton, which is more advantageous than argon due to its higher atomic weight and lower thermal conductivity (which also allows use of smaller bulbs), but its use is hindered by much higher cost, confining it mostly to smaller-size bulbs.
5. Krypton mixed with xenon, where xenon improves the gas properties further due to its higher atomic weight. Its use is however limited by its very high cost. The improvements by using xenon are modest in comparison to its cost.
6. Hydrogen, in special flashing lamps where rapid filament cooling is required; its high thermal conductivity is exploited here.



1. ***Glass bulb***
2. ***Inert gas***
3. ***Tungsten filament***
4. ***Contact wire (goes to foot)***
5. ***Contact wire (goes to base)***
6. ***Support wires***
7. ***Glass mount/support***
8. ***Base contact wire***
9. ***Screw threads***
10. ***Insulation***
11. ***Electrical foot contact***

Figure 11 | Outline of glass bulb

Halogen bulb [2, 5, 6]

Halogen bulbs are technically incandescent light bulbs – illumination is produced in both when a tungsten filament is heated sufficiently to emit light or "incandescence." The difference between the two is in the composition of the glass envelope and the gas inside the envelope. A standard incandescent bulb, as it is already depicted above, has a heat sensitive glass envelope that contains an inert gas mixture, usually nitrogen-argon. When the tungsten filament is heated it evaporates and deposits metal on the cooler glass envelope (this is why incandescent bulbs appear black at the end of life). This process

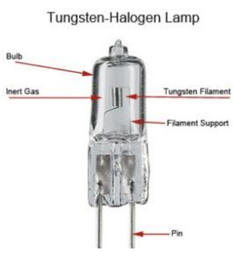


Figure 12 | Outline of halogen lamp

requires incandescent bulb filaments to be heated less than optimally to give the bulb a reasonable life. The lower filament temperature gives incandescent bulbs their typical orange-yellow, warm appearing light. Halogen light bulbs utilize a fused quartz envelope ("capsule") allowing for higher temperatures. Inside the quartz envelope is a vapor, originally iodine, now usually bromine. The tungsten filament evaporates as usual but the higher temperatures are sufficient to cause the tungsten to mix with the vapor instead of depositing on the envelope. Some of the evaporated tungsten is re-deposited on the filament. The combination of this "regenerative cycle" and higher filament temperature results in a bulb that has a longer life and slightly higher efficiency than standard incandescent bulbs. The higher temperature filament also produces the "white" light often associated with halogen bulbs.

Spectral Curves

The heated filaments of incandescent light bulbs emit light that approximates a continuous spectrum. The useful part of the emitted energy is visible band (400-700nm) but most energy is given off as heat in near-infrared wavelengths. As referred above, standard incandescent lamp emits orange-yellow warm appearing light, which comes in contrast with Halogen lamp which emits a neutral white light. This is easy to understand just looking to the spectral curves bellow. Standard incandescent lamp emits less photons in UV and blue region while Halogen lamp emits a sufficient amount of photons in these regions, so the light emitted is much colder.

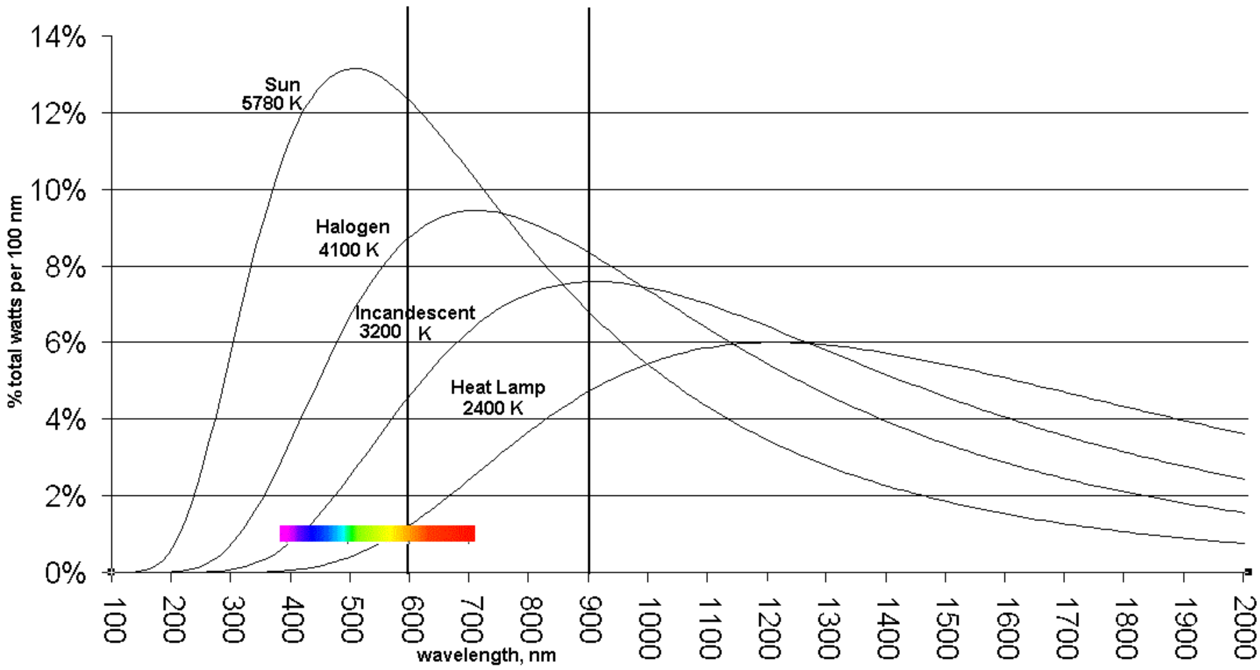


Figure 13 | Halogen and incandescent lamps spectral curves compared to a heat lamp and Sun.

Advantages & disadvantages

Advantages

- ✓ Good for lighting small areas.
- ✓ Cheap for the consumer.

- ✓ No toxic materials are present.
- ✓ Safe to handle.
- ✓ Fast on time.
- ✓ No flicker.

Disadvantages

- Not energy Efficient.
- Not good for large areas.
- Low lifespan compared to other light bulbs.

1.3.2 Gas discharge lamps [2, 7]

Gas-discharge lamps are a family of artificial light sources that generate light by sending an electrical discharge through an ionized gas, a plasma. The character of the gas discharge depends on the pressure of the gas as well as the frequency of the current.

Working Principle

Typically, such lamps use a noble gas (argon, neon, krypton and xenon) or a mixture of these gases. Most lamps are filled with additional materials, like mercury, sodium, and metal halides. In operation the gas is ionized, and free electrons, accelerated by the electrical field in the tube, collide with gas and metal atoms. Some electrons in the atomic orbitals of these atoms are excited by these collisions to a higher energy state**. When the excited atom falls back to a lower energy state, it emits a photon of a characteristic energy, resulting in infrared, visible light, or ultraviolet radiation.** The excitation of these electrons results in a linear emission spectra. In case the metallic element requires the presence of auxiliary gas or carbon electrode, then the spectrum of the metallic element coexists with the spectrum of the auxiliary gas or carbon.

For example, the table below shows the spectral series emission lines of hydrogen, according to combinations of the transition of the unique electron from atomic layer n2 to atomic layer n1:

n_1	n_2	Spectral series	Spectral band
1	2,3,4,…	Lyman	Deep UV
2	3,4,5…	Balmer	Near UV and Visible
3	4,5,6…	Parschen	Near IR
4	5,6,7…	Bracket	IR
5	6,7,8…	Pfund	IR

Table 1 | Atomic transitions of Hydrogen.

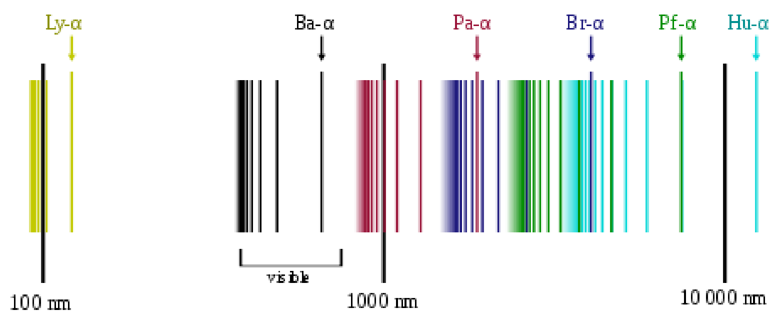


Figure 14 | The spectral series of Hydrogen.

Each gas, depending on its atomic structure emits certain wavelengths which translates in different colors of the lamp (Figure 14).

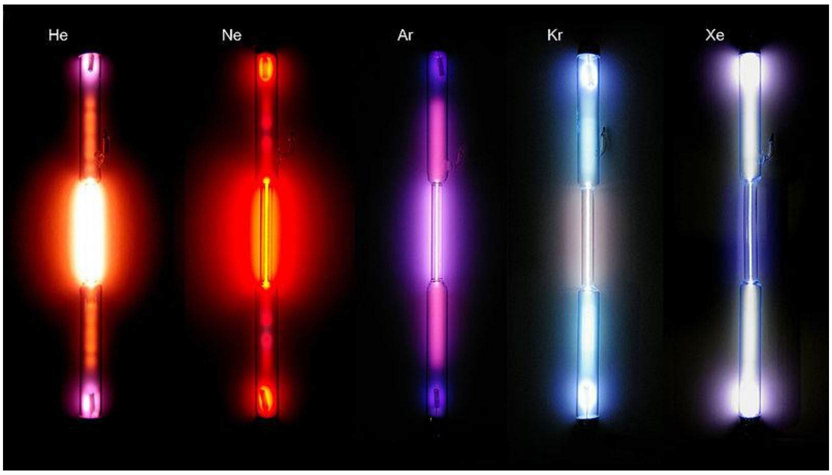


Figure 15 | Noble gas discharge tubes.

Also, some lamps convert the ultraviolet radiation to visible light with a fluorescent coating on the inside of the lamp's glass surface. The fluorescent lamp is perhaps the best known gas-discharge lamp.

Types

Gas discharges lamps are separated in 3 basic categories depending on the pressure of gas in the bulb: Low pressure discharge lamps, High pressure discharge lamps and high-intensity discharge lamps.

Low pressure discharge lamps

These lamps have gas inside the tube, with lower pressure than the atmospheric pressure. The classic fluorescent lamps are of this kind, the well known to PC modders Neon lamps also, as well as the low pressure sodium lamps which are used for street lighting. They all have very good efficiency, with the sodium lamps being the most efficient among all gas discharge lamps. The problem with this type of lamp is that it produces only an almost monochromatic yellow light.

High pressure discharge lamps

These lamps have pressurized gas inside the tube, with higher pressure than the atmospheric pressure. Some examples of high pressure discharge lamps are the metal halide lamps, the high pressure sodium lamps and the high pressure mercury-vapor lamps which are very old, being replaced in most applications.

High intensity discharge lamps

In this category, there are those lamps which produce light by means of an electric arc between the electrodes. The electrodes are usually tungsten electrodes, housed inside a semi-transparent or transparent material. There are many different example of HID (High Intensity Discharge) lamps such as the metal halide lamps, the sodium vapor lamps, the mercury-vapor lamps, the ceramic discharge metal halide lamps, the Xenon arc lamps and the Ultra-High Performance (UHP) lamps.

Also, there is a **second distinction** of gas discharge lamps depending on the fact that the cathode is heated or not:

Hot cathode

Hot-cathode lamps have electrodes which operate at a high temperature, which during operation are heated by the arc current in the lamp. The electrons are generated by the electrode itself with thermionic emission, and that is why they are referred to as thermionic cathodes. The cathode is usually an electrical filament made of tungsten or tantalum. Later cathodes were covered with an emissive layer, which could produce more electrons with less heat, thus increasing the efficiency. Hot cathodes produce significantly more electrons than cold cathodes from the same surface. They are used in electron guns for electron microscopes, cathode ray tubes, vacuum tubes and fluorescent lamps.

Cold cathode

In Cold Cathode, the electron emission is not done with thermionic emission. Cold-cathode lamps have electrodes which operate at room temperature. To start conduction in the lamp a high enough voltage (the striking voltage) must be applied to ionize the gas, so these lamps require higher voltage to start. Cold Cathode Lamps are often met in electronic devices. CCFLs (Cold Cathode Fluorescent Lamps) are used by computer modders to spice up their mods. Also, it is widely used as an LCD backlit. Laptops for example have CCFLs to light the monitor. Another example of wide use is the Nixie tubes. Nixie tubes are also cold cathode lamps. Lately, cold cathode fluorescent lamps are used to light bigger areas. These lamps come with a built-in inverter and they can directly replace a normal lamp.

Fluorescent lamp [2, 8]

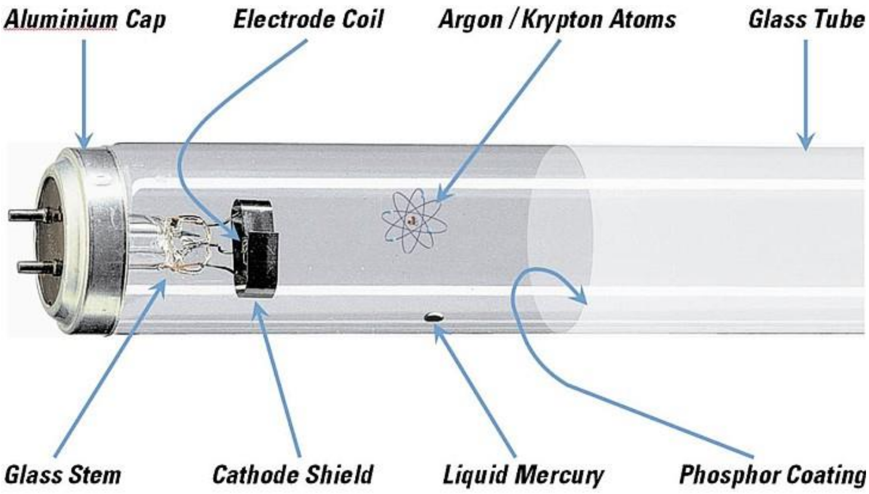


Figure 16 | Glow of a germicidal lamp excited by a high voltage probe.

Fluorescent lamp is a heated-cathode low pressure gas discharge lamp that uses fluorescence to produce visible light. It is the most common lamp in office lightning and many other applications. A fluorescent lamp tube is filled with a gas containing low pressure mercury vapor and argon, xenon, neon, or krypton. In operation the gas is ionized, and free electrons, accelerated by the electrical field in the tube, collide with gas and mercury metal atoms. Some electrons in the atomic orbitals of these atoms are excite d by these collisions to a higher energy state. When the excited atom falls back to a lower energy state, it emits a photon of a characteristic energy. Most of the photons that are released from the mercury atoms have wavelengths in the ultraviolet region of the spectrum, predominantly at wavelengths of 253.7 and 185 nanometers. These are not visible to the human eye, so they must be converted into visible light. This is done by making use of fluorescence. Ultraviolet photons are absorbed by electrons in the atoms of the lamp's interior fluorescent coating, causing a similar energy jump, then drop, with emission of a further photon. The photon that is emitted from this second interaction has a lower energy than the one that caused it. The chemicals that make up the phosphor are chosen so that these emitted photons are at wavelengths visible to the human eye. The difference in energy between the absorbed ultra-violet photon and the emitted visible light photon goes toward heating up the phosphor coating. The fluorescent coating is made of varying blends of metallic and rare-earth phosphor salts. At this point it is important to refer to the germicidal lamp. The most common form of germicidal lamp looks similar to an ordinary fluorescent lamp but the tube contains no fluorescent phosphor. In other words, one could say that a fluorescence lamp is a germicidal lamp with phosphor coated tube.

Figure 17 | Glow of a germicidal lamp excited by a high voltage probe.

The fill gas helps determine the operating electrical characteristics of the lamp, but does not give off light itself. The fill gas effectively increases the distance that electrons travel through the tube, which allows an electron a greater chance of interacting with a mercury atom. For example, argon atoms, excited to a metastable state by impact of an electron, can impart this energy to a neutral mercury atom and ionize it, described as the Penning effect. This has the benefit of lowering the breakdown and operating voltage of the lamp, compared to other possible fill gases such as krypton.

The lamp's electrodes are typically made of coiled tungsten and usually referred to as cathodes because of their prime function of emitting electrons. For this, they are coated with a mixture of barium, strontium and calcium oxides chosen to have a low thermionic emission temperature.

As the fluorescent lamp is a gas discharge lamp, one can expect that the spectrum is consisted by spectral lines emitted by the various elements inside the tube. Also is it important to remember that the spectrum of a fluorescence lamp is the result of the fluorescence of the inner coating of the lamp tube by mercury's emitted photons (most of the photons emitted are in UV region as depicted in Figure 18). So, the spectrum of a common fluorescent lamp is presented in Figure 19.

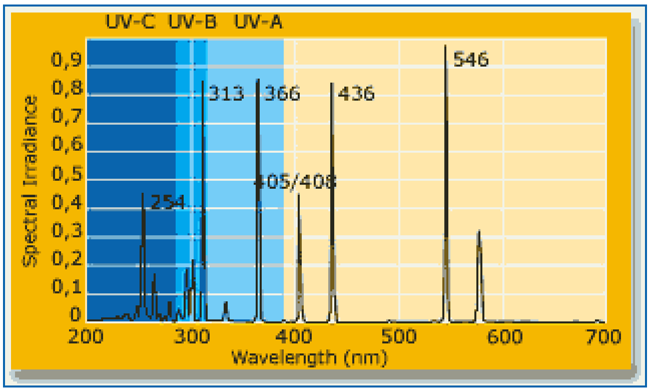


Figure 18 | An emission spectrum for pure mercury.

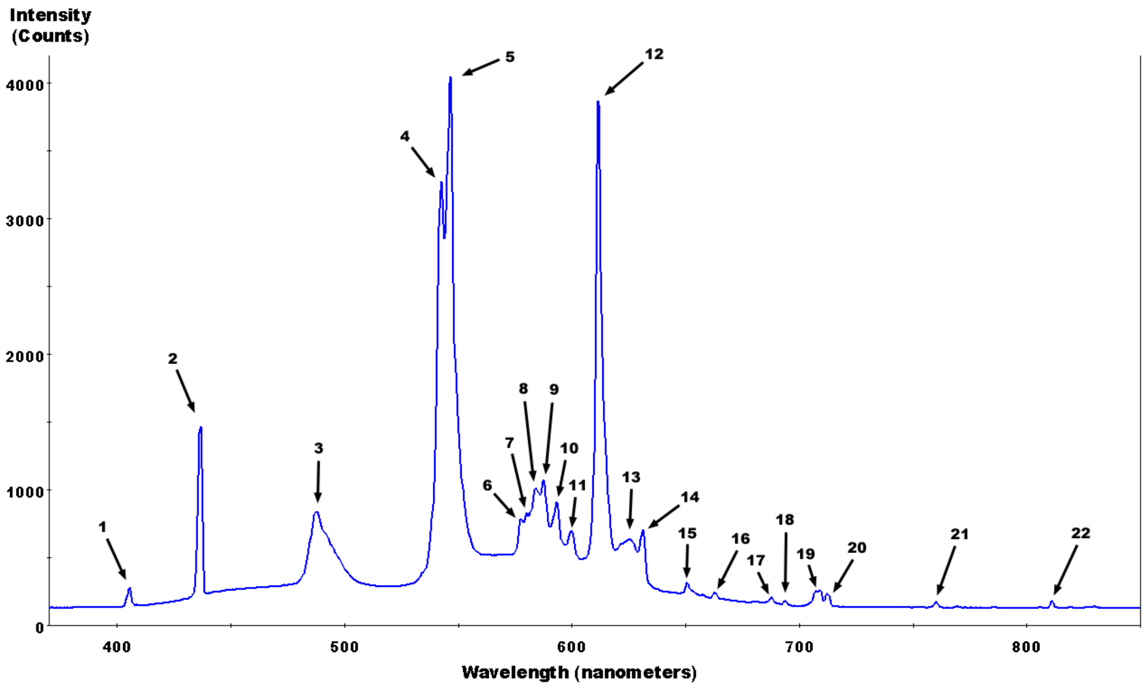


Figure 19 | Emission spectrum of a fluorescence lamp

Advantages and disadvantages of fluorescence tubes

Advantages

- ✓ Energy efficient, so far the best light for interior lighting
- ✓ Low production cost (of tubes, not of the ballasts)
- ✓ Long life of tubes
- ✓ Good selection of desired color temperature (cool whites to warm whites)
- ✓ Diffused Light (good for general, even lighting, reducing harsh shadows)

Disadvantages

- Flicker of the high frequency can be irritating to humans (eye strain, headaches, migraines)
- Flicker of common fluorescent light looks poor on video, and creates an ugly greenish or yellow hue on camera
- Diffused Light (not good when you need a focused beam such as in a headlight or flashlight)
- Poorly/cheaply designed ballasts can create radio interference that disturbs other electronics
- Poorly/cheaply designed ballasts can create fires when they overheat
- There is a small amount of mercury in the tubes
- Irritating flicker at the end of the life cycle

1.3.3 Light emitting diode (LED) [2]

A light-emitting diode (LED) is a semiconductor light source. LEDs are used as indicator lamps in many devices and are increasingly used for general lighting. Appearing as practical electronic components in 1962, early LEDs emitted low-intensity red light, but modern versions are available across the visible, ultraviolet, and infrared wavelengths, with very high brightness. **LEDs have many advantages over incandescent and gas discharge light** sources including lower energy consumption, longer lifetime, improved physical robustness, smaller size, and faster switching.

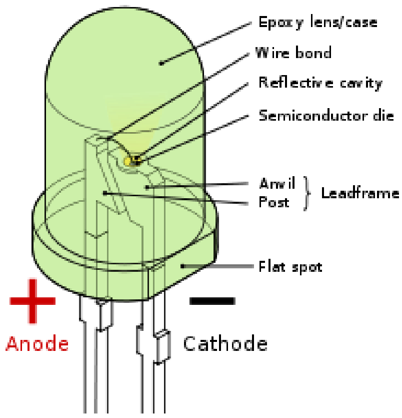


Figure 20 – Parts of a (through-hole) LED

Physics

The LED consists of a chip of semiconducting material doped with impurities to create a p-n junction. As in other diodes, current flows easily from the p-side, or anode, to the n-side, or cathode, but not in the reverse direction. When an electron meets a hole, it falls into a lower energy level, and releases a photon.

The wavelength of the light emitted, and thus its color depends on the band gap energy of the materials forming the p-n junction. In

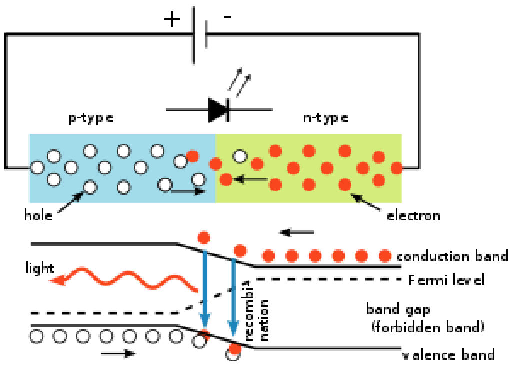


Figure 21 - Circuit and Band diagram

silicon or germanium diodes, the electrons and holes recombine by a non-radiative transition, which produces no optical emission, because these are indirect band gap materials. The materials used for the LED have a direct band gap with energies corresponding to near-infrared, visible, or near-ultraviolet light.

LED development began with infrared and red devices made with gallium arsenide. Advances in materials science have enabled making devices with ever-shorter wavelengths, emitting light in a variety of colors.

As we discussed in laser physics, laser working principle is similar with led working principle. Both of them use p-n junctions and electrons-holes combination takes place. The main differences are the materials used to form the p-n junction and also the optical cavity, where pumping takes place in laser diode.

LEDs are made from a variety of inorganic semiconductor materials. This leads to different wavelengths emitted by the LED.

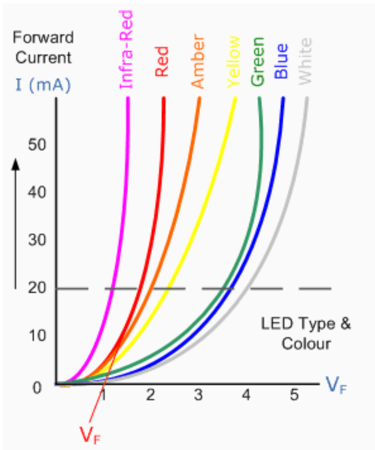


Figure 22 - I-V Characteristics Curves showing different LEDs.

Also, the spectral width of a LED is greater than lasers, where monochromatic light is approximated in a better way.

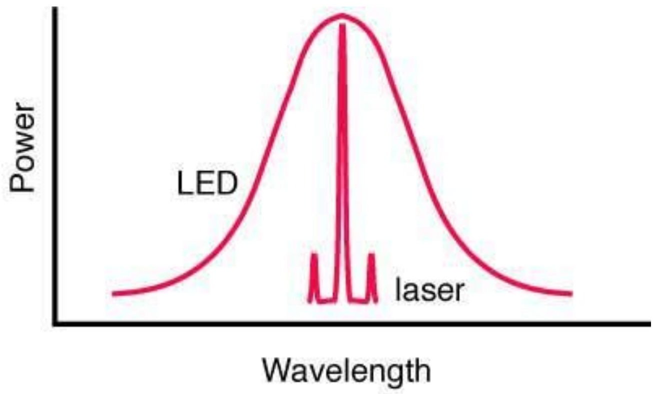


Figure 23 - Spectral width of Led and Laser

Blue Led [9]

The blue led passed through many stages of development to improve many features but mainly the brightness. The first blue led using GaN were made in 1971. The problem with the GaN Led was the little light output. In later years, blue led using SiC was developed but it had very low efficiency.

Nowadays, blue leds have an active region consisting of one or more InGaN quantum wells sandwiched between thicker layers of GaN, called cladding layers. This structure reminds us of the structure of Quantum – Well Lasers. By varying the relative In/Ga fraction in the InGaN quantum wells, the light emission can in theory be varied from violet to amber.

Figure 24 - Blue Led

Aluminium gallium nitride (AlGaN) of varying Al/Ga fraction can be used to manufacture the cladding and quantum well layers for ultraviolet LEDs, but these devices have not yet reached the level of efficiency and technological maturity of InGaN/GaN blue/green devices. If un-alloyed GaN is used in this case to form the active quantum well layers, the device will emit near-ultraviolet light with a peak wavelength centred around 365 nm. With nitrides containing aluminium, most often AlGaN and AlGaInN, even shorter wavelengths are achievable. Deep-UV wavelengths were obtained in laboratories using aluminium nitride (210 nm), boron nitride (215 nm) and diamond (235 nm). However, as we descend in wavelength the greater the cost.

White Led [10]

There are two popular ways to construct Leds that emit high-brightness white light. The first way is to combine three different leds of green, red and blue color. By mixing the colors of these three leds white color is forming, as illustrated in figure 26. The other way is to use a phosphor material to convert a blue or UV led to broad-spectrum white led, much in the same way a fluorescent light bulb works. In figure 27, emission spectrum of a phosphor-based white LED is illustrated. The total spectrum is a combination of the blue led spectrum and the spectrum caused by phosphorescence.

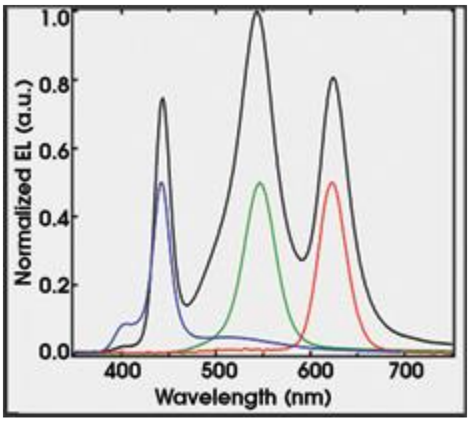


Figure 25 - White Led by mixing red, green and blue Leds

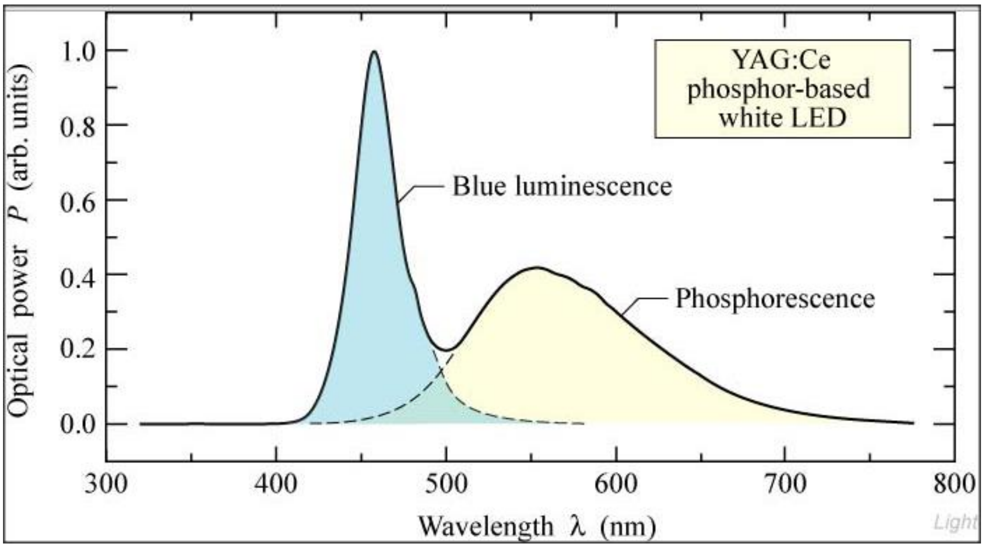


Figure 26 - Spectrum of a phosphor-based white LED

Organic LEDs (OLEDs) [11]

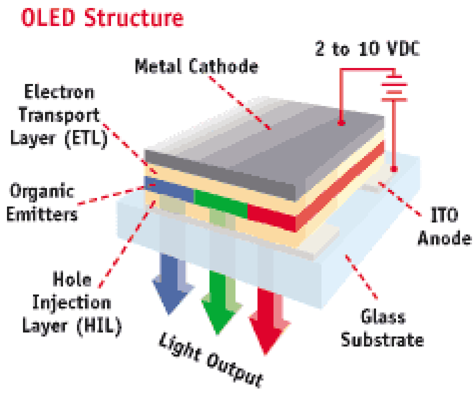


Figure 27 - OLED structure

Organic light emitting diodes are a relatively new technology for solid state light sources. A typical OLED consists of two organic layers (electron and hole transport layers), embedded between two electrodes. The top electrode is usually a metallic mirror with high reflectivity and the bottom electrode a transparent ITO layer on top of the glass substrate. The organic materials can be small organic molecules in a crystalline phase, or polymers. Different materials and dopants can be used to generate different colors and the combination of them allows building up a white light source.

The potential advantages of OLEDs include thin, low-cost displays with a low driving voltage, wide viewing angle, and high contrast and color gamut. Polymer LEDs have the added benefit of printable and flexible displays. OLEDs have been used to make visual displays for portable electronic devices such as cellphones, digital cameras, and MP3 players while possible future uses include lighting and televisions.

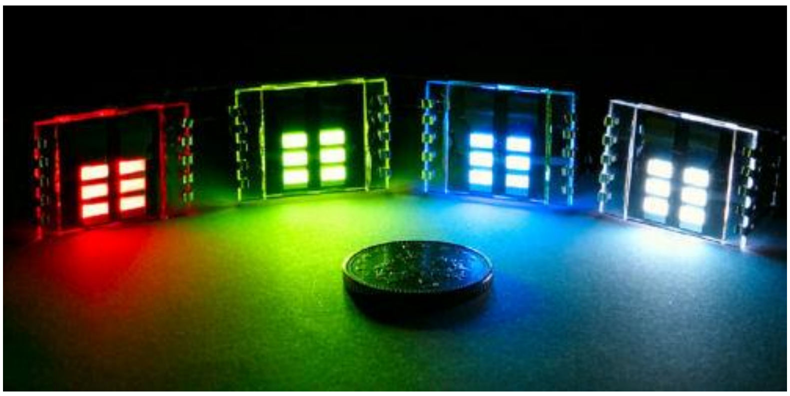


Figure 28 – OLEDs of different wavelengths

RGB LEDs

The most common RGB LEDs are three separate LED packaged together, Red, Green and Blue. In some, all three of the LEDs are electrically isolated and some have either all of the Anodes connected together or all of the Cathodes connected together. For example (Figure 30), if the three different LEDs have common cathode, we can adjust the contribution of each LED by altering the voltage (with an external power source or PWM pulses) on each anode.

The combination of colors of the three LEDs, depending on how much each contributes, can give various colors. Also, RGB LEDs can produce white color, which is the one method that mentioned before for constructing white LED.

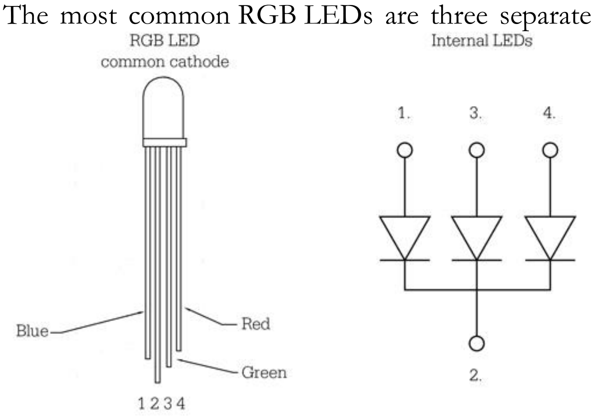


Figure 29 – Common Cathode RGB Led

Also, except for trichromatic LEDs there are dichromatic and tetrachromatic LEDs. Several key factors that play among these different methods, include color stability, color rendering capability, and luminous efficacy. Often, higher efficiency will mean lower color rendering, presenting a trade-off between the luminous efficiency and color rendering. For example, the dichromatic LEDs have the best luminous efficacy (120 lm/W), but the lowest color rendering capability. However, although tetrachromatic LEDs have excellent color rendering capability, they often have poor luminous efficiency. Trichromatic LEDs are in between, having both good luminous efficacy (>70 lm/W) and fair color rendering capability.

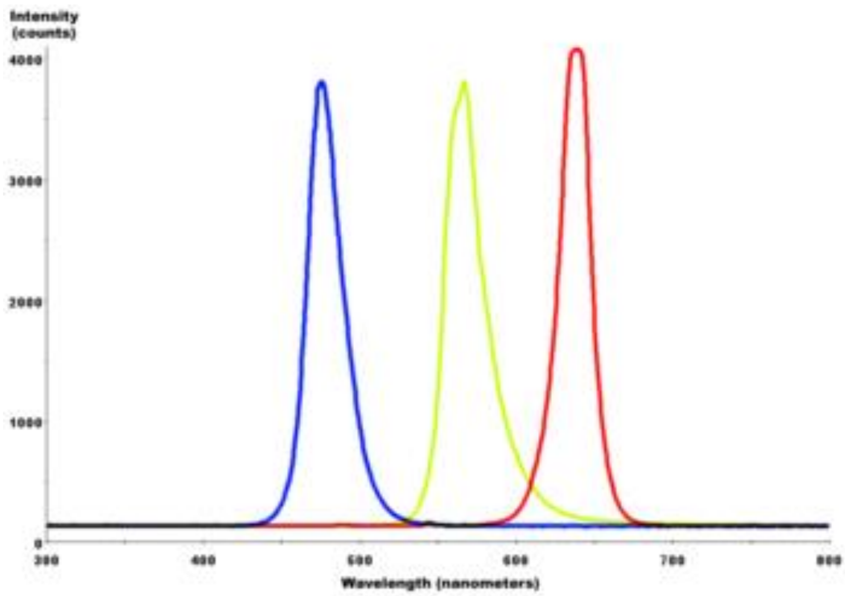


Figure 30 - Combined spectral curves for blue, yellow-green, and high-brightness red solid-state semiconductor LEDs.

LED types

There are several types of LEDs differentiated in characteristics such as size, voltage, current and brightness. Let's see miniature LEDs, mid-range LEDs, high power LEDs. Each LED type are used in different applications according to the applications' needs.

Miniature LEDs

Miniature LEDs are single-die LEDs used as indicators, and they come in various sizes from 2 mm to 8 mm. They are constructed in through-hole and surface mount packages. Typical current ratings range from around 1 mA to above 20 mA. The encapsulation may also be clear or tinted to improve contrast and viewing angle. The small size sets a natural upper boundary on power consumption due to heat caused by the high current density and need for a heat sink. Nowadays, miniature LEDs are developing rapidly resulting in high brightness LEDs, so they are suitable for constructing miniature electronic devices. These LEDs are used for constructing high efficiency LED lamps (Figure 32).

Figure 31 – LED lamp using miniature white LEDs

Moreover, miniature LEDs come to a variety of wavelengths, from monochromatic LEDs, RGB LEDs to white LEDs.

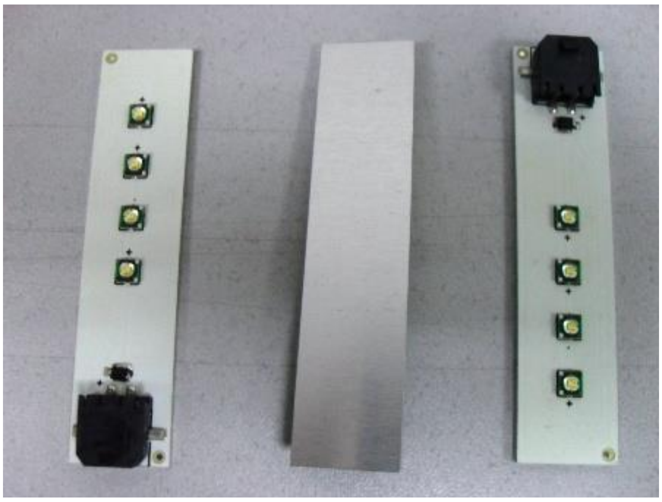


Figure 32 – High Power White LEDs on an Aluminium PCB

Some miniature LEDs require heat dissipation techniques. The most popular technique is the use of Aluminium PCB, where the LED is soldered. Aluminium PCB provides good heat dissipation in contrast with standard epoxy plastic PCB. Especially, in miniature UV LEDs a heatsink must be used as way to avoid LED "burn-out". Also, there are miniature white LEDs which have power of 10W. This means that the current which flows through the LED has the value of about 2.5 A. These LEDs cannot work without a cooling assembly.

Mid-range LEDs

Figure 33 – Mid-range LEDs used in automotive light.

Medium-power LEDs are often through-hole-mounted and mostly utilized when an output of just a few lumen is needed. These LEDs are most commonly used in light panels, emergency lighting, and automotive lights. Due to the larger amount of metal in the LED, they are able to handle higher currents (around 100 mA). The higher current allows for the higher light output required for tail-lights and emergency lighting.

High power LEDs

High-power LEDs can be driven at currents from hundreds of mA to several Amperes. High-power LEDs must be mounted on a heat sink to allow for heat dissipation because overheating is destructive for the LED. Often, High power LEDs are formed by several chips of miniature high-power LED of the same type. This combination leads to highly increased lumen output and efficiency. Chips emitting in different wavelengths can combined to produce various colors and with a proper driving circuit, control of channels of several LED chips is achievable.

The cooling assembly must have very good heat dissipation. The most common assembly is combination of a copper/aluminium heatsink with one or multiple fans. Figure 35 illustrates a High power LED on a big heatsink, which is cooled by 3 6sfans.

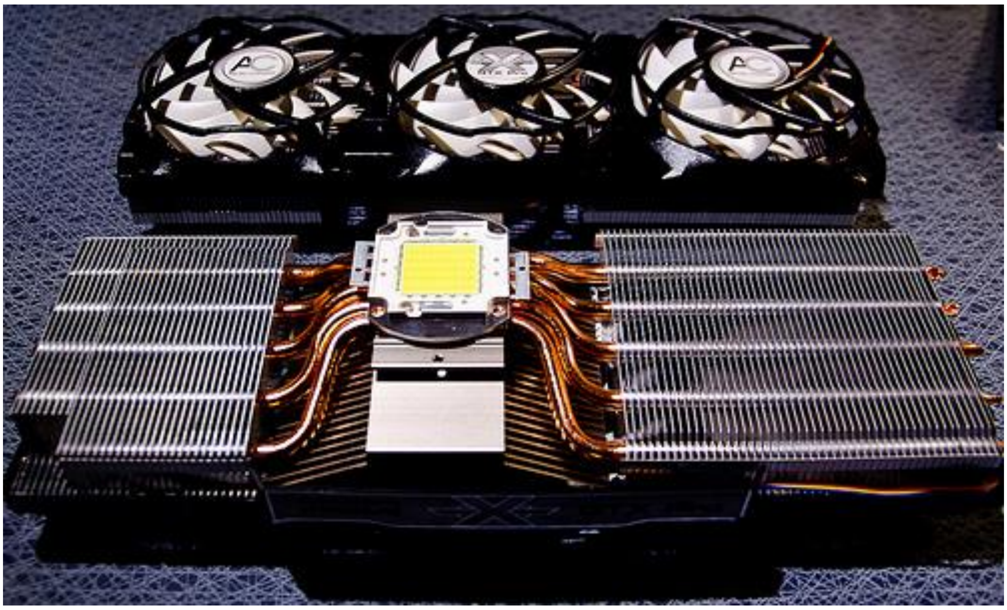


Figure 34 –High Power LED cooled with a big cooling assembly.

Main Advantages and Disadvantages of LEDs

Advantages

1. **Energy efficient** – LEDs emit more light per watt than incandescent light bulbs. The efficiency of LED lighting fixtures is not affected by shape and size, unlike fluorescent light bulbs or tubes. LEDs are now capable of outputting 135 lumens/watt.
2. **Long Lifetime** – 50,000 hours or more if properly engineered.
3. **Color** - LEDs can emit light of an intended color without using any color filters as traditional lighting methods need. This is more efficient and can lower initial costs.
4. **Excellent Color Rendering** – LEDs do not wash out colors like other light sources such as fluorescents, making them perfect for displays and retail applications.
5. **No warm-up period** - LEDs light instantly – in nanoseconds.
6. **Controllable** - LEDs can be controlled for brightness and color. About dimming, LEDs can easily be dimmed either by PWM or lowering the forward current.
7. **Size** – LEDs size can be extremely small (lower than 2mm) and are easily soldered in PCBs.
8. **Environmental friendly** – LEDs contain no mercury or other hazardous substances.
9. **Directional** – With LEDs you can direct the light where you want it, thus no light is wasted.
10. **Shock resistance** – LEDs, being solid-state components, are difficult to damage with external shock, unlike fluorescent and incandescent bulbs, which are fragile.

Disadvantages

1. **High initial price** – LEDs are currently more expensive, price per lumen, on an initial capital cost basis, than more conventional lighting technologies. However, when considering the total cost of ownership (including energy and maintenance costs), LEDs far surpass incandescent or halogen sources and begin to threaten compact fluorescent lamps.
2. **Temperature dependence** - LED performance largely depends on correctly engineering the fixture to manage the heat generated by the LED, which causes deterioration of the LED chip itself. Over-driving the LED or not engineering the product to manage heat in high ambient temperatures may result in overheating of the LED package, eventually leading to device failure.
3. **Voltage sensitivity** - LEDs must be supplied with the correct voltage and current at a constant flow. This requires some electronics expertise to design the electronic drivers.
4. **Color shifting due to ageing** - LED's can shift color due to age and temperature. Also two different white LED will have two different color characteristics, which affect how the light is perceived.

2 COHERENT LIGHT SOURCES

In the previous chapter incoherent light sources are presented such as incandescent lamps, gas discharge lamps and LEDs. In this chapter, coherent light sources will be presented.

Coherent light is a beam of photons (almost like particles of light waves) that have the same frequency and are all at the same frequency. Only a beam of laser light will not spread and diffuse.

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for Light Amplification by Stimulated Emission of Radiation. Lasers differ from other sources of light because they emit light coherently. Its spatial coherence allows a laser to be focused to a tight spot, and this enables applications like laser cutting and laser lithography. Its spatial coherence also keeps a laser beam collimated over long distances, and this enables laser pointers to work. Lasers also have high temporal coherence which allows them to have a very narrow spectrum, i.e., they only emit a single color of light. Their temporal coherence also allows them to emit pulses of light that only last a femtosecond.

The gain medium of the laser could be solid, liquid, gas, plasma and the spectrum extends, depending on the gain medium, from the infrared to the ultraviolet range.

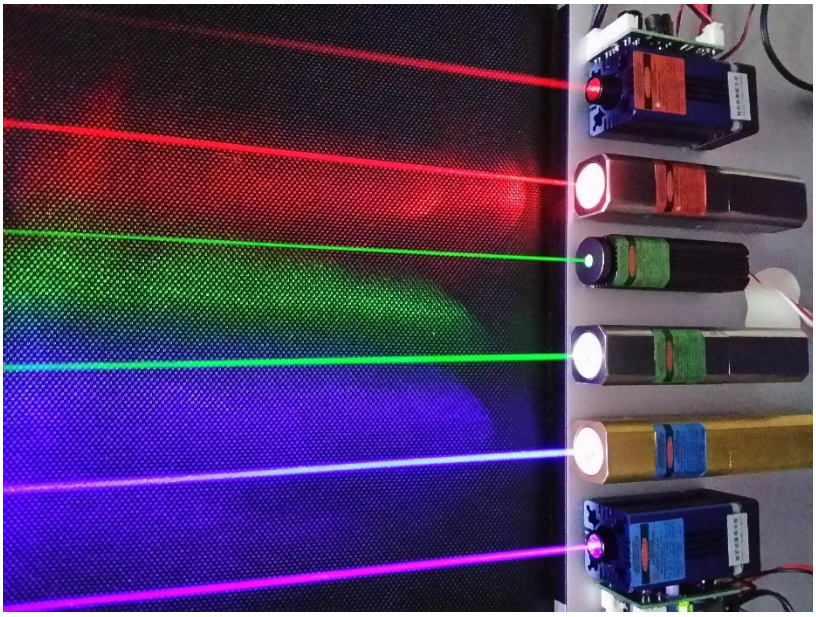


Figure 35 – Lasers of various wavelengths

2.1 Physics [12]

Laser is photon amplifier combined with a positive optical-feedback mechanism. Positive optical-feedback, which is necessary for lasing, is achieved by two mechanisms:

- One mechanism is consisting of a pair of mirrors between which there is the gain medium that produces the laser. Thus, the radiation leaving the gain medium returns many times to it. So we have a **laser oscillator**.
- The other mechanism is the principle of stimulated emission, which says that the probability of photon emission depends on the number of existing photons.

2.1.1 Absorption and emission

Consider an atomic system that consists of two electronic energy states, a lower level state (possibly the ground state) (1) and an excited state (2), with energies E1 and E2 respectively. Assume the atom is in lower level state with energy E1. The electrons of this atom could be excited to state (2), with energy E2 which is much higher than E1, if the atom interacts with radiation with energy density J and frequency v, such that the product hv equals the energy difference between the two levels, ie $hv=E_1-E_0$. This mechanism called **absorption**.

The transition from the excited state (2) to the lower level state (1), with the simultaneous emission of a photon with frequency v, where $hv=E_1-E_0$, called emission. In a state of thermodynamic equilibrium, the rate of excitation is equal to the rate of decay. The decay can be done either automatically after a residence time 10 in the excited state or under the influence of another photon. The first case is called spontaneous decay, while the second case is called stimulated decay.

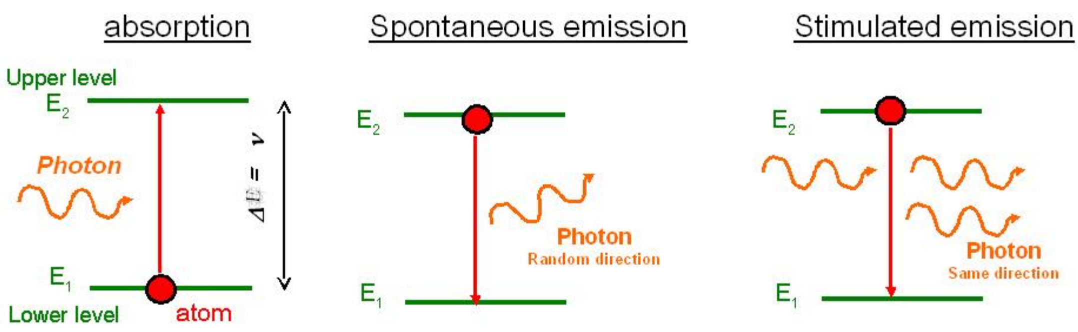


Figure 36 - Mechanism of the interaction between an atom and a photon

2.1.2 Population Inversion

A population inversion occurs when a system (such as a group of atoms or molecules) exists in a state with more members in an excited state than in lower energy states. We know that the rate of stimulated excitation (optical pumping) is equal to the rate of stimulated decay. We also know that there is an additional mechanism of excitation (and even more likely than the above): the spontaneous decay. This means that in a two level system the decay probability is always greater than the probability of excitation and therefore is not possible to produce laser with the use of such material.

A transition from one energy level En to another Em is permissible when not violating the principles of energy conservation, momentum, Angular Momentum, Spin and Parity (parity). When a switch is closed for violating one of the above quantities, the transition probability tends to zero, so the characteristic time of transition theory tends to infinity. The average time an atom remains in this state before decay is quite large. The levels in this capacity are called metastable. For comparison for transitions where not violated the above principles those atoms decay very quickly-within 10^{-15} s, while in the metastable levels atoms remain for a time longer than 10^{-7} s. The presence of metastable state systems in three levels or more are necessary to produce laser because the decay is very slow and thus population inversion is achieved.

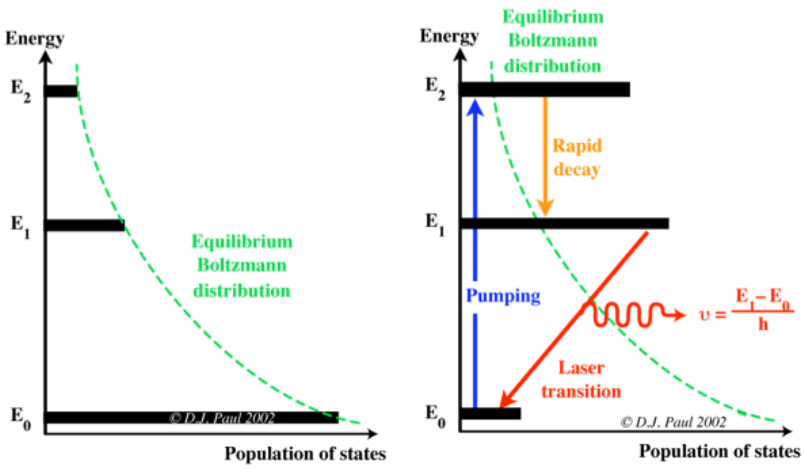


Figure 37 - Population Inversion

2.1.3 Gain medium and cavity

To preserve the Laser emission should provide positive optical-feedback so that operates as an optical oscillator. The most common type of laser uses feedback from an optical cavity—a pair of mirrors on either end of the gain medium. Light bounces back and forth between the mirrors, passing through the gain medium and being amplified each time. Typically one of the two mirrors, the output coupler, is partially transparent. Some of the light escapes through this mirror. Depending on the design of the cavity (whether the mirrors are flat or curved), the light coming out of the laser may spread out or form a narrow beam. This type of device is sometimes called a laser oscillator in analogy to electronic oscillators, in which an electronic amplifier receives electrical feedback that causes it to produce a signal.

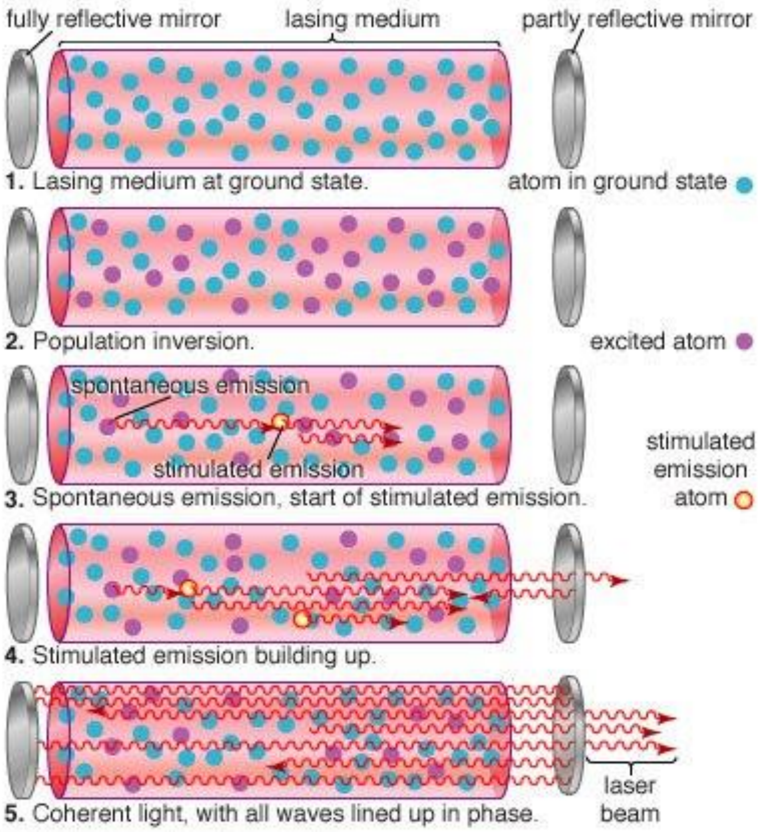


Figure 38 – Stimulated Emission in a mirrored laser cavity

The two parallel mirrors of the cavity forming a resonance cavity around the area of the gain. Only a limited number of wavelengths can exist in such a cavity. This is because the total path (2L) traveled by the photon must be an integer multiple of the wavelength of (pλ) to be supportive contribution. All other wavelengths are disappearing due to destructive contribution. The frequency difference between the permitted modes of oscillation is determined by the length of the cavity. As the length of cavity shortens the greater the difference in frequency and wavelength. Permitted modes refer to these wavelengths are maintained and enhanced in the cavity.

2.2 Gas Lasers [7]

The laser gas is consisting of a glass (or ceramic) tube with two electrodes, in which gas in low pressure is injected or, in the case of metal elements, small amount of amount of metal is placed into the tube. A high voltage (~ 1 kV) is applied on the electrodes resulting in electric discharge which causes excitation of individual electrons. The spontaneous decay of these electrons results, initially, in a linear spectrum emission of incoherent radiation. This radiation required, with the help of two parallel mirrors, inside of which is the tube, to return to the area of excited gas, causing stimulated decay of excited atoms. These processes result in the emission of a linear spectrum of coherent radiation. A prism usually is inserted between the two mirrors (optical cavity) and the lamp, as a way to select a single wavelength.

The table below presents various systems gas lasers and the wavelengths of the main lines of the emission spectrum.

Gas	Type	Wavelength (nm)
He – Ne	Atomic	632, 1152, 3391
CO_2	Molecular	9600, 10600
Ar	Ionized	351, 364, 458, 466, 476, 478, 488, 496, 511, 514
Kr	Ionized	521, 531, 568, 647, 676, 752, 793, 799

Table 3 - Gas lasers and their wavelengths

2.3 Solid-state Laser [7]

Solid-state lasers use a crystalline or glass rod which is "doped" with ions that provide the required energy states. For example, the first working laser was a ruby laser (Figure 12), made from ruby (chromium-doped corundum). The population inversion is actually maintained in the "dopant", such as chromium or neodymium. These materials are pumped optically using a shorter wavelength than the lasing wavelength, often from a flashtube or from another laser.

Neodymium is a common "dopant" in various solid-state laser crystals, including yttrium orthovanadate (Nd:YVO4), yttrium lithium fluoride (Nd:YLF) and yttrium aluminium garnet (Nd:YAG). All these lasers can produce high powers in the infrared spectrum at 1064 nm. They are used for cutting, welding and marking of metals and other materials, and also in spectroscopy and for pumping dye lasers.

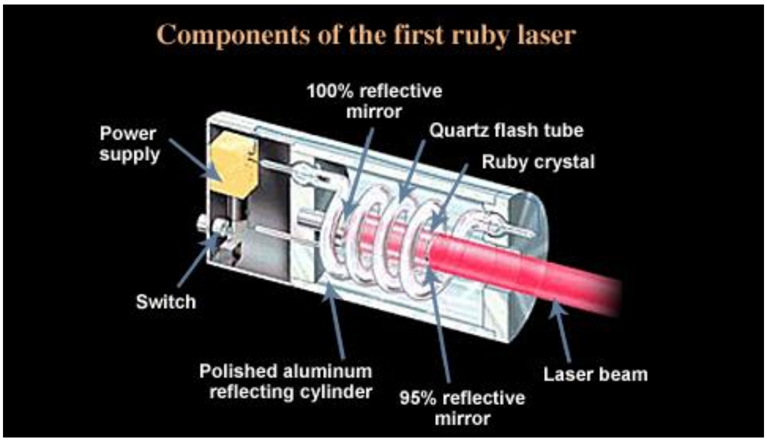


Figure 39 - Ruby Laser

Ytterbium, holmium, thulium, and erbium are other common "dopants" in solid-state lasers. Ytterbium is used in crystals such as Yb:YAG, Yb:KGW, Yb:KYW, Yb:SYS, Yb:BOYS, Yb:CaF2, typically operating around 1020–1050 nm. They are potentially very efficient and high powered due to a small quantum defect. Extremely high powers in ultrashort pulses can be achieved with Yb:YAG. Holmium-doped YAG crystals emit at 2097 nm and form an efficient laser operating at infrared wavelengths strongly absorbed by water-bearing tissues. The Ho-YAG is usually operated in a pulsed mode, and passed through optical fiber surgical devices to resurface joints, remove rot from teeth, vaporize cancers, and pulverize kidney and gall stones.

Titanium-doped sapphire (Ti:sapphire) produces a highly tunable infrared laser, commonly used for spectroscopy. It is also notable for use as a mode-locked laser producing ultrashort pulses of extremely high peak power.

2.4 Semiconductor Laser [2, 7]

A laser diode is an electrically pumped semiconductor laser in which the active medium is formed by a p-n junction of a semiconductor diode similar to that found in a light-emitting diode. A laser diode is formed by doping a very thin layer on the surface of a crystal wafer. The crystal is doped to produce an n-type region and a p-type region, one above the other, resulting in a p-n junction, or diode. Laser diodes form a subset of the larger classification of semiconductor p-n junction diodes.

Figure 40 - Laser Diode

Forward electrical bias across the laser diode causes the two species of charge carrier – holes and electrons – to be "injected" from opposite sides of the p-n junction into the depletion region. Holes are injected from the p-doped, and electrons from the n-doped, semiconductor. A depletion region, devoid of any charge carriers, forms as a result of the difference in electrical potential between n- and p-type semiconductors wherever they are in physical contact.

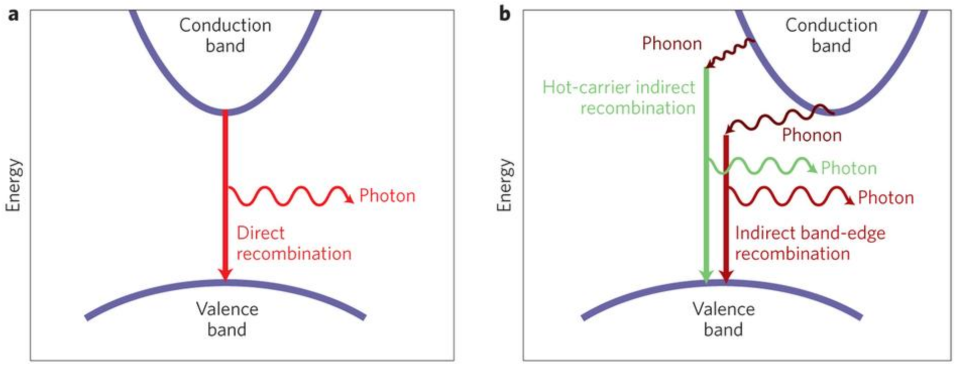


Figure 41 - Radiative recombination in direct and indirect bandgap semiconductor.

When an electron and a hole are present in the same region, they may recombine or "annihilate" with the result being spontaneous emission — i.e., the electron may re-occupy the energy state of the hole, emitting a photon with energy equal to the difference between the electron and hole states involved. Spontaneous emission gives the laser diode below lasing threshold similar properties to an LED. **Spontaneous emission is necessary to initiate laser oscillation**, but it is one among several sources of inefficiency once the laser is oscillating.

The 'key' to succeed "lasing" is the semiconductor material. These photon-emitting semiconductors are the so-called **semiconductors**. In "direct bandgap" semiconductors the momentum of electrons and holes is the same in both conduction band and valence band. Thus, an electron can directly emit a photon. In an "indirect bandgap" a photon cannot be emitted because the electron must pass through an intermediate state and transfer momentum to the crystal lattice. The properties of silicon and germanium, which are single-element semiconductors, have bandgaps that do not align in the way needed to allow photon emission and are considered "indirect". From the other hand, compound semiconductors, have virtually identical crystalline structures as silicon or germanium but use alternating arrangements of two different atomic species in a checkerboard-like pattern to break the symmetry. The transition between the materials in the alternating pattern creates the critical "direct bandgap" property. Gallium arsenide, indium phosphide, gallium antimonide, and gallium nitride are all examples of compound semiconductor materials that can be used to create junction diodes that emit light.

Population Inversion

In the absence of stimulated emission, electrons and holes may coexist in proximity to one another, without recombining, for a certain time, termed the "upper-state lifetime" or "recombination time" (about a nanosecond for typical diode laser materials), before they recombine. Then a nearby **photon with energy equal to the recombination energy can cause recombination by stimulated emission**. This generates another photon of the same frequency, travelling in the same direction, with the same polarization and phase as the first photon. This means that stimulated emission causes gain in an optical wave (of the correct wavelength) in the injection region, and the gain increases as the number of electrons and holes injected across the junction increases.

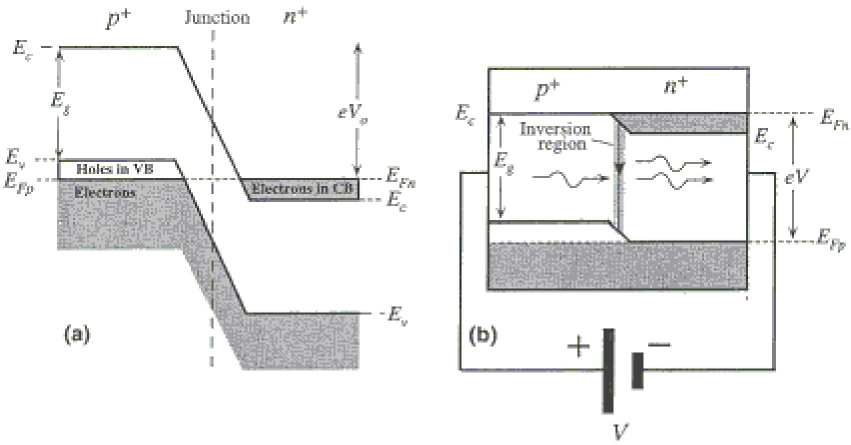


Figure 42 – (a) Diode is zero biased (b) Forward electrical bias across the laser diode causes the electrons to be excited in the conduction band and in a very small area population inversion takes place.

Optical Cavity

The gain region is surrounded with an optical cavity to form a laser. In the simplest form of laser diode, an optical waveguide is made on that crystal surface, such that the light is confined to a relatively narrow line. The two ends of the crystal are cleaved to form perfectly smooth, parallel edges, forming a Fabry–Pérot resonator. Photons emitted into a mode of the waveguide will travel along the waveguide and be reflected several times from each end face before they are emitted. As a light wave passes through the cavity, it is amplified by stimulated emission, but light is also lost due to absorption and by incomplete reflection from the end facets. Finally, if there is more amplification than loss, the diode begins to "lase".

The simple laser diode structure, described above, is extremely inefficient. Such devices require so much power that they can only achieve pulsed operation without damage. Let's see some other type laser and present their structure.

2.4.1 Double Heterostructure Lasers [13]

In Double Heterostructure Lasers, a layer of low bandgap material is sandwiched between two high bandgap layers. Usually, the pair of materials is GaAs (active layer) and AlGaAs (cladding p and n layers). The operating principle of this diode laser is the use of heterojunctions to achieve simultaneous carrier and photon confinement in the active region. **A high laser efficiency demands that the light and injected charge carriers be confined as closely as possible to the same volume.** As presented in the figure 15 we have the AlGaAs Laser Diode which consists of a double hetero-junction formed by an undoped (or lightly p-doped) active region surrounded by higher bandgap p and n AlGaAs cladding layers. The role of surrounding cladding layers is to provide an energy barrier to confine carriers to the active region. The actual operation wavelengths may range from 750-880 nm due to the effects of dopants, the size of the active region, and the compositions of the active and cladding layers. When a bias voltage is applied in the forward direction, electrons and holes are injected into the active layer. Since the bandgap energy is larger in the cladding layers than in the active layer, the injected electrons and holes are prevented from diffusing across the junction by the potential barriers formed between the active layer and cladding layers. The electrons and holes confined to the active layer create a state of population inversion, allowing the amplification of light by stimulated emission.

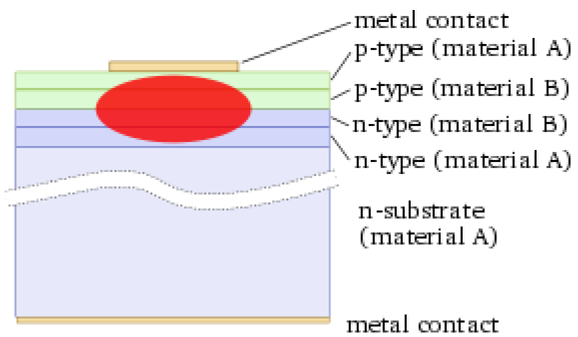


Figure 43 – Internal structure of the Double Heterostructure Laser

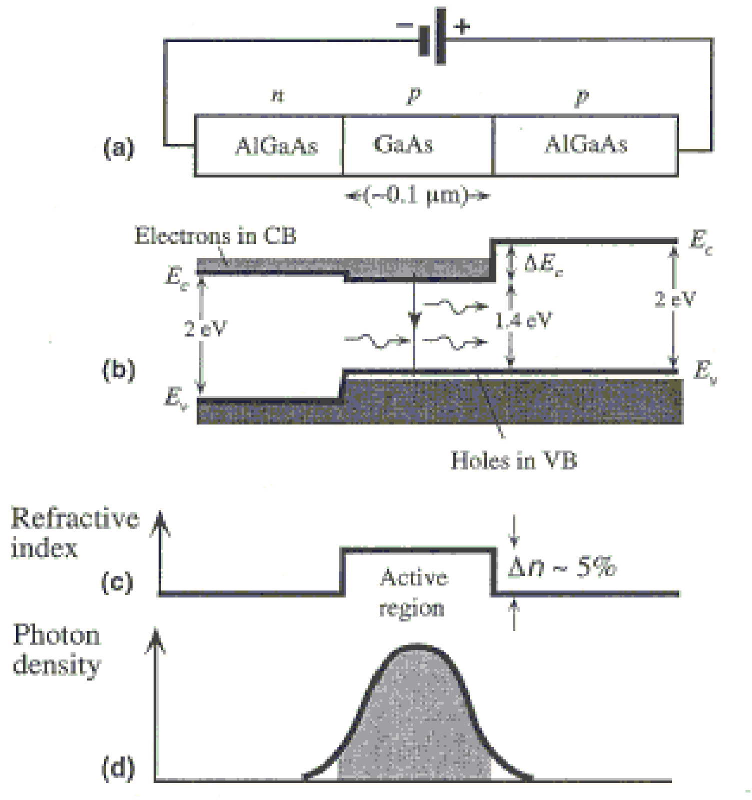


Figure 44 - Double Heterostructure Laser diode

2.4.2 Quantum Well Lasers[14, 15]

In Double Heterostructure Lasers the active region, which is sandwiched between two high bandgap materials, is about 0.1μm thick. What will happen if the active region is made thin enough? The answer is that it acts as a quantum well. So quantum confinement occurs. This is the basic idea behind the Quantum well lasers.

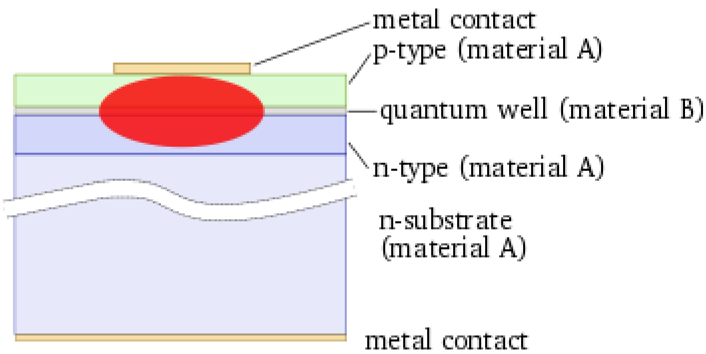


Figure 45 - Quantum Well Laser

A quantum well laser is a laser diode in which the active region of the device is so narrow that quantum confinement occurs.

When materials, like the active region in the Quantum well lasers, are so small, their electronic and optical properties deviate substantially from those of bulk materials. **A particle behaves as if it were free when the confining dimension is large compared to the wavelength of the particle**. During this state, the bandgap remains at its original energy due to a continuous energy state. However, as the confining dimension decreases and reaches a certain limit, typically in **nanoscale**, the energy spectrum turns to discrete. As a result, the bandgap becomes size dependent. This ultimately results in a blue shift in optical illumination as the wavelength decreases.

We can say that a quantum laser is an improved LED. As illustrated in figure 18 electrons and holes are kept together inside the semiconductor at the center, which has a smaller gap. That makes it easier for electrons to find holes. I also creates quantized energy levels with a high-concentrated density of states.

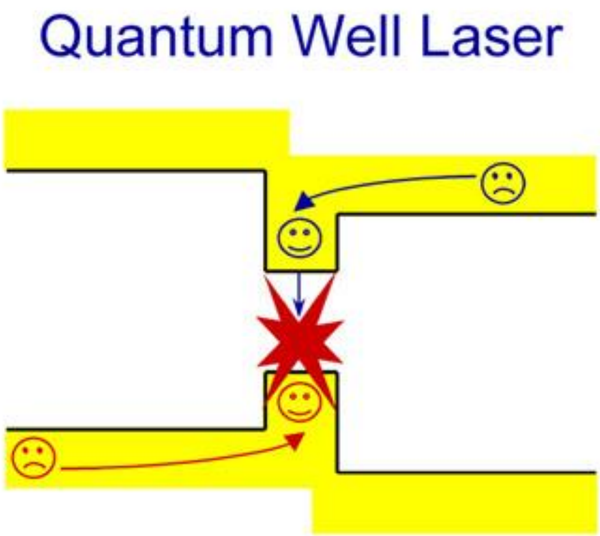


Figure 46 - Quantum Well

According to the above, the wavelength of the light emitted by a quantum well laser is determined by the width of the active region rather than just the bandgap of the material from which it is constructed. This means that much shorter wavelengths can be obtained from quantum well lasers than from conventional laser diodes using a particular semiconductor material. The efficiency of a quantum well laser is also greater than a conventional laser diode due to the stepwise form of its density of states function.

2.4.3 Quantum Cascade Lasers [15, 16]

This laser, as its name implies, is like the Quantum Well Lasers with multiple cascade quantum wells. We can say Quantum Cascade Lasers are "updated" Quantum Well Lasers. Quantum Cascade Laser is usually emitting mid-infrared light. Unlike typical interband semiconductor lasers described above, that emit electromagnetic radiation through the recombination of electron–hole pairs across the material band gap, Quantum Cascade Lasers are unipolar and laser emission is achieved through the use of intersubband transitions in a repeated stack of semiconductor multiple quantum well heterostructures. In a Quantum Cascade Lasers, electrons are making transitions between bound states created by quantum confinement in ultrathin alternating layers of semiconductors materials. Since these ultrathin layers, called quantum wells restrict the electron motion perpendicular to the plane of the layer. Because of this effect called quantum confinement, the electron can only jump from one state to the other by discrete steps, emitting photons of light. **The spacing between the steps depends on the width of the well, and increases as the well size is decreased.** The emission wavelength depends now on the layer thicknesses and not on the bandgap of the constituent materials. The cascade of identical stages allows one electrons to emit many photons, so emitting more optical power and having higher power efficiency than the above lasers. Also, cascade enables laser action at relatively long wavelengths, which can be tuned simply by altering the thickness of the layer.

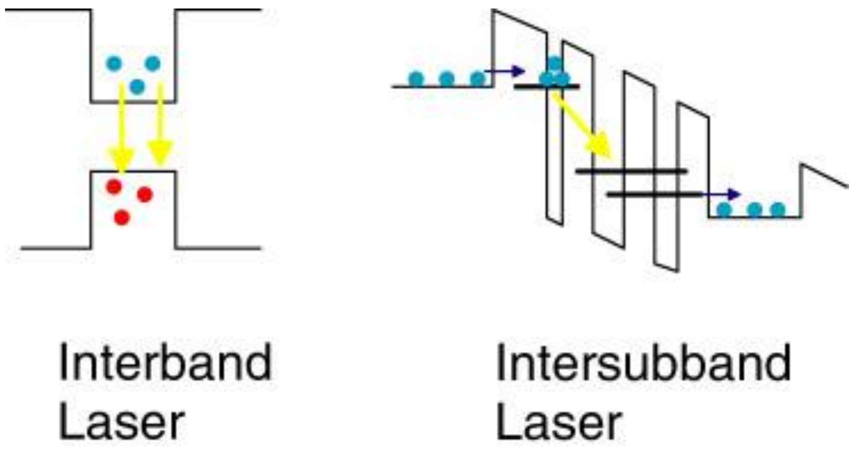


Figure 47 - In an intersubband laser, there is no electron-hole recombination.

2.4 Tunable Lasers

In the lasers presented above we cannot achieve wavelength selection. Let's see lasers with the characteristic of wavelength tunability.

2.4.1 Distributed Bragg Reflector (DBR) Laser [17]

One method to achieve wavelength selection is shorter optical cavities, which is not practical since it is difficult to handle very small chips. Another possible method is to insert an optical feedback in the device to eliminate other frequencies. Periodic grating incorporated within the lasers waveguide can be utilized as a means of optical feedback. The devices incorporating the grating in the pumped region are termed Distributed Feedback (DFB) lasers, while those incorporating the grating in the passive region are termed Distributed Bragg Refractor (DBR) Lasers.

The gratings or distributed Bragg reflectors (DBRs) are used for one or both cavity mirrors. The grating thereby consists of corrugations with a periodic structure. They are used because of their frequency selectivity of single axial mode operation. The period of grating is chosen as half of the average optical wavelength, which leads to a constructive interference between the reflected beams. Significant reflections can also occur in harmonics frequencies of the medium. The corrugations are typically etched on the surface of the waveguide, and these are refilled with a different index material during a second growth.

The concept of the grating is that many reflections can add up to a large net reflection. At the Bragg frequency the reflections from each discontinuity add up exactly in phase. As the frequency is deviated from the Bragg condition, the reflections from discontinuities further into the grating return with progressively larger phase mismatch.

A DBR Laser can be formed by replacing one or both of the discrete laser mirrors with a passive grating reflector. Figure 16 shows a schematic of such a laser with one grating mirror. Besides the single frequency property provided by the frequency-selective grating mirrors, this laser can include wide tunability. **Since the refractive index depends on the carrier density this can be exploited to vary the refractive index electro optically on the sections by separate electrodes.**

The potential tunability of DBR Lasers is one of the main reasons why they are of great importance. As indicated in Figure 37, there are usually three sections, one active, one passive, and the passive grating. The first provides the gain, the second allows independent mode phase control and the grating is a mode selective filter. **By applying a current or voltage to the sections the refractive index changes, shifting the axial modes of the cavity and thus the wavelength of the laser.**

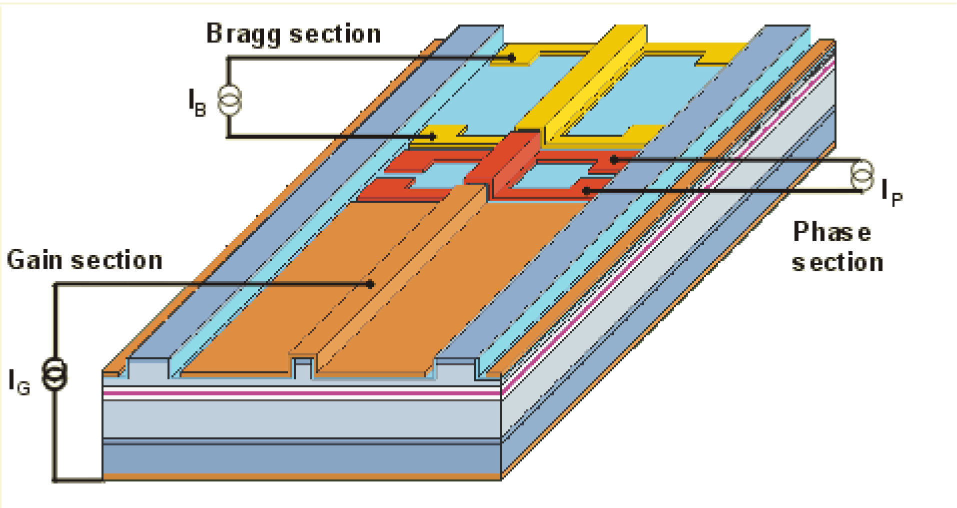


Figure 48 – Schematic of a DBR Laser

The DBR is widely tunable, but relatively complex since a lot of structure must be created along the surface of the wafer. For this reason DBR Lasers are only formed when their properties are required. The laser works in single mode.

2.4.2 Distributed Feedback (DFB) Laser [18]

A distributed feedback laser (DFB) is a type of laser diode, quantum cascade laser or optical fibre laser where the active region of the device is periodically structured as a diffraction grating. A distributed feedback laser (DFB) uses grating mirrors, but the grating is included in the gain region. Reflections from the ends are suppressed by antireflection coatings. Thus, it is possible to make a laser from a single grating, although it is desirable to have at least a fraction of a wavelength shift near the center to facilitate lasing at the Bragg frequency. Altering the temperature of the device causes the pitch of the grating to change due to the dependence of refractive index on temperature. This dependence is caused by a change in the semiconductor laser's bandgap with temperature and thermal expansion. A change in the refractive index alters the wavelength selection of the grating structure and thus the wavelength of the laser output, producing a wavelength tunable laser. The idea behind this concept is, apart from the wavelength selectivity, to improve the quality of the laser, as the active length is a quarter-wavelength long. This applies for no shift in the gratings, where the cavity can be taken to be anywhere within the DFB, since all periods look the same.

For the standard DFB grating, we can see that the laser is antiresonant at the Bragg frequency. The modes of this laser are placed symmetrically around the Bragg frequency. However only the modes with lowest losses will lase. With symmetrical gain profile around the Bragg frequency, this means that two modes are resonant. To suppress one mode we need to apply additional perturbation reflections, such as from uncoated cleaves at the end.

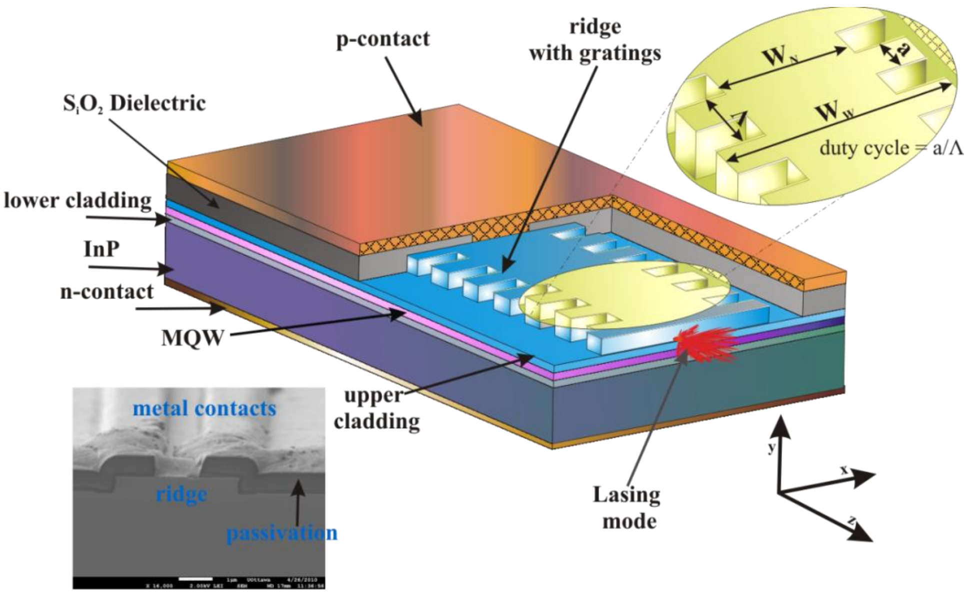


Figure 49 – Schematic of a DFB Laser

In contrast with DBR, DFB Lasers are easier to fabricate and show less losses and therefore have a lower threshold current. DFB Lasers, like DBR, work in single mode.

2.4.3 Tunable External Cavity Lasers [19]

External-cavity diode lasers use mainly double heterostructures diodes of the AlxGa(1-x)As type. One type of external-cavity laser has one end anti-reflection coated and the laser resonator is completed with collimating lens and an external mirror (Figure 39). Another type of external-cavity laser uses resonator based on an optical fiber rather than on free-space optics. Narrowband optical feedback can then come from a fiber Bragg grating.

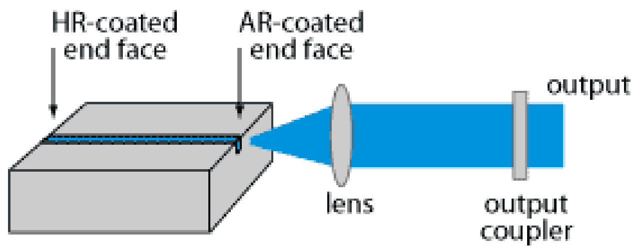


Figure 50 – Schematic of a DFB Laser

By adjusting optical filter in the external resonator, Tunable External Cavity Laser is "born". This optical filter is diffraction grating. There are two popular configurations for Tunable External Cavity Lasers:

- The common **Littrow configuration** contains collimating lens and a diffraction grating as the end mirror. The first-order diffracted beam provides optical feedback to the laser diode chip, which has an anti-reflection coating on the right-hand side. **The emission wavelength can be tuned by rotating the diffraction grating.** A disadvantage is that this also changes the direction of the output beam, which is inconvenient for many applications.
- **In the Littman–Metcalf configuration, the grating orientation is fixed, and an additional mirror is used to reflect the first-order beam back to the laser diode. The wavelength can be tuned by rotating that mirror.** This configuration offers a fixed direction of the output beam, and also tends to exhibit a smaller linewidth, as the wavelength selectivity is stronger. A disadvantage is that the zero-order reflection of the beam reflected by the tuning mirror is lost, so that the output power is lower than that for a Littrow laser.

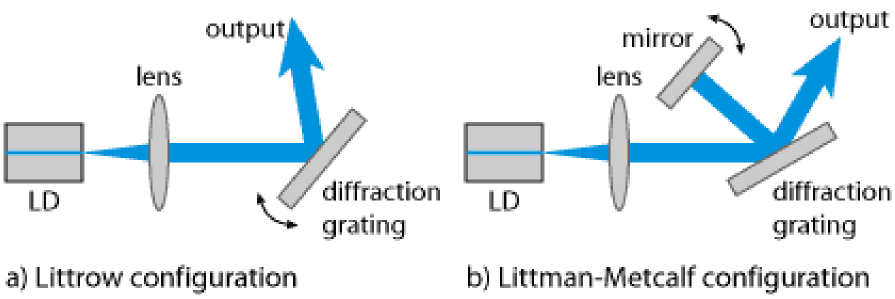


Figure 51 – Tunable external-cavity diode lasers in Littrow and Littman–Metcalf configuration.

2.4.4 MEMs Tunable Vertical-cavity surface-emitting laser [20]

Vertical-cavity surface-emitting laser are semiconductor lasers, more specifically laser diodes with a monolithic laser resonator, where the emitted light leaves the device in a direction perpendicular to the chip surface.

The laser resonator consists of two distributed Bragg reflector (DBR) mirrors parallel to the wafer surface with an active region consisting of one or more quantum wells for the laser light generation in between. The planar DBR-mirrors consist of layers with alternating high and low refractive indices. Each layer has a thickness of a quarter of the laser wavelength in the material, yielding intensity reflectivities above 99%. High reflectivity mirrors are required in VCSELs to balance the short axial length of the gain region.

VCSELs can have a good beam quality only for fairly small mode areas (diameters of a few microns) and are thus limited in terms of output power. In addition to the high beam quality of low-power VCSELs, an important aspect is the low beam divergence, compared with that of edge-emitting laser diodes, and the symmetric beam profile. This makes it easy to collimate the output beam with a simple lens, which does not have to have a very high numerical aperture. An important practical advantage of VCSELs, as compared with edge-emitting semiconductor lasers, is that they can be tested and characterized directly after growth, before the wafer is cleaved. This makes it possible to identify quality problems early on, and to react immediately.

Furthermore, it is possible to combine a VCSEL with an array of optical elements. This concept leads to MEMs Tunable Vertical-cavity surface-emitting laser. MEMS-tunable VCSELs utilize micro-electromechanical mirror systems (MEMS) to vary the cavity length of the laser, thereby tuning the output wavelength. MEMs Tunable Vertical-cavity surface-emitting lasers are capable of tuning over 100nm.

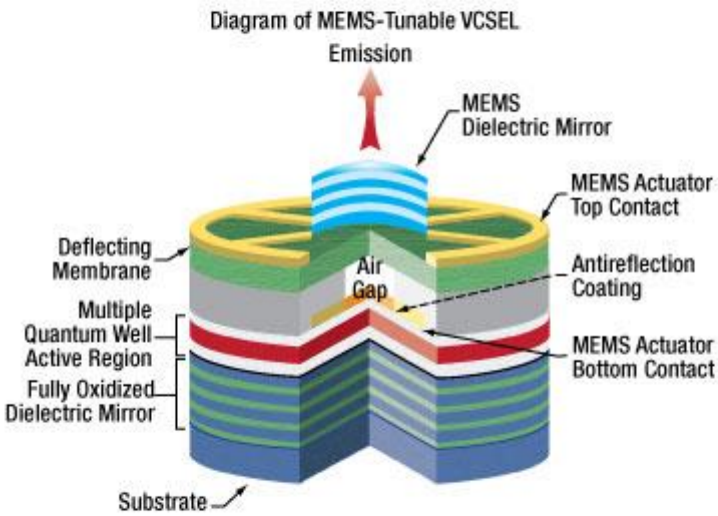


Figure 52 – MEMs Tunable Vertical Cavity Surface Emitting Diode

2.4.5 Ion Laser [21]

An ion laser is a gas laser which uses an ionized gas as its lasing medium. Like other gas lasers, ion lasers feature a sealed cavity containing the laser medium and mirrors forming a resonator. Unlike HeNe lasers, the energy level transitions that contribute to laser action come from ions. Because of the large amount of energy required to excite the ionic transitions used in ion lasers, **the required current is much greater**, and as a result all but the smallest ion lasers are **water-cooled**.

Some ion lasers have several transition wavelengths on which laser operation can be achieved. To understand better, let's take the case of an Argon Laser. Argon lasers emit at 13 wavelengths through the visible, ultraviolet, and near-visible spectrum, including: 351.1 nm, 363.8 nm, 454.6 nm, 457.9 nm, 465.8 nm, 476.5 nm, 488.0 nm, 496.5 nm, 501.7 nm, 514.5 nm, 528.7 nm, 1092.3 nm. This implies a continuous spectrum.

If a dispersive element, such as a prism, is introduced into the optical cavity, tilting of the cavity's mirrors can cause tuning of the laser as it "hops" between different laser lines (Figure 42).

Also, White Laser is an ion laser with a mixture of Argon and Krypton gases. The combination of the two gasses causes wavelengths combination. Thus, a continuous spectrum is implied.

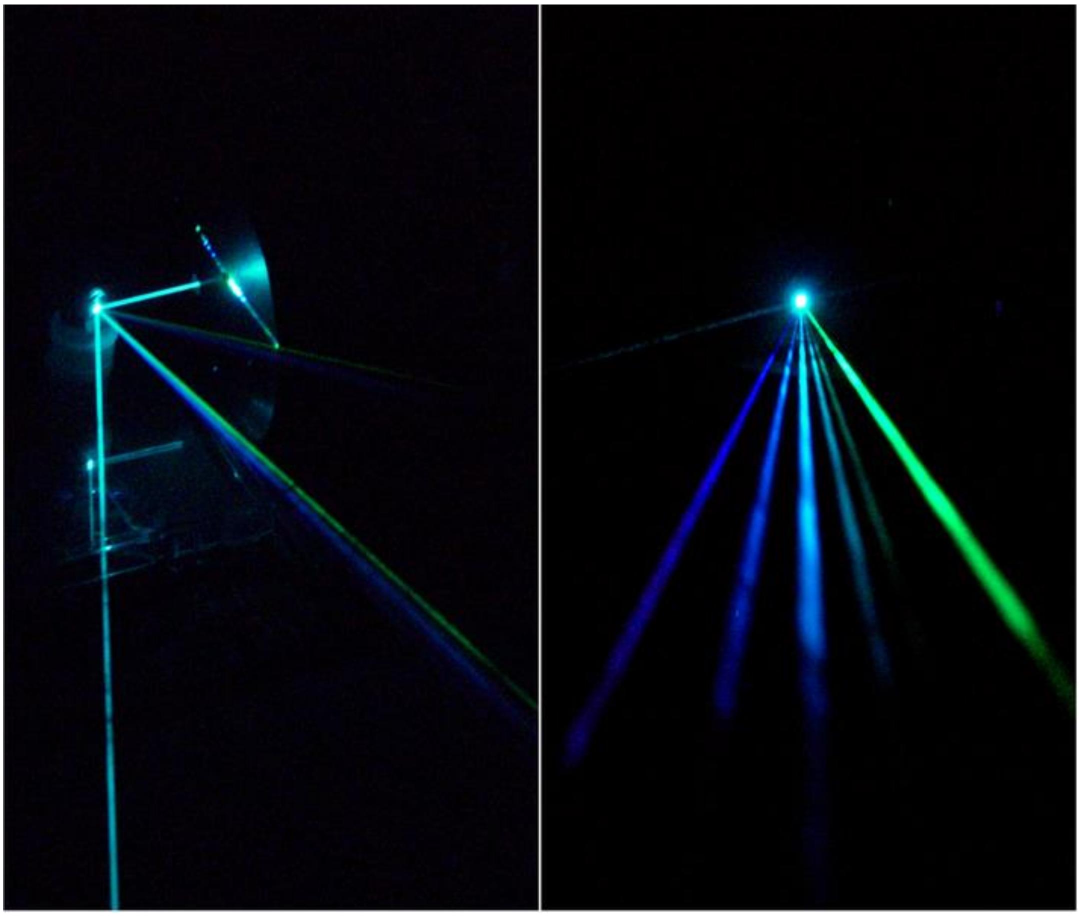


Figure 53 - An argon laser beam consisting of multiple wavelengths strikes a silicon diffraction mirror grating and is separated into several beams, one for each wavelength.

2.4.6 Dye Laser [22]

Dye laser is the first true broadly tunable laser. A dye laser is a laser which uses an organic dye as the lasing medium, usually as a liquid solution. Compared to gases and most solid state lasing media, a dye can usually be used for a much wider range of wavelengths. The wide bandwidth makes them particularly suitable for tunable lasers and pulsed lasers.

A dye laser consists of an organic dye mixed with a solvent, which may be circulated through a dye cell, or streamed through open air using a dye jet. A high energy source of light is needed to 'pump' the liquid beyond its lasing threshold. A fast discharge flashlamp or an external laser is usually used for this purpose. Mirrors are also needed to oscillate the light produced by the dye's fluorescence, which is amplified with each pass through the liquid. The output mirror is normally around 80% reflective, while all other mirrors are usually more than 99.9% reflective. The dye solution is usually circulated at high speeds, to help avoid triplet absorption and to decrease degradation of the dye. A prism or diffraction grating is usually mounted in the beam path, to allow tuning of the beam.

Some of the dyes are rhodamine, fluorescein, coumarin, stilbene, umbelliferone, tetracene, malachite green, and others. While some dyes are actually used in food coloring, most dyes are very toxic, and often carcinogenic. Many dyes, such as rhodamine 6G, (in its chloride form), can be very corrosive to all metals except stainless steel.

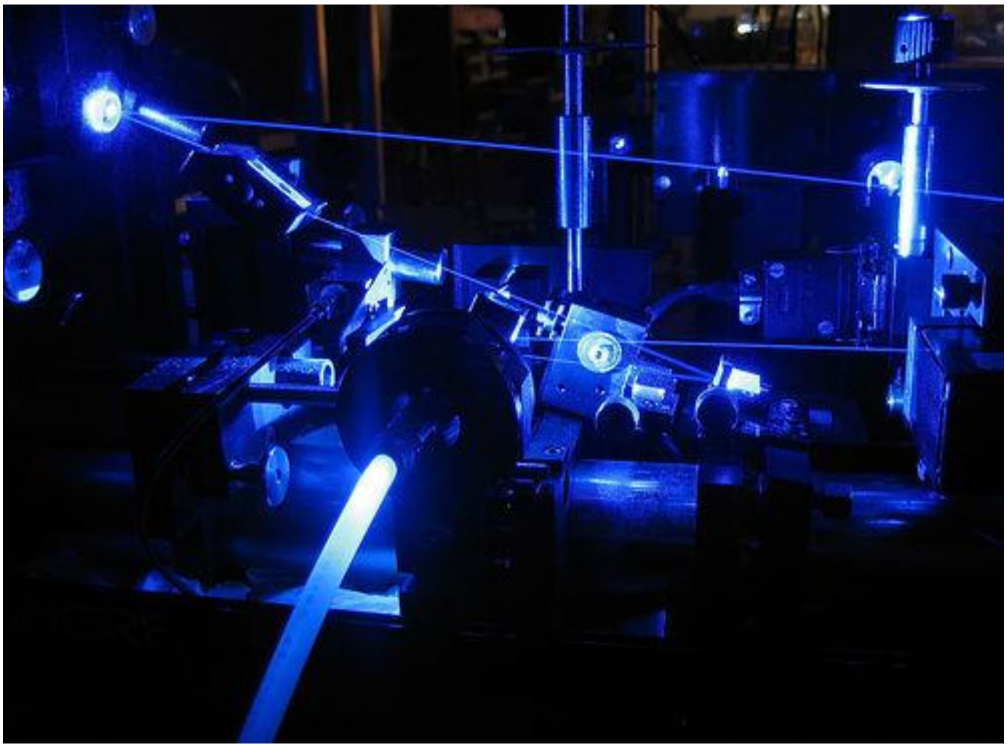


Figure 54 - Blue Dye Laser

3 COHERENT AND INCOHERENT LIGHT SOURCES IN BIOMEDICAL APPLICATIONS

3.1 Incoherent light sources for optical microscopy

The first light source used for microscopy was the sun and the second was a candle flame. Both are hot plasmas that emit essentially black-body radiation with the addition of a few elemental lines. The introduction of light sources powered by electricity, both arcs and incandescent filaments, added a new level of convenience and flexibility but required improvements in the light-harvesting optics needed to illuminate the imaged area with light that was both intense and uniform.

Microscope illumination parts [23]

There are numerous light sources available to illuminate microscopes, both for routine observation and critical photomicrography. A most common light source, because of its low cost and long life is the 50 or 100W tungsten halogen lamp as illustrated at the base of the microscope diagram in Figure 44. Figure 44 also details the optical pathways in a typical modern transmitted light microscope. In this point, it is useful to explain the difference between transmitted and reflected microscopes. A transmitted light microscope, like that shown in Figure 44, has a light source below the microscope stage and sends light upwards towards the sample and up to

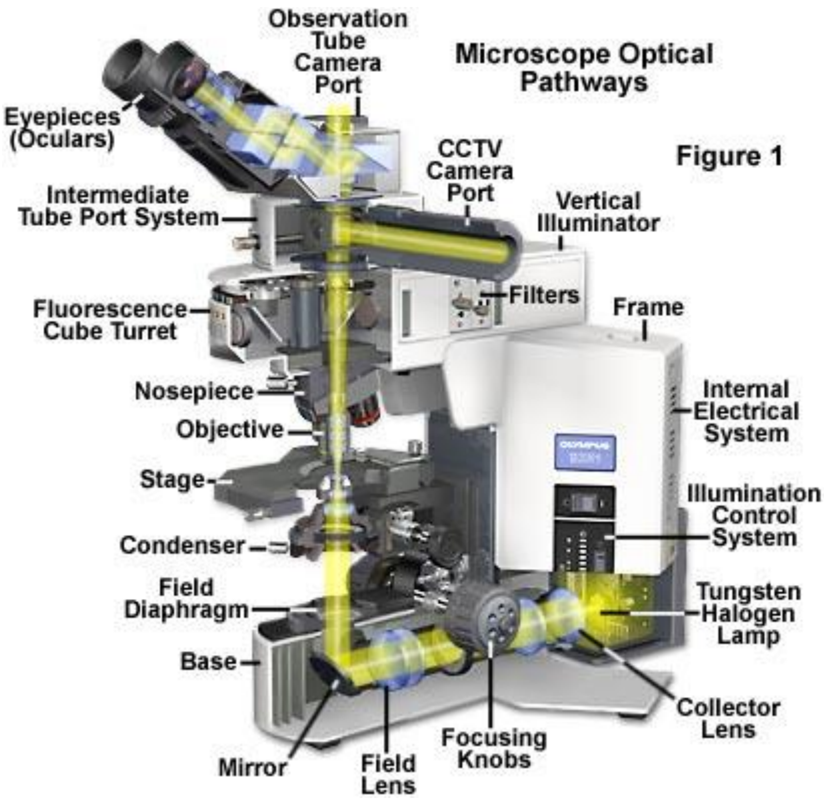


Figure 55 – Optical microscope optical pathways

the viewing point. A reflected light microscope has a light source above the sample (the light source is plugged in Vertical Illuminator Socket as shown in Figure 44) and what is seen though the view point are light waves that have reflected off the sample.

The tungsten-halogen lamp emits a continuous spectrum of light centered at 3200 K, which is then passed through a collector and field lens before being reflected into the substage condenser and onto the specimen. Image forming light rays are captured by the microscope objective and passed either into the eyepieces or directed by a beamsplitter into one of several camera ports. Throughout the optical pathway of the microscope, illumination is directed and focused through a series of diaphragms and lenses as it travels from the source to illuminate the specimen and then into the eyepieces or camera attachment. Alignment of the optical components of a microscope to optimize illumination in modern microscopes is carried out following the rules of Köhler illumination. The optical pathways shown above in Figure 44 are typical for a transmitted light microscope and involve a number of lenses, diaphragms, mirrors, and beamsplitters to direct light through the microscope.

Light sources for transmitted and reflected light microscopy 24

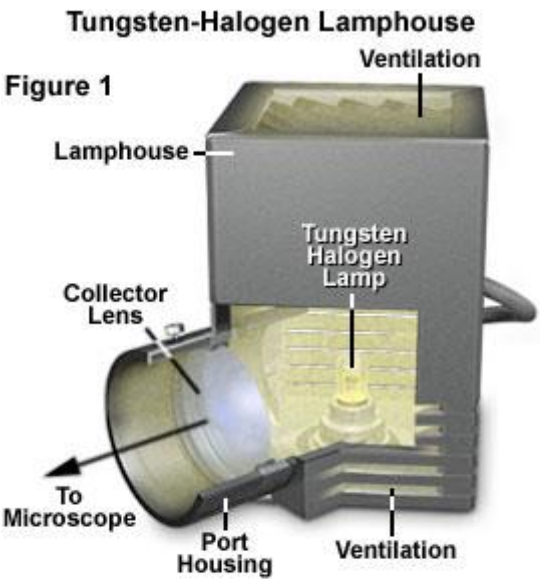


Figure 56 – Tungsten-Halogen Lamphouse

As already written above, the most common source for today's microscopy the incandescent tungsten-halogen bulb positioned in a reflective housing that projects light through the collector lens and into the substage condenser. Lamp voltage is controlled through a variable rheostat that is commonly integrated into the microscope stand. A typical illuminator lamp and housing is illustrated in Figure 45. The bulb is a tungsten-halogen lamp that operates on a direct current (DC) voltage of 12 volts and produces up to 100 watts of power for illumination. Lamp voltage is controlled by a DC power supply that is often built into the microscope housing, with a voltage control knob that is usually a potentiometer mounted somewhere on the microscope stand. These bulbs generate a large amount of heat during operation, and the housing is provided with several layers of heat sinks to help dissipate excess heat. The position of the lamp is controlled by a series of knobs on the side of the illuminator housing or is pre-centered specifically for the housing. Light from the lamphouse is directed into the microscope base through a collector lens (Figure 45), and then frequently through a sintered glass diffuser before being focused on the aperture diaphragm of the condenser.

Incandescent lamps

Incandescent tungsten-based lamps are the primary illumination source used in modern microscopes, with the exception of those intended for fluorescence microscopy investigations. These lamps are thermal radiators that emit a continuous spectrum of light extending from about 300 nanometers to upward of 1200-1400 nanometers, with a majority of the wavelength intensity centered in the 600-1200 nanometer region.

The bulbs produce a tremendous amount of heat and light, but the light accounts for only 5 to 10 percent of their energy output. Tungsten lamps (but not tungsten-halogen) are similar in operation to common household light bulbs and likewise tend to suffer several drawbacks such a decreased intensity with age and a blacking of the inside envelope as evaporated tungsten is slowly deposited.

Tungsten Halogen lamp

Tungsten Halogen lamps are now a standard equipment on most microscopes. Tungsten-halogen lamps have compact bulbs that introduce a number of advantages over normal incandescent lamps, most notably their brilliant light, smaller dimension, uniformity of illumination, longer lamp life and greater economy. Unlike tungsten-filament incandescent lamps, tungsten-halogen lamps have halogens added to the filler glass. The halogens (usually iodine) ensure that all vaporized tungsten is returned to the filament and not deposited upon the glass envelope. They have very high filament operating temperatures, restricting their use to well-ventilated lamphouses with fan-shaped heat sinks to eliminate the tremendous amount of heat generated by these bulbs. tungsten-halogen bulbs is remarkably uniform throughout the bulb life, which can range from 1000-2500 hours. Tungsten-halogen bulbs emit a continuous spectrum of light with a color temperature ranging from 2700-3350 K (depending upon voltage), although there is some decline in the color temperature value as the bulbs begin to age.

Arc lamps

Mercury vapor, xenon and zirconium arc lamps are also useful sources of illumination for specialized forms of microscopy. These lamps are controlled by external power supplies that are designed to meet the electrical requirements of first igniting the lamp, then providing the correct current to maintain constant illumination. The lamp in Figure 46(a) is a mercury vapor lamp equipped with an igniter electrode and the lamp in Figure 46(b) is a modern HBO 200 watt mercury short arc lamp powered with alternating current through an external power supply. This and other similar arc lamp power supplies will furnish enough start-up power to ignite the burner (by ionization of the gaseous vapor) and keep it burning with a minimum of flicker. Arc lamps have an average lifetime of about 200 hours and most external power supplies are equipped with a timer that allows the microscopist to monitor how much time has elapsed.

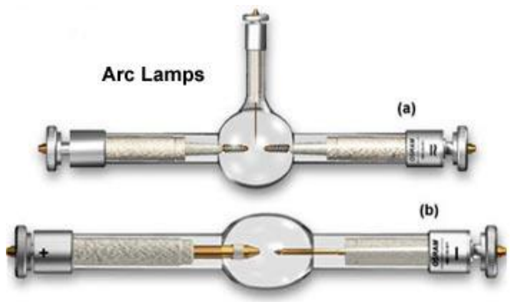


Figure 57 – Arc lamps

Mercury Arc lamps

Mercury arc lamps range in wattage from 50 watts to 200 watts and consist usually of two electrodes sealed under high pressure in a quartz glass envelope which also contains mercury. These arc lamps do not provide even intensity across the spectrum from near-ultraviolet to infrared. Mercury arc lamps in microscopy will be presented in more detail in the Fluorescing Microscopy paragraph bellow.

Xenon Arc lamps

The xenon arc lamps have much more even intensity across the visible spectrum than do the mercury vapor lamps. Also, they do not have the very high spectral intensity peaks that are characteristic of the mercury lamps. Xenon lamps are deficient in the ultraviolet. They expend a large proportion of their intensity in the infrared, and therefore the use of such lamps requires care in control of heat. Short-gap xenon burners are usually more desirable because the size of the arc is such that its light may be much more readily included within the back aperture of the objective, thus avoiding waste of light intensity. Xenon arc lamps have a life of several hundreds of hours. Frequent on-off switching reduces lamp life. When the burners reach their rated lifetime, the spectral emissions may change and the quartz envelope weakens.

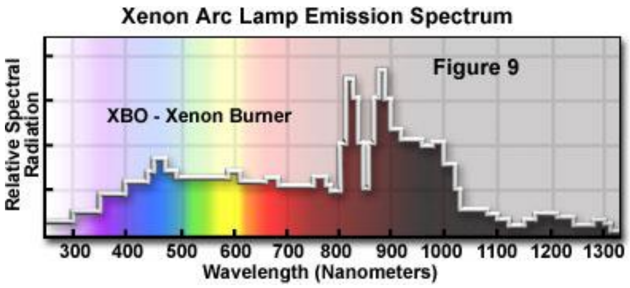


Figure 58 – Xenon arc lamp emission spectrum

Zirconium Arc lamps

Zirconium arc lamps are another excellent source for microscope illumination. They provide a very small (almost a point source) beam of light that has a color temperature of about 3200 K. While these lamps do not emit light as bright as the mercury or xenon arc lamps, they do provide a continuous spectrum of light that is suitable for photomicrography using color film.

Light emitting diodes

Among the most promising of emerging technologies for illumination in optical microscopy is the light-emitting diode (LED). These versatile semiconductor devices possess all of the desirable features that incandescent (tungsten halogen) and arc lamps lack, and are now efficient enough to be powered by low-voltage batteries or relatively inexpensive switchable power supplies. The diverse spectral output afforded by LEDs makes it possible to select an individual diode light source to supply the optimum excitation wavelength band for fluorophores spanning the ultraviolet, visible, and near-infrared regions. Furthermore, newer high-power LEDs generate sufficient intensity to provide a useful illumination source for a wide spectrum of applications in fluorescence microscopy.

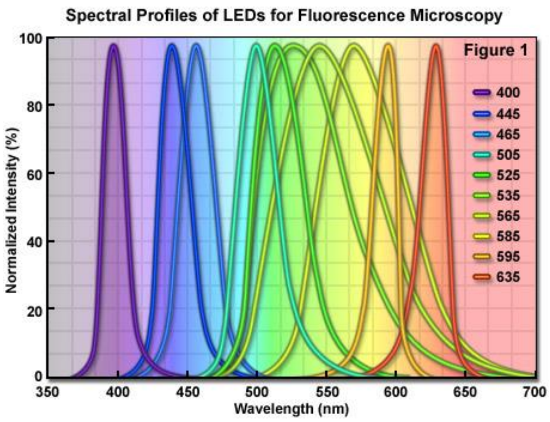


Figure 59 – Spectral profiles of LEDs for fluorescence microscopy

Light sources for fluorescence microscopy [25]

When specimens, living or non-living, organic or inorganic, absorb and subsequently re-radiate light, the process is described as photoluminescence. If the emission of light persists for up to a few seconds after the excitation

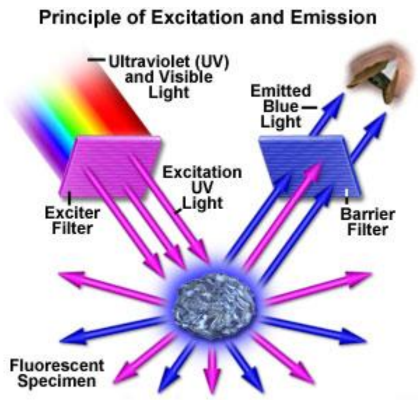


Figure 60 – Principle of excitation and emission

energy (light) is discontinued, the phenomenon is known as phosphorescence. Fluorescence, on the other hand, describes light emission that continues only during the absorption of the excitation light.

In most fluorescence microscopy applications, the number of photons reaching the eye or other detector, such as a video camera or photomultiplier, is usually very low. This is because the quantum yield of most fluorochromes is low (quantum yield is the ratio of the number of quanta emitted by the specimen as compared to the number of quanta absorbed). To generate enough excitation light intensity to furnish emission capable of detection, powerful light sources are needed, usually arc lamps like the mercury arc lamp, which is the most common lamps.

Mercury arc lamps

The mercury arc lamps are ranging from 50W to 200W. Mercury arc lamps are usually powered by a D.C. power supply furnishing enough start-up power to ignite the burner (by ionization of the gaseous vapor) and to keep it burning with a minimum of flicker. The power supply should have a timer to enable you to keep track of the number of hours the burner has been in use. The mercury burners do not provide even intensity across the spectrum from ultraviolet to infrared. Much of the intensity of the mercury arc lamp is expended in the near-ultraviolet, with peaks of intensity at 313, 334, 365, 406, 435, 546, and 578 nanometers. These lamps are not generally useful for most forms of microscopy (with the exception of fluorescence microscopy), but serve as excellent monochromatic light sources for black and white photomicrography. Using the appropriate filters, the green line at 546 nanometers, the blue line at 435 nanometers, and the near-ultraviolet line at 365 or 406 nanometers can yield excellent monochromatic light in selected wavelength regions. A mercury vapor arc lamp should never be used for brightfield, darkfield, DIC, or polarized color photomicrography because the limited emission spectrum of the lamps will not yield true color renditions of the specimen.

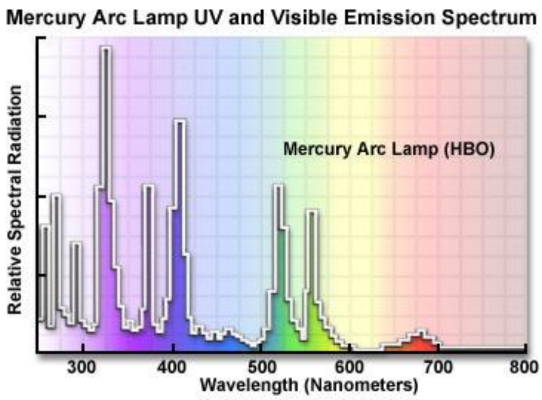


Figure 61 – Mercury arc lamp emission spectrum

3.2 Coherent light sources for optical microscopy [26, 27]

The lasers commonly employed in optical microscopy are high-intensity monochromatic light sources, which are useful as tools for a variety of techniques including optical trapping, lifetime imaging studies, photobleaching recovery, and total internal reflection fluorescence. In addition, lasers are also the most common light source for scanning confocal fluorescence microscopy, and have been utilized, although less frequently, in conventional widefield fluorescence investigations.

Lasers emit intense packets of monochromatic light that are coherent and highly collimated to form a tight beam with a very low rate of expansion. Compared to other light sources, the extremely pure wavelength ranges emitted by the laser have a bandwidth and phase relationship that is unparalleled by tungsten-halogen or arc-discharge lamps. As a result, laser light beams can travel over long distances and can be expanded to fill apertures or focused to a very small spot with a high level of brightness. Beyond the similarities common to all lasers, which include a gain medium (light source), excitation source (power supply), and resonator, these light sources differ radically in size, cost, output power, beam quality, power consumption, and operating life.

The coherence of monochromatic light produced by most laser systems introduces problems in the application of these light sources for classical widefield microscopy. Light scattering and diffraction patterns are introduced by interference at every surface in the optical path. In addition, the field and aperture diaphragms, as well as dirt, also produce artifacts. These undesirable effects can be minimized or eliminated by a variety of techniques. The most common methods include temporally scrambling laser light by rapidly varying the optical path length between the light source and the microscope, or scanning the specimen point by point as is the case in confocal microscopy systems. In addition, interference and other artifacts can often be eliminated by the aperture scanning technique. If the path length or coherence state of the laser beam fluctuates at a faster interval than the detector integration time (in effect, the video frame rate), the speckle and scattering artifacts are eliminated from the image.

Several laser categories are used as microscope light sources and they are listed below:

- Gas lasers.
- Solid-state lasers
- Dye lasers
- Semiconductor (diode) lasers

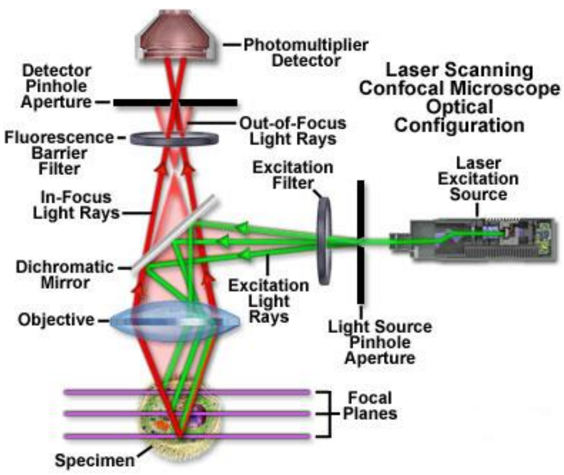


Figure 62 - Laser scanning confocal microscopy

One of the most popular microscopy technique in which laser light sources are used, is laser scanning confocal microscopy. Laser scanning confocal microscopy offers several advantages over conventional widefield fluorescence microscopy, including controllable depth of field, the elimination of image degrading out-of-focus information, and the ability to collect serial optical sections from thick specimens. The key to the confocal approach is the use of spatial filtering to eliminate out-of-focus light or flare in specimens that are thicker than the plane of focus by illuminating the objective through a pinhole. An image of the pinhole in the form of a small spot is formed on the specimen by a focused laser driven by a galvanometer-based scanning system. This spot, in turn, forms a reflected epi-fluorescence image on the original pinhole. If the specimen is in focus, the light passes through the pinhole to a detector (usually a photomultiplier). When the specimen is not in focus, the light reflected from it is defocused at the pinhole and very little passes through. Thus, fluorescence emission returning from the specimen to the detector is spatially filtered. As the pinhole aperture is reduced in size, it blocks more of the stray light from being detected but also lowers the total signal level. Although the absolute signal value is far less than observed with the widefield microscope configuration, rejecting the light from other focal planes increases the specific signal-to-noise ratio for the features of interest.

3.3 Stability of Light sources in microscopy applications [28, 29]

Illumination sources based on plasma discharge (arc lamps), incandescence (tungsten-halogen lamps), or stimulated emission in a gaseous environment (gas lasers) require a **considerable period after ignition to reach thermal equilibrium**, a factor that can affect temporal, spatial, and spectral stability. All lamps that produce a significant level of **heat**, including light-emitting diodes, also exhibit a dependence of emission output on the source temperature. In many cases, a period of up to one hour is required until the illumination source is sufficiently stable to enable reproducible measurements or to record time-lapse video sequences without significant temporal variations in intensity. Once the proper operating temperature has been reached, the tungsten-halogen lamp is the most stable conventional light source over time periods of a few milliseconds due to the high thermal inertia of the tungsten filament. Light-emitting diode sources are capable of reacting extremely fast (within a few microseconds), but the highest power versions can also generate a significant amount of heat during warm-up and, due to their high speed, are **affected by high-frequency instability in the power supply**. Generally, **arc discharge lamps are the most unstable illumination sources** currently used in optical microscopy. Besides the fact that the arc exhibits a significant degree of chaotic, flickering discharge that worsens with age, the light output can also be affected by ambient electromagnetic fields or an unstable power supply.

For long-term stability, incandescent tungsten-halogen and light-emitting diode light sources exhibit the best performance when compared to arc lamps and gas lasers (although several of the newer diode lasers are far more stable). Once a tungsten-halogen lamp has achieved its operating temperature, and if the lamp is controlled by a regulated power supply, this source is suitable for conducting sensitive photometric measurements. Thus, the 100-watt tungsten-halogen lamp is one of the preferred light sources for imaging living cells using transmitted light contrast-enhancing techniques in experiments ranging from only a few frame captures to those requiring hundreds or even thousands of sequential images. The incandescent lamp is particularly stable over long time periods and is subject only to minor degrees of output fluctuation (both temporal and spatial) under normal operating conditions.

Perhaps one of the most important stability aspects of any light source designed for optical microscopy is coping with the potentially damaging heat using an efficient heat sink. Incandescent and arc lamps generate a significant amount of heat due to their low optical conversion efficiency (ranging from 5 to 10 percent). The holders and housings of these lamps are fabricated using a material that is resistant to high temperatures and designed to dissipate around 100 watts of heat. As a result, arc and incandescent lamps cannot be physically mounted inside the microscope. Although the currently available LEDs have a similar conversion efficiency, their photon output occurs over a narrow spectral range so that LEDs operate at much lower temperatures. Thus, LEDs require less electrical power to produce the same optical output, and they can be more compact and bonded directly to a metal heat sink cooled by a fan. This technology enables LEDs, unlike other sources, to be mounted inside the microscope and closer to the specimen (to avoid light loss during transit). Despite this level of flexibility, it should be borne in mind that LED-based sources still require an efficient heat sink because operating above room temperature reduces their lifetime and results in a loss of optical output efficiency.

Lasers from the other hand, have the excellent benefit to emit coherent monochromatic light. Coherence is related to brightness due to the fact that large number of photons are focused into a small area. Thus, coherence make lasers a perfect choice for fluorescence microscopy because of the high power, narrow spectrum and perfectly monochromatic light. But due to the coherence, microscope images illuminated by lasers, develop fringes produces by interference of the coherent wavefronts reflected from internal optical surfaces, including the lenses, mirrors, dust windows and the cover glass. This complex interference pattern can appear as sharply defined concentric rings, but more commonly it is manifested as a high-contrast granular **speckle**, superimposed upon the image, obscuring details. Furthermore, if the specimen is transparent and has multi-layered microstructure, the speckle pattern becomes more complex. So, the need for speckle reduction devices and techniques is essential for acquiring clear images.

4 INCOHERENT LIGHT SOURCE

The goal of this thesis is the development of an incoherent and a coherent light source for various applications including biomedical applications. In this chapter the development of the incoherent LED light source will be presented.

Our goal is designing a Coherent Light Source that will have the ability of controlling its intensity distribution over its emission spectrum. Other design challenges are the compact size of the source, its energy efficiency as well as a high but stable output power. Finally, another important challenge is the light multiplexing of the LEDs.

Design specifications will be discussed. Also implementation procedure including electronic design, software interface, light multiplexing method will be presented in detail. In the end, technical validation of the incoherent light source will be presented including stability of the source, spectral emission and spectral curves on demand. Also several applications that the light source could be used will be presented.

The following figure illustrates a general overview of the device. Components and analysis will be the subject of this chapter and the following paragraphs.

Figure 63 – Why choose LEDs?

4.1 Design Specifications

Our goal is to fill the technology gap in incoherent lighting for various scientific and medical applications. In previous chapter, various incoherent light sources have been presented which are used in many applications. These incoherent light sources haven't got the best balance of several available emitting wavelengths, high optical power and low cost. For example, incandescent lamps, gas discharge lamps have a wide emission spectrum without the ability to emit a narrow band wavelength without the use of optical filters. These devices although emit high power of radiation, they develop high temperatures and have very low efficiency. Even LED assemblies developed for medical applications emit up to 4 only narrowband wavelengths limiting the spectral range of the system. Also, the above sources could not achieve emittance of multiple wavelengths simultaneously with narrow spectral linewidth without complex and expensive assemblies.

Our goal is to develop an incoherent light source for scientific and medical applications having large spectral range, high tunability, high optical power, high efficiency, high stability, long lifetime and low cost. For that reason, LEDs are the fundamental parts for building our incoherent source. LEDs as the years pass become more efficient and powerful. Also, LEDs have got small dimensions than others incoherent devices such as incandescent or gas discharge lamps, and this feature allows to develop small LED lightning devices. Also LEDs have longer lifetime than incandescent filaments and gas discharge lamps. Also another important factor that we consider during the development of our incoherent light source is the cost. Our goal to develop an Incoherent Light Source with low cost which means that the light source consists of low cost parts by with high quality and efficiency.

Considering all the above factors, our overall goal is to develop a computer controlled Incoherent Light Source emitting multiple wavelengths simultaneously with narrow spectral linewidth from Ultraviolet to Infrared, having high optical power and having low cost.

Thus, the design specifications of our incoherent light source are the following:

- Spectral range: Ultraviolet to Infrared, 380nm-810nm
- LED components: Twenty-one (21) monochromatic and one (1) white high power LEDs covering the above spectral range
- LED optical power up to 1Watt
- PWM control of each LED individually via computer interface
- Designing high efficiency LED drivers
- Light multiplexing using custom fiber optic lightguide bundle

4.2 Implementation

4.2.1 LED components

A critical point of the construction of the light source is the selection of the LEDs. **The assembly consists of white and monochromatic LEDs.** For the selection of LEDs we have three basic criteria: maximum intensity, small FWHM and small size. However, the small size contrasts with maximum intensity because very high power LEDs have great sizes. For this reason we use LEDs that combine these two features in the best way. Also we choose LEDs that have the smallest FWHM.

Full width at half maximum (FWHM) is an expression of the extent of a function, given by the difference between the two extreme values of the independent variable at which the dependent variable is equal to half of its maximum value.

FWHM is applied to such phenomena as the duration of pulse waveforms and the spectral width of sources used for optical communications and the resolution of spectrometers.

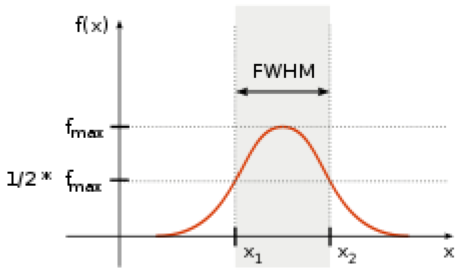


Figure 64 - FWHM

Furthermore, we choose LEDs that cover the entire spectrum from ultraviolet to infrared. In the next paragraphs, we will present the chosen LEDs and their basic characteristics.

4.2.1.1 White LED

Figure 65 – Cree XM-L2

In this paragraph we will present the output characteristics and performance of the white LED used as the illumination component of the system. The white LED is used in order to produce white light which is guided onto the variable filter. Figure 52 illustrates the specific white LED used in this project, Cree XM-L2. This LED emits cold white light.

Cree XM-L2 LED is a high power SMD LED from Cree. Of course, considering its small size (5mm x 5mm) we can characterize it as high power LED for its category. At 3 electric Watt, this LED can reach an amazing 357 lumen for warm white. Durability, extreme brightness and performance are among the major strengths of this LED. Also, the viewing angle of the LED is 125^{o}.

The color of the LED is neutral white. The spectrum of the LED is illustrated below in Figure 53.

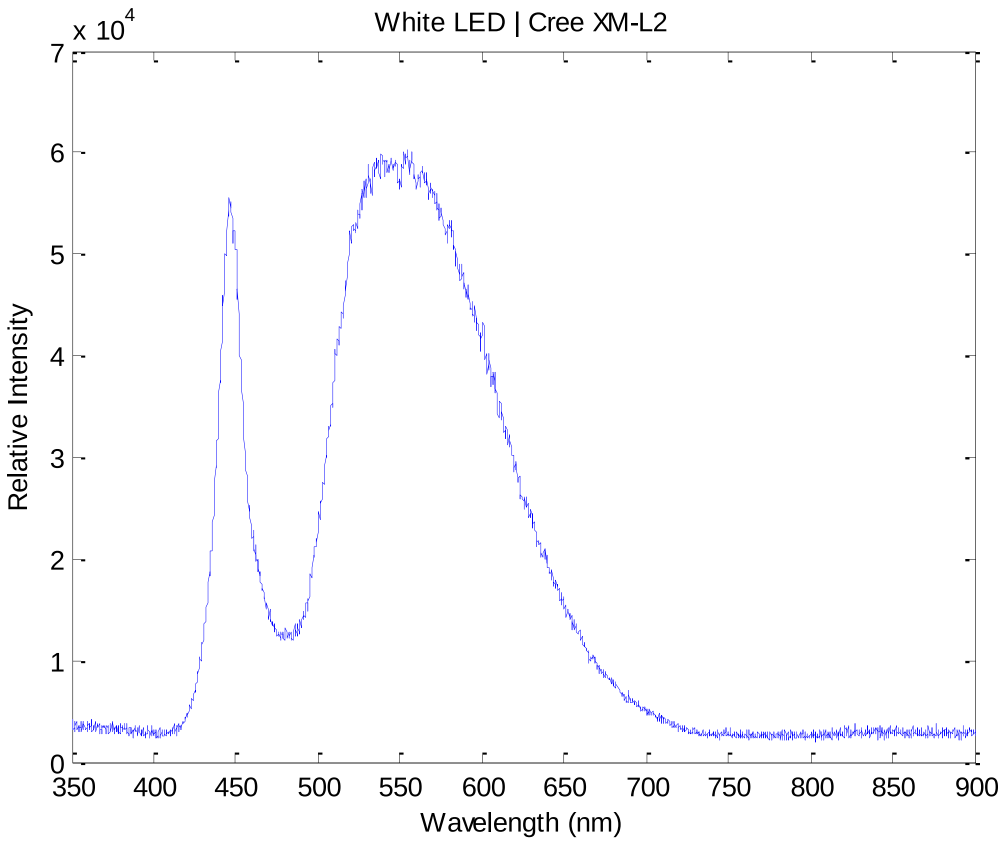


Figure 66 – Spectrum of the Cree LED

The spectrum is similar to the spectrum of the classic white LED we discussed in previous section, which is a blue LED converted to white by using phosphor material. In above spectrum the blue led spectrum is the lobe with a peak in 450 nm. The other part of the spectrum is caused by the phosphorescence. Moreover, we observe that it has high intensity values in "red" wavelengths. This is because the LED emits warm white light.

The spectrum range extends from 410 nm to 780nm. However, the wavelengths at both ends of the spectrum have very low emission intensity. So, in order to have enough emission intensity before 430nm and after 650nm we should use monochromatic LEDs in these areas, which can achieve satisfactory emission intensity.

About heat dissipation, Cree XM-L2 LED requires a cooling assembly because the combination of its high power and its small size causes high heat generation. The cooling assembly will be presented in more detail in a next section.

4.2.1.2 Monochromatic LEDs

380nm peak

This LED is an Ultraviolet single chip Emitter LED by Roithner Laser Technik, model RLCU440-380. The peak wavelength of this LED is λ_{peak}=380nm. It is high radiation intensity SMD LED on AIN ceramics submount with silver plated soldering pads. The dimensions of the LED are 3.8x3.8x0.9 and the operation temperature is -40….85^{o}C. The output optical power of this LED is up to 160mW. The spectrum of the LED is illustrated bellow.

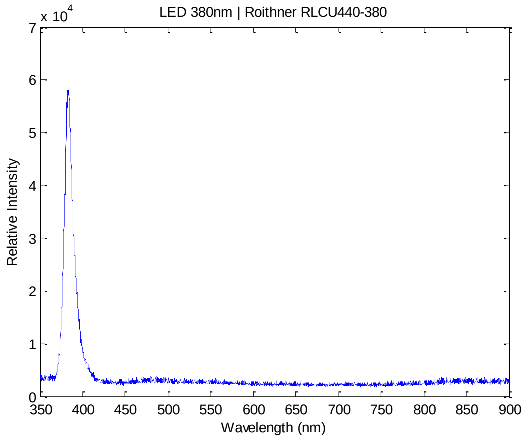


Figure 67 – Spectrum of 380nm monochromatic LED

390nm peak

This LED is an Ultraviolet single chip Emitter LED by Roithner Laser Technik, model RLCU440-390. The peak wavelength of this LED is λ_{peak}=390nm. It is high radiation intensity SMD LED on AIN ceramics submount with silver plated soldering pads. The dimensions of the LED are 3.8x3.8x0.9 and the operation temperature is -40….85^{o}C. The output optical power of this LED is up to 260mW. The spectrum of the LED is illustrated bellow.

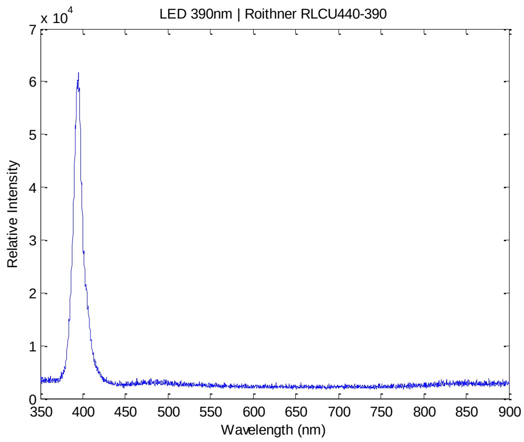


Figure 68 – Spectrum of 390nm monochromatic LED

400nm peak

This UV LED belongs to the RLCU440 series by Roithner Laser Technik. The output optical power of this LED is up to 310mW. The spectrum of the LED is illustrated bellow.

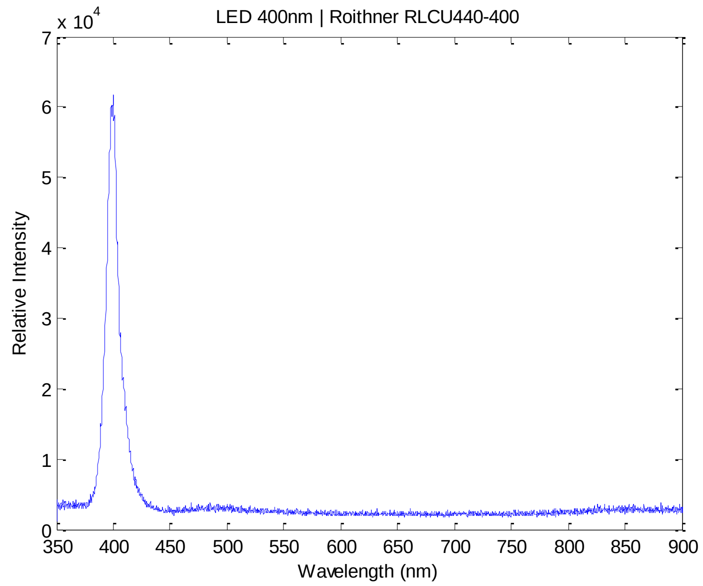


Figure 69 – Spectrum of 400nm monochromatic LED

410nm peak

This UV LED belongs to the RLCU440 series by Roithner Laser Technik. The output optical power of this LED has a typical value of 250mW. The spectrum of the LED is illustrated bellow.

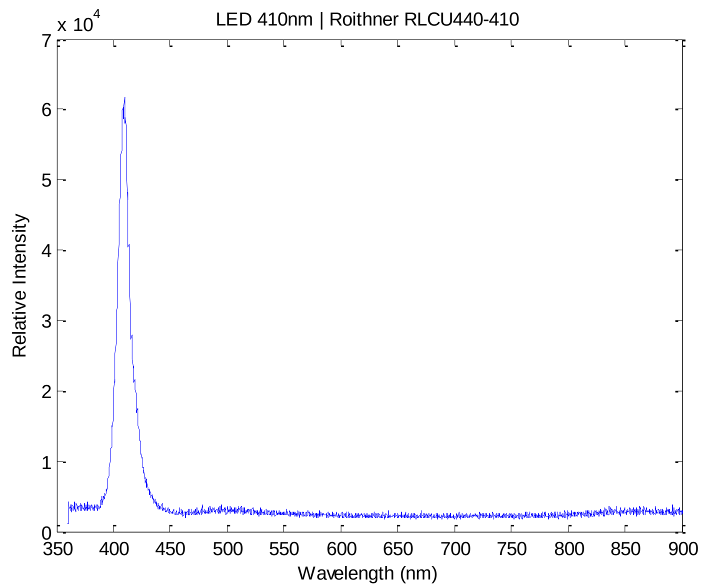


Figure 70– Spectrum of 410nm monochromatic LED

420nm peak

This UV LED belongs to the RLCU440 series by Roithner Laser Technik. The output optical power of this LED is up to 310mW. The spectrum of the LED is illustrated bellow.

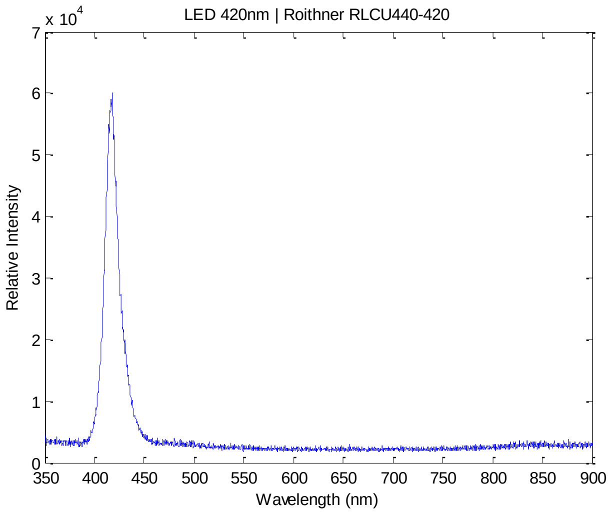


Figure 71 – Spectrum of 420nm monochromatic LED

445nm peak

This LED is a blue single chip Emitter LED by Avago Technologies, model LXML-PR02. The peak wavelength of this LED is λpeak=445nm. The dimensions of the LED are 3.1x.4.6x2 and the operation temperature is -40….120oC. The output electrical power of this LED is up to 3W. Also, the viewing angle is 125o. The spectrum of the LED is illustrated bellow.

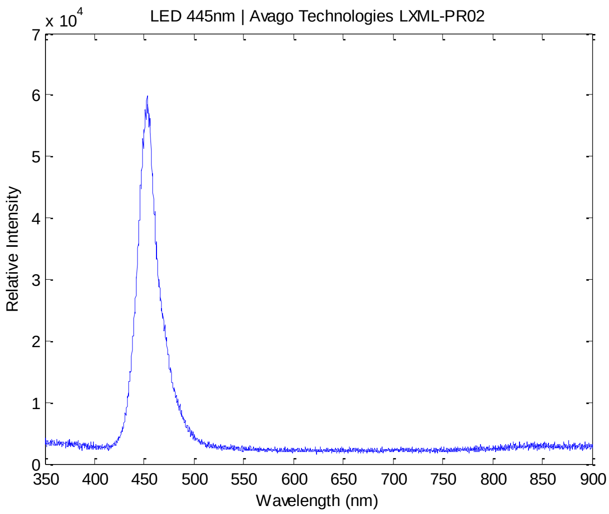


Figure 72 – Spectrum of 445nm monochromatic LED

470nm peak

Figure 73 – Avago 470nm

This LED is a blue single chip Emitter LED by Avago Technologies, model ASMT-JB31-NMP01. The peak wavelength of this LED is λpeak=470nm. The dimensions of the LED are 5.0x.5.0x1.8mm and the operation temperature is -40….120oC. The output electrical power of this LED is up to 3W. Also, the viewing angle is 120º. The spectrum of the LED is illustrated bellow.

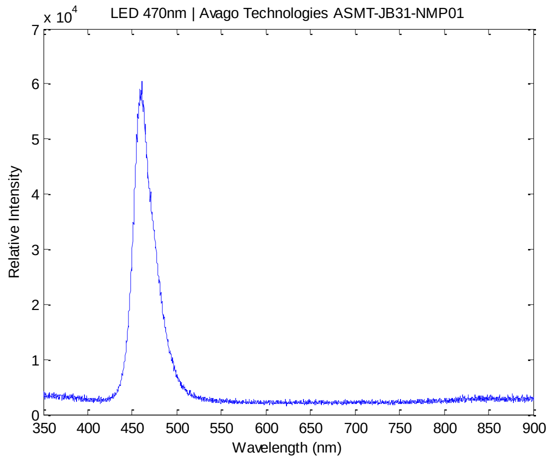


Figure 74 – Spectrum of 470nm monochromatic LED

505nm peak

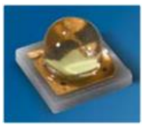


Figure 75 – Osram 505nm

This LED is a green single chip Emitter LED by Osram Opto Semiconductors, model LV CK7p. The peak wavelength of this LED is λpeak=505nm. This LED is a high performance energy efficient device which can handle high thermal and high driving current. The dimensions of the LED are 3.1x3.1x2.1mm and the operation temperature is -40….120oC. The luminous flux of this LED is up to 112lm. Also, the viewing angle is 80º. The spectrum of the LED is illustrated bellow.

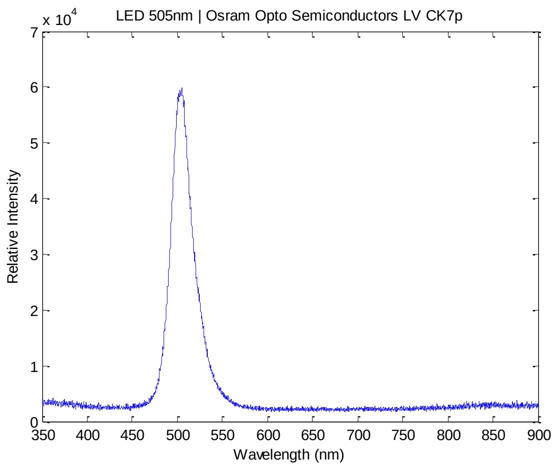


Figure 76 – Spectrum of 505nm monochromatic LED

520nm peak

Figure 77 – Philips LV CK7P

This LED is a green single chip Emitter LED by Philips, model LV CK7p. The peak wavelength of this LED is λpeak=520nm. This LED is a high performance energy efficient device which can handle high thermal and high driving current. The dimensions of the LED are 3.17x4.61x2.1mm and the operation temperature is -40….120º C. The typical luminous flux of this LED is 130lm. Also, the viewing angle is 140º. The spectrum of the LED is illustrated bellow.

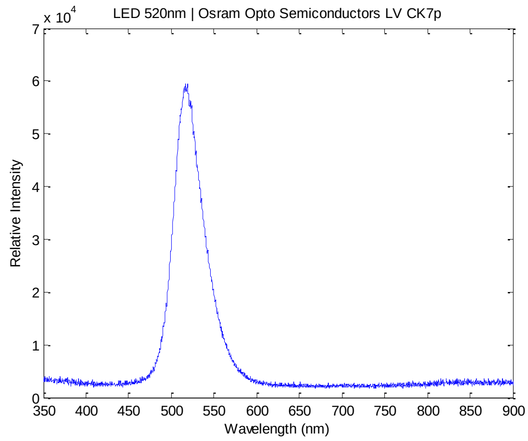


Figure 78 – Spectrum of 520nm monochromatic LED

535nm peak

Figure 79 – Cree 535nm

This LED is a green single chip Emitter LED by Cree, model XPCGRN-L1-0000-00801. The peak wavelength of this LED is λpeak=535nm. dimensions of the LED are 3.45x3.45x2mm and the operation temperature is -40….120º C. The typical luminous flux of this LED is 80,6lm. Also, the viewing angle is 125º. The spectrum of the LED is illustrated bellow.

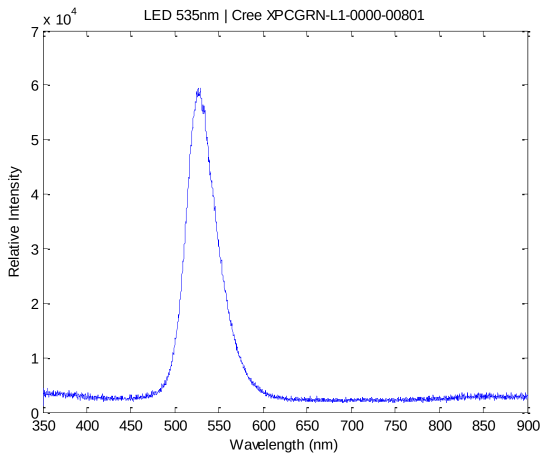


Figure 80 – Spectrum of 535nm monochromatic LED

550nm peak

Figure 81 – Luxeon 550nm

This LED is a green single chip Emitter LED by Luxeon, model LXML-PM01-0050. The peak wavelength of this LED is λpeak=550nm. This LED is a high performance energy efficient device which can handle high thermal and high driving current. The dimensions of the LED are 4.6x3.1x2mm and the operation temperature is -40….120º C. The typical luminous flux of this LED is 50lm. Also, the viewing angle is 125º. The spectrum of the LED is illustrated bellow.

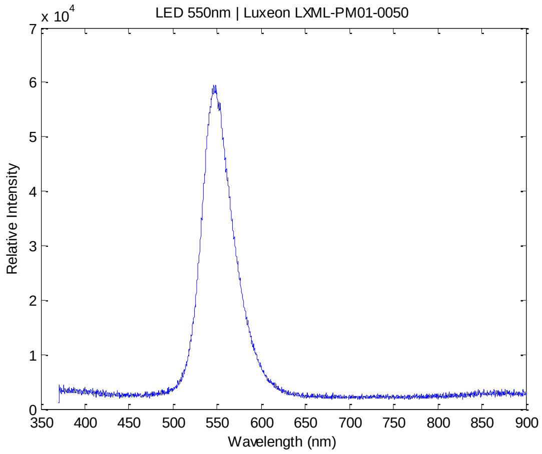


Figure 82 – Spectrum of 550nm monochromatic LED

590nm peak

Figure 83 – LedEngin LZ1 590nm

This LED is a green single chip Emitter LED by Ledengin, model LZ1-00A100. The peak wavelength of this LED is λpeak=590nm. The dimensions of the LED are 4.9x4.9x2.8mm and the operation temperature is -40….120º C. The typical luminous flux of this LED is 105lm. Also, the viewing angle is 90º. The spectrum of the LED is illustrated bellow.

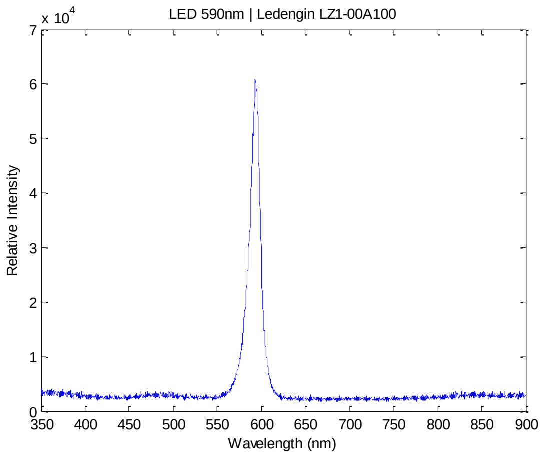


Figure 84 – Spectrum of 590nm monochromatic LED

625nm peak

Figure 85 – 625nm LED by Broadcom

This LED is a green single chip Emitter LED by Broadcom Limited, model ASMT-JR30-ARS01. The peak wavelength of this LED is λpeak=625nm. This LED is a high performance energy efficient device which can handle high thermal and high driving current. The dimensions of the LED are 5x4x1.85mm and the operation temperature is -40….120° C. The typical luminous flux of this LED is 48lm. Also, the viewing angle is 165°. The spectrum of the LED is illustrated bellow.

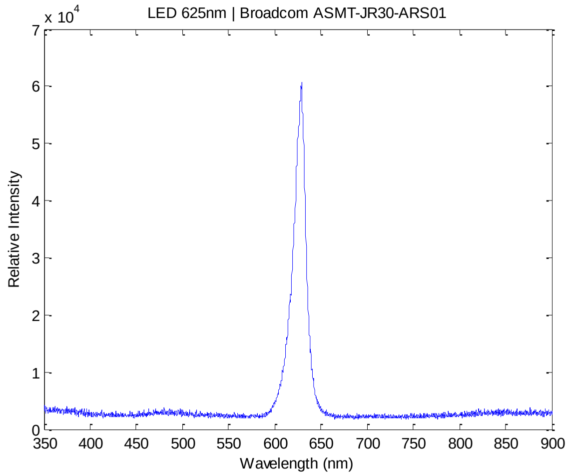


Figure 86 – Spectrum of 625nm monochromatic LED

656nm peak

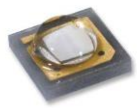


Figure 87 – 656nm LED by Osram

This LED is a green single chip Emitter LED by Osram, model LHCPDP-2T3T-1-0-350-R18. The peak wavelength of this LED is λpeak=656nm. This LED is a high performance energy efficient device which can handle high thermal and high driving current. The dimensions of the LED are 4.6x3.1x2mm and the operation temperature is -40….120° C. The typical radiant flux of this LED is 365lm. Also, the viewing angle is 150°. The spectrum of the LED is illustrated bellow.

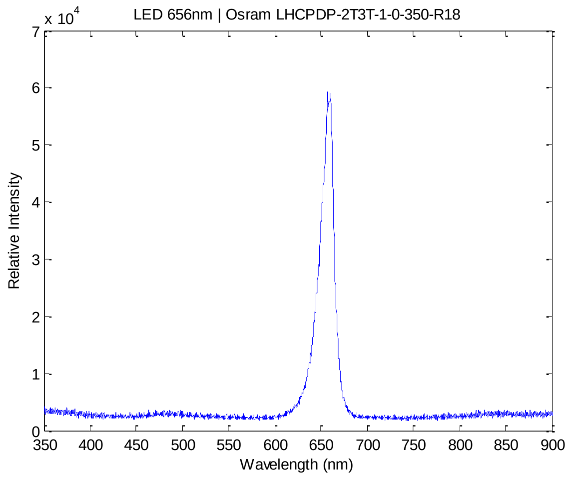


Figure 88 – Spectrum of 656nm monochromatic LED

670nm peak

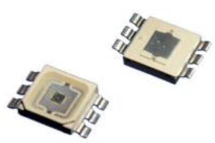


Figure 89 – SMB1W Series 670nm LED

This LED is a red single chip Emitter LED Emitter LED by Roithner Laser Technik, model SMB1W-670R. The peak wavelength of this LED is λpeak=670nm. The dimensions of the

LED are 5.0x5.0mm and the operation temperature is -40….85oC. The output optical power of this LED is up to 200mW. Also, the viewing angle is 124o. The spectrum of the LED, as measured with spectrometer, is illustrated bellow.

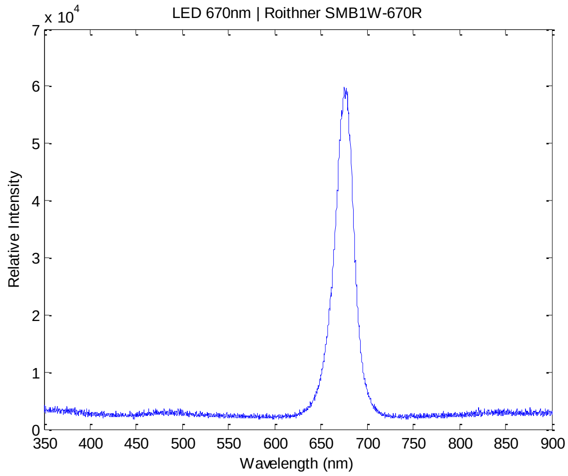


Figure 90 – Spectrum of 670nm monochromatic LED

680nm peak

This LED belongs to the SMB1W series by Roithner Laser Technik, such as the above LED. So, this LED has the same package as the above. The output optical power of this LED is up to 260mW. The spectrum of the LED is illustrated bellow.

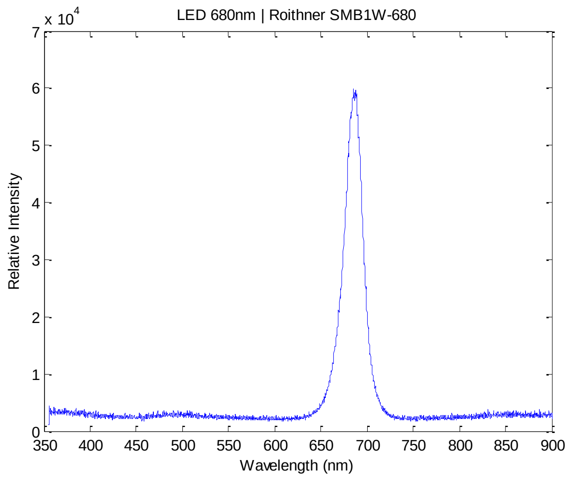


Figure 91 – Spectrum of 656nm monochromatic LED

700nm peak

This LED belongs to the SMB1W series by Roithner Laser Technik, such as the above LED. So, this LED has the same package as the above. The output optical power of this LED is up to 100mW. The spectrum of the LED is illustrated bellow.

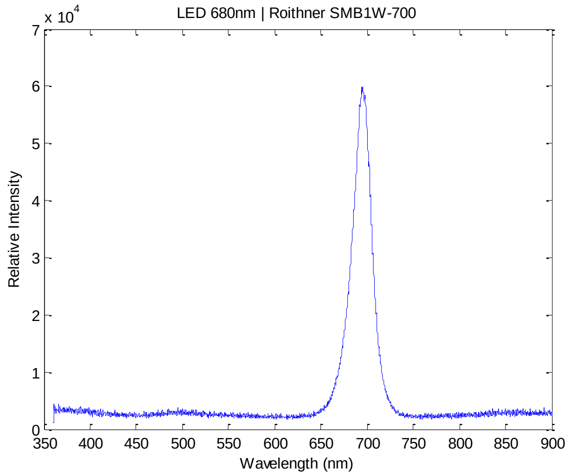


Figure 92 – Spectrum of 700nm monochromatic LED

720nm peak

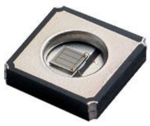


Figure 93 – Roithner 720nm LED

This LED is an Infrared single chip Emitter LED by Roithner Laser Technik, model RLCU440-720. The peak wavelength of this LED is λ_{peak}=720nm. It is high radiation intensity SMD LED on AIN ceramics submount with silver plated soldering pads. The dimensions of the LED are 3.8x3.8x0.9 and the operation temperature is -40….85^{o}C. The output optical power of this LED is up to 50mW/sr. Also, the viewing angle is 120^{o}. The spectrum of the LED, as measured with spectrometer, is illustrated bellow.

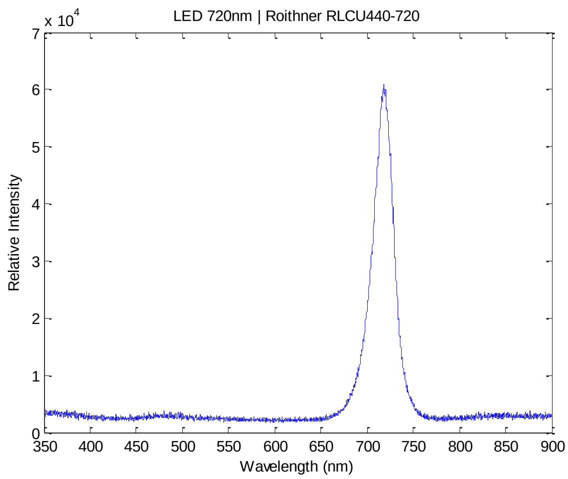


Figure 94 – Spectrum of 720nm monochromatic LED

740nm peak

Figure 95 – LEDEngin 740nm

This LED is an Infrared single chip Emitter LED by LED ENGIN, model LZ1-00R300. The peak wavelength of this LED is λ_{peak}=740nm. It is a high power SMD LED. The dimensions of the LED are 4.4x4.4x2.8mm and the operation temperature is -40….125°C. The output optical power of this LED is up to 310mW. Also, the viewing angle is 90°. The spectrum of the LED, as measured with spectrometer, is illustrated bellow.

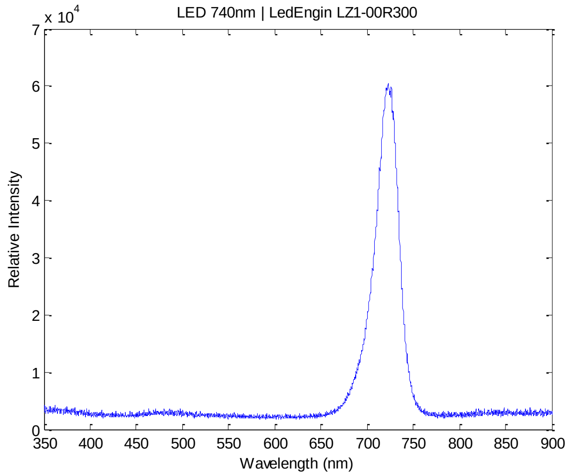


Figure 96 – Spectrum of 740nm monochromatic LED

770nm peak

This infrared LED belongs to the SMB1W series by Roithner Laser Technik, such as the above LED of the same series. So, this LED has the same package as the above of the same series. The output optical power of this LED is up to 330mW. The spectrum of the LED is illustrated bellow.

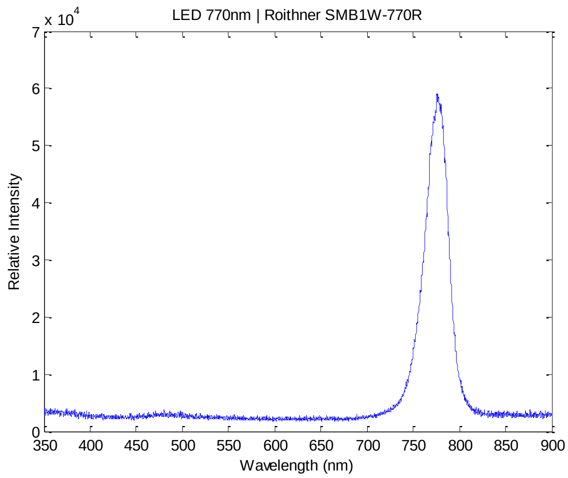


Figure 97 – Spectrum of 770nm monochromatic LED

810nm peak

This IR LED belongs to the SMB1W series by Roithner Laser Technik, such as the above LED of the same series. So, this LED has the same package as the above of the same series. The output optical power of this LED is up to 280mW. The spectrum of the LED is illustrated bellow.

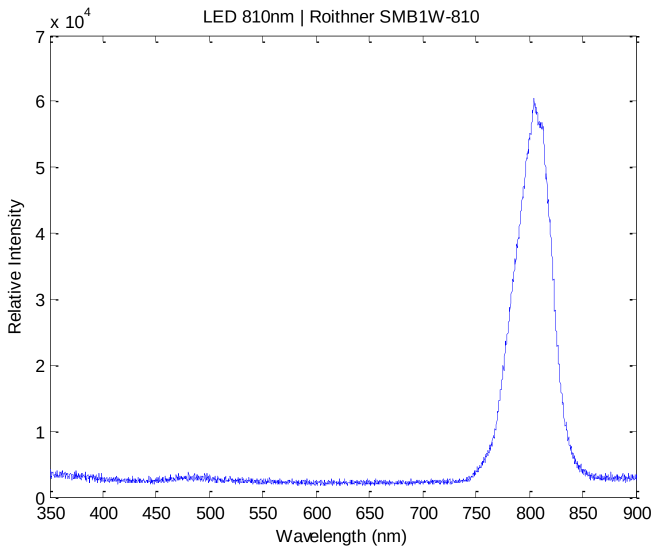


Figure 98 – Spectrum of 810nm monochromatic LED

4.2.2 LED Driving

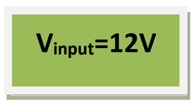
4.2.2.1 Power Supply

An important part of the hardware assembly is the design of the LEDs' power supply. LEDs must be supplied with the correct voltage and current at a constant flow. For this reason, we gave much attention to the design of the power supply.

The power supply has a 12V input voltage, supplied by an external ac-dc power supply. The external power supply must have big current outputs, short circuit protection and reasonably tight voltage regulation on the 12V line.

The LEDs' power supply circuit has 3 outputs. Each output supplies each LED-group (same forward voltage), as we mentioned in the previous chapter.

The voltage of each output is shown in the Figure below:



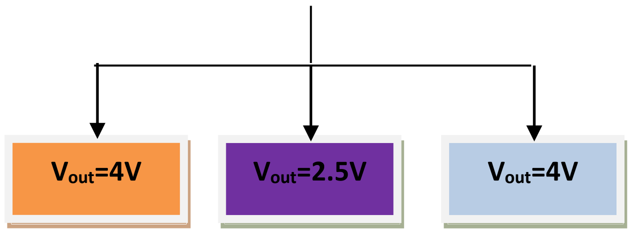


Figure 99 – Voltage outputs

So as to create the 3 different voltage outputs from an input of 12V, the power supply circuit includes components called voltage regulators. A voltage regulator is an electrical regulator designed to automatically maintain a constant voltage level. A voltage regulator may be a simple "feed-forward" design or may include negative feedback control loops. Electronic voltage regulators are found in devices such as computer power supplies where they stabilize the DC voltages used by the processor and other elements.

Figure 100 – Voltage regulator PTN78xxx series

We used the PTN78060W wide input adjustable switching regulator. The PTN78060W is a series of high efficiency, step down integrated switching regulators. Operating from a wide input voltage range, the PTN78000 provides high-efficiency, step-down voltage conversion for loads up to 3A. The output voltage is set using a single external resistor within the range 2,5V to 12,6V. The PTN78060 has undervoltage lockout and an integral on/off inhibit. The modules are suited to a wide variety of general-purpose applications that operate off 12-V, 24-V, or 28-VDC power. Also, PTN78060W does not develop high temperatures during operation like the linear voltage regulators, so does not need any heat dissipation assembly due to switching technology.

After we have finished the design, we proceed to the printing process and components soldering. The next figure illustrates the final power supply board:

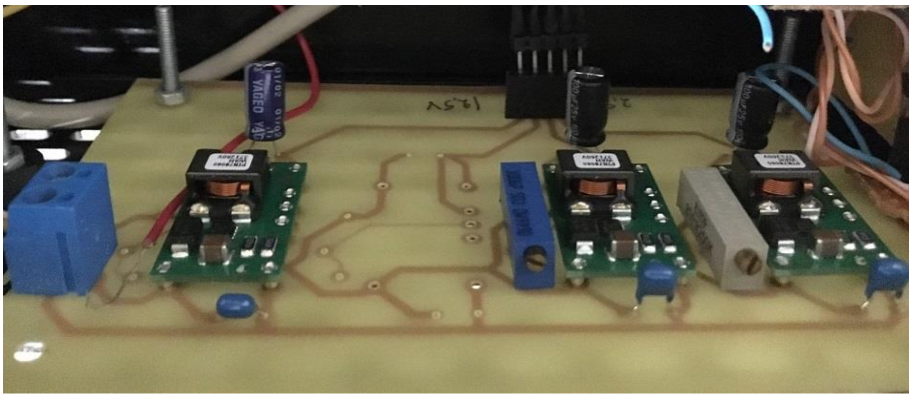


Figure 101 – Incoherent Source's Power Supply

After various stress tests on the power supply we noticed that the voltage regulators do not reach significant temperatures. So, there is no need for a cooling assembly.

4.2.2.2 Microcontroller

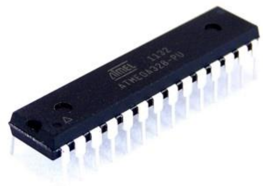


Figure 102 – ATmega328

A microcontroller is needed to govern and synchronize all the signals of the system. Its goal is to control directly the TLC5940 LED drivers and indirectly the dimming of the LEDs, which will be presented in the next paragraph.

The model used is the Atmel AVR ATmega328, 8-bit microcontroller, which covers the needs sufficiently. The microcontroller was mounted and preassembled on a development board. A development board also consists of complementary components to facilitate programming and incorporation into other circuits. The board includes a 5-volt linear regulator and a 16MHz crystal oscillator. The microcontroller is pre-programmed with a bootloader so that an external programmer is not necessary. The interface with the computer is done through USB connection, which is downgraded to USB-to-serial, and supportive adapter chips on the board.

Control of the TLC5940 is achieved by the Microcontroller. Also, the 5V and GND pins give the appropriate power to the TLCs and CAT4101 chips. Furthermore, the interface with the computer is done through USB connection, as a way to control the dimming and enabling/disabling of the LEDs.

4.2.2.3 LED Driving board

LED driving board is the main PCB in our device. Its purpose is the dimming and enabling/disabling of the LEDs. Driver Board is connected via cables with the LED board, the microcontroller and the 5V power supply for powering chip components which are necessary for driving the LEDs.

Before analyzing the driving circuit let's present the basic structure and components of the LED driving board.

TLC5940 Led Driver

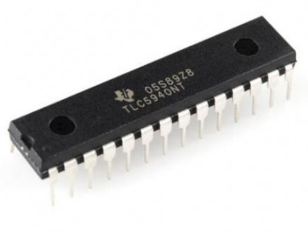


Figure 103 - TLC5940 in 28-pin PDIP package (TLC5940NT)

The heart of the LEDs' driver circuit is the TLC5940 chip by Texas Instruments. The TLC5940 is a 16-channel, constant-current sink LED driver. Each channel has an individually adjustable 4096-step grayscale PWM brightness control and a 64-step, constant-current sink (dot correction). The dot correction adjusts the brightness variations between LED channels and other LED drivers. The dot correction is stored in an integrated EEPROM. Both grayscale control and dot correction are accessible via a serial interface. A single external resistor sets the maximum current value of all 16 channels. The maximum current per channel is 130mA. Also, the maximum LED voltage is 17V.

The TLC5940 features two error information circuits. The LED open detection (LOD) indicated a broken or disconnected LED at an output terminal. The thermal error flag (TEF) indicated an over temperature condition.

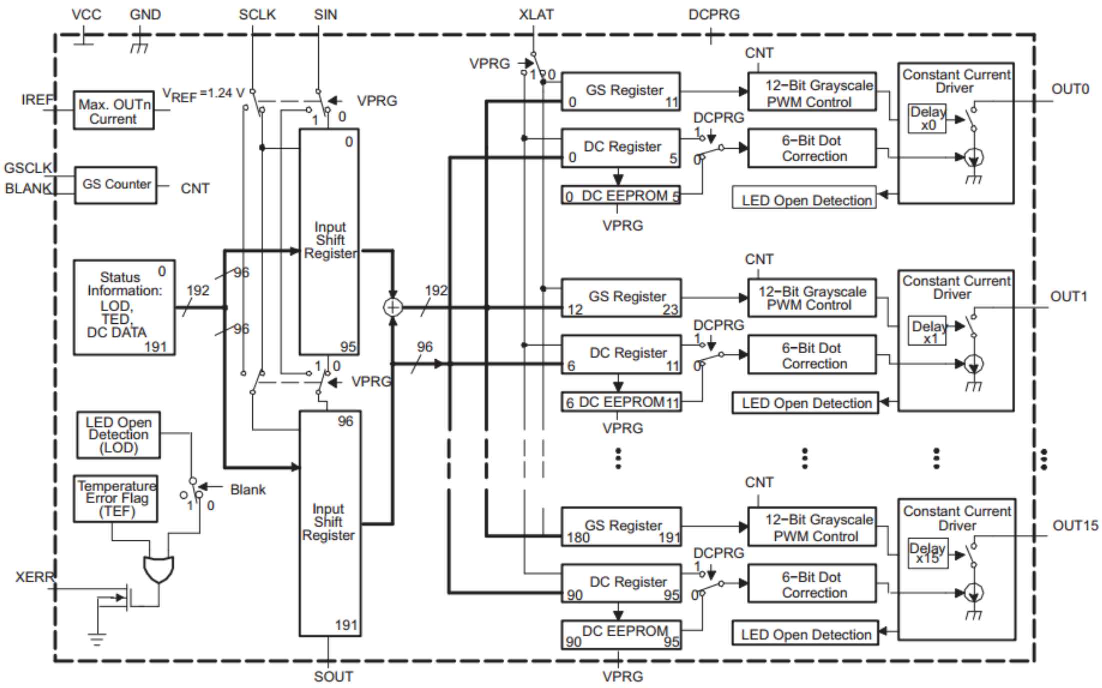


Figure 104 – TLC5940 Circuit diagram

The TLC5940 has a daisy chainable serial interface, which can be connected to microcontrollers or digital signal processors in various ways. Only 3 pins are needed to input data into the device. The rising edge of SCLK signal shifts the data from the SIN pin to the internal register. After all data is clocked in, a high-level pulse of XLAT signal latches the serial data to the internal registers. The internal registers are level-triggered latches of XLAT signal. All data are clocked in with the MSB first. The length of serial data is 96 bit or 192 bit, depending on the programming mode. Grayscale data and dot correction data can be entered during a grayscale cycle. Although new grayscale data can be clocked in during a grayscale cycle, the XLAT signal should only latch the grayscale data at the end of the grayscale cycle. Latching in new grayscale data immediately overwrites the existing grayscale data.

Because of the chainable serial interface there is a **delay between outputs**. The TLC5940 has graduated delay circuits between outputs. These circuits can be found in the constant current driver block of the device. The fixed-delay time is 20ns (typical), OUT0 has no delay, OUT1 has 20ns delay, and OUT2 has 40ns delay, etc. The maximum delay is 300ns from OUT0 to OUT15. The delay works during switch on and switch off of each output channel. These delays prevent large inrush currents which reduces the bypass capacitors when the outputs turn on.

More than two TLC5940s can be connected in series by connecting an SOUT pin from one device to the SIN pin of the next device. An example of cascading two TLC5940s is shown in Figure.

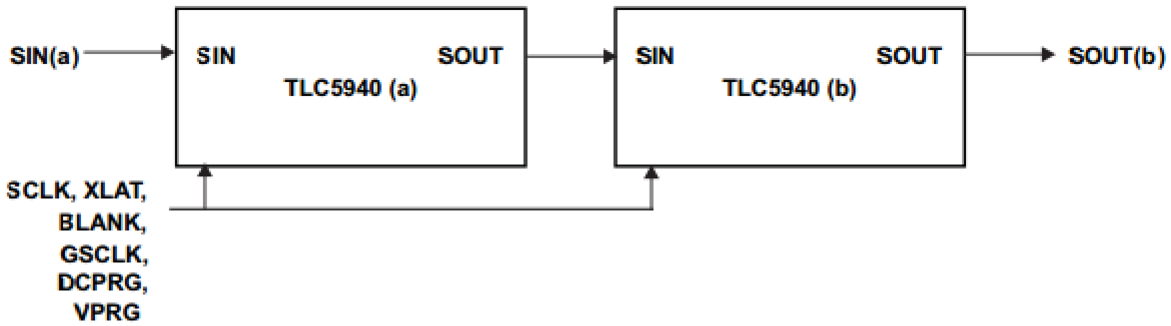


Figure 105 - Cascading two TLC5940 devices

CAT4101 constant-current LED driver

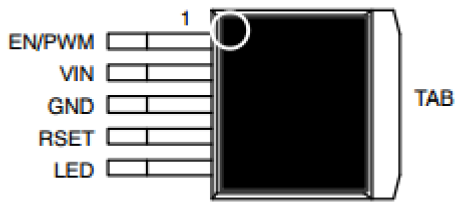


Figure 106 - CAT4101 pin connections

The CAT4101 is a constant−current sink driving a string of high−brightness LEDs up to 1 A with very low dropout of 0.5 V at full load. It requires no inductor, provides a low noise operation and minimizes the number of components. The LED **current is set by an external resistor** connected to the RSET pin. The LED pin is compatible with high voltage up to 25 V, allowing the driving of long strings of LEDs. The device ensures an accurate and regulated current in the LEDs independent of supply and LED forward voltage variation.

The PWM/EN input allows the device shutdown and the LED brightness adjustment by using an external pulse width modulation (PWM) signal.

The driver features a thermal shutdown protection that becomes active whenever the die temperature exceeds 150°C. CAT4101 is available in a high−power, 5−lead TO−263 package offering excellent thermal dissipation characteristics.

Let’s present the basic operation of the device. The CAT4101 has one highly accurate LED current sink to regulate LED current in a string of LEDs. The LED current is mirrored from the current flowing from the RSET pin. The LED channel needs a minimum of 500 mV headroom to sink constant regulated current. If the input supply falls below 2 V, the under−voltage lockout circuit disables the LED channel. For applications requiring current higher than 1 A, several CAT4101 devices can be connected in parallel. The LED channel can withstand and operate at voltages up to 25 V. This makes the device ideal for driving long strings of high power LEDs from a high voltage source.

Combining TLC5940 & CAT4101

The combination of the TLC5940 and CAT4101 leads to an ultimate LED driver supporting PWM function with a maximum current per channel of 1A.

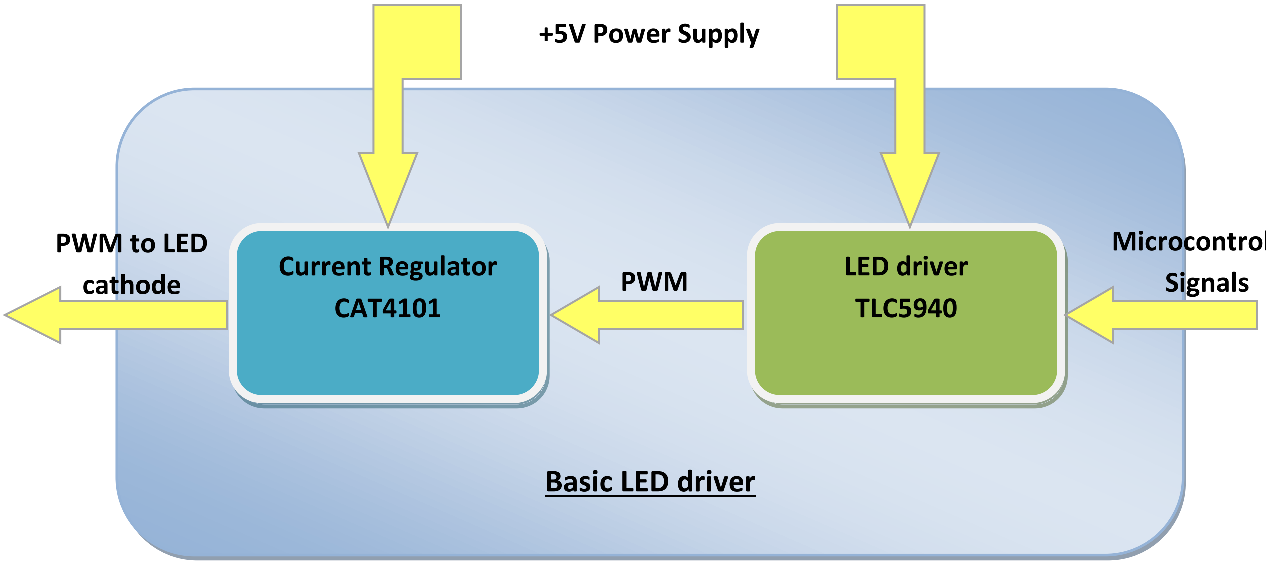


Figure 107 – Basic structure of LED driver

The combination of the two chips is necessary. One reason is that the TLC5940 offers many individually controlled PWM outputs, which are multiplexed as explained above. The multiplexing is important as this reduces the spatial complexity of the circuit. So two TLC5940 chips cover fully our needs for controlling 22 LEDs, since every TLC5940 has 16 PWM outputs. At this point one might ask why we do not use directly the PWM outputs of the TLCs and why we use CAT4101 chips. The answer is that the current per channel in the TLC5940 is maximum 120mA, which is a current much smaller than the typical current of every LED in our assembly. For that reason, we use CAT4101 as a way to achieve higher currents up to 1A. We use one CAT4101 for one LED, i.e. 22 CAT4101 chips. Each CAT4101 has a specific resistor (as a way to adjust the current limit) connected to its RSET pin according to the current LED's forward current.

The procedure of driving a LED is as follows:

1. The microcontroller controls the PWM port of the TLC5940.
2. The PWM output of the TLC enters as input in CAT4101.
3. The cathode of the LED is connected to the port LED of the CAT4101 and finally the CAT4101 adjusts the brightness of the LED.

After presenting the basic driving components and the connectivity between them as a way to achieve LED driving, we will present the complete block diagram of the LED driving board.

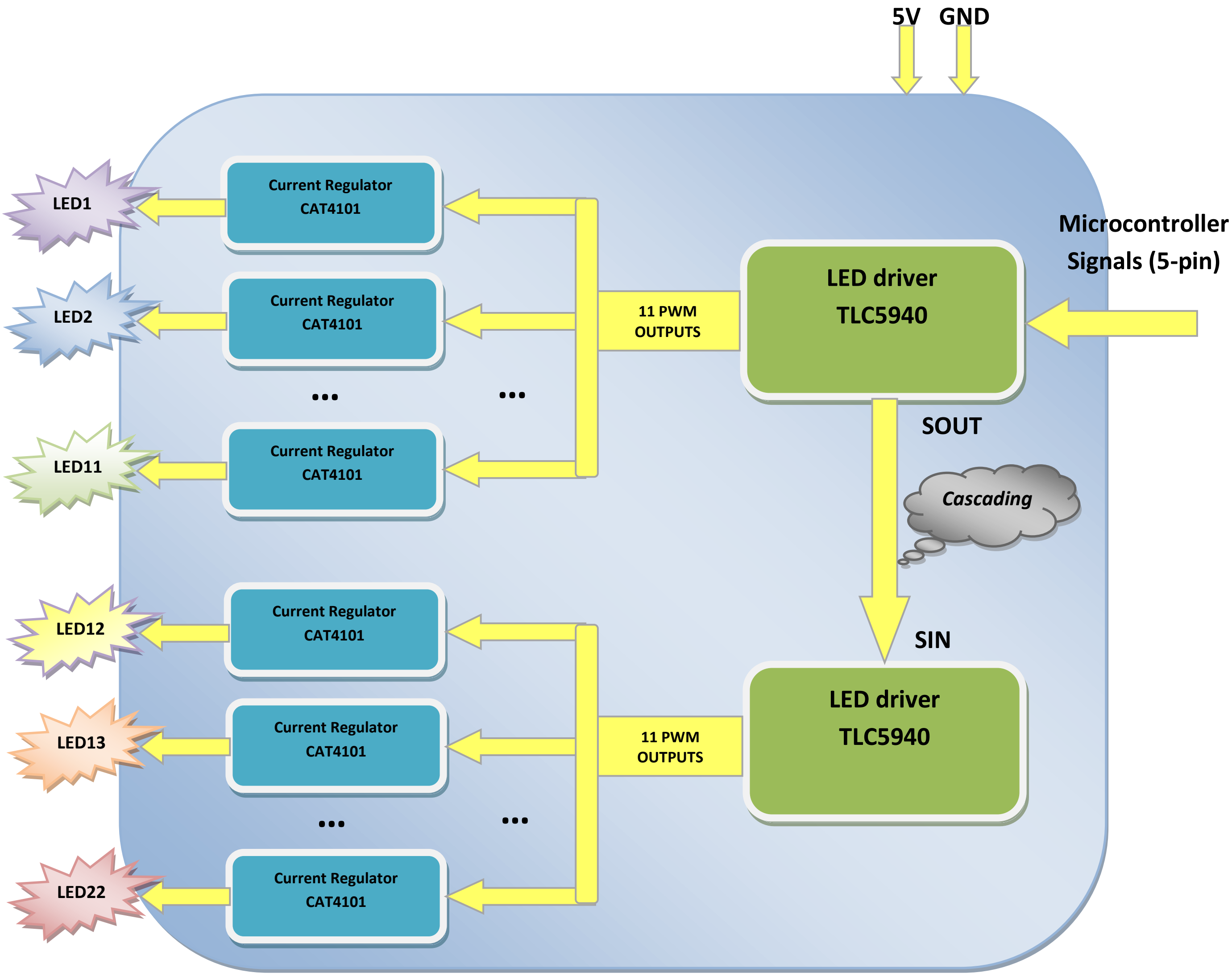


Figure 108 – LED driving board Block diagram

In this project we need to drive, as we mentioned before, 22 high power LEDs. So, we need 22 PWM outputs, i.e. 2 TLCs, and 22 CAT4101. The two TLC5940s are connected in series by connecting the SOUT pin from one TLC to the SIN pin of the other TLC.

The **inputs** of the LED driving board are 5-pin Microcontroller Signals, 5V port and GND port. The board has 22 **outputs**. Each output is connected to a LED's cathode in the LED board.

The next figure illustrates the final LED driving board:

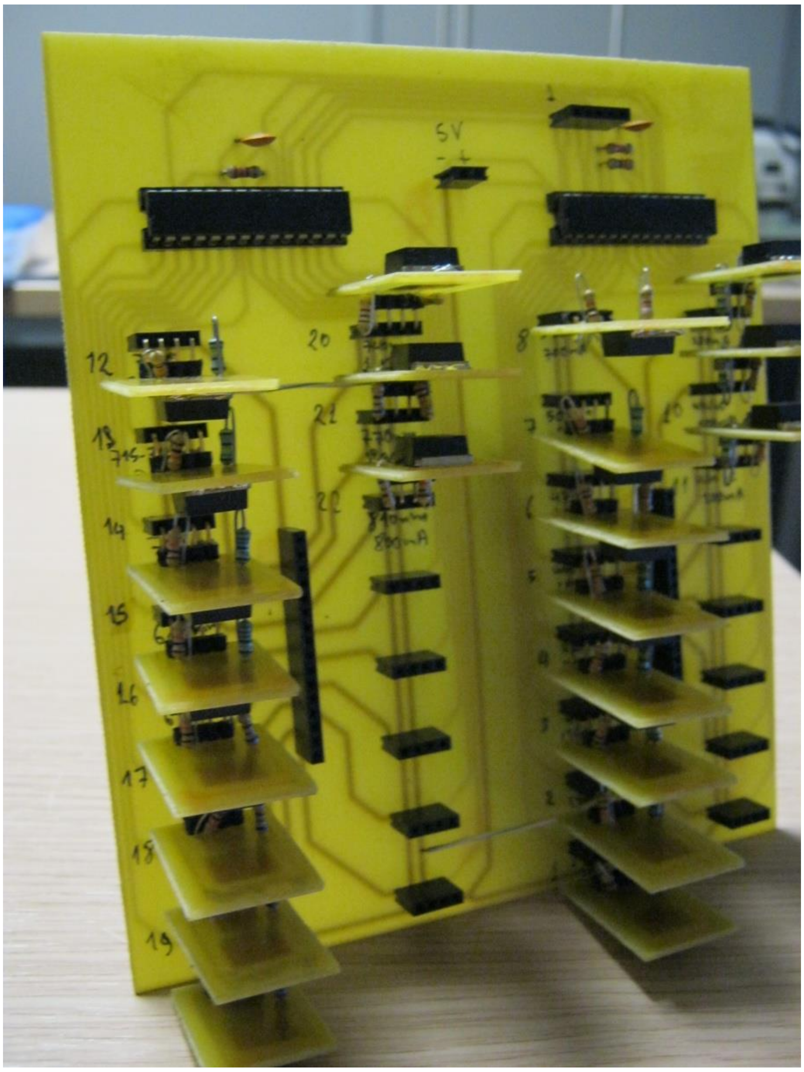


Figure 109 – LED driving board Block diagram

As we see in the above figure, the two TLCs are connected on 28-pin PDIP sockets which are soldered on the PCB. The CAT4101 soldered onto small boards which are placed into female slots on the main PCB. In each CAT4101 a specific resistor is soldered on the mini board as a way to the set the current of the LED. Also, we see the 5-pin female connector, which sets the connectivity between the microcontroller and the driving board, and the 2-pin, 5V and GND ports, female connector. Furthermore, the two 16-pin female connectors set the connectivity between LED cathodes and driving board.

4.2.3 Light Multiplexing

One important feature of our Incoherent Light Source is the multiplexing technique we use. Before designing the LED board where the LEDs are soldered on we should define the light multiplexing technique we are going to use.

Multiplexing light waves from 22 LED components is a major challenge for us. There are several techniques for multiplexing light such as the technique using dichroic mirrors. Various companies like Carl Zeiss make use of dichroic mirrors to multiplex light waves emitted by LED components simultaneously. But the number of LEDs that are on these assemblies are up to 4. In our case, using dichroic mirrors to multiplex light waves emitted by 22 LEDs is not preferred because due to the large number of available LED wavelengths we need many dichroic mirrors which results in very large and very expensive assemblies with great power losses.

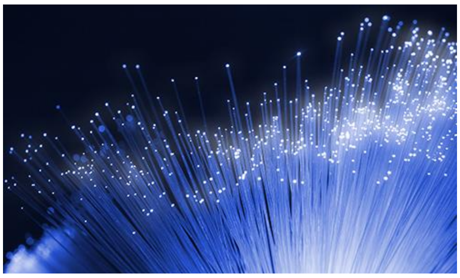


Figure 110 – Optical Fibers

So, we decided to follow the solution of the fiber optic lightguides. Fiber Optic Light Guides interface with illuminators to transfer light to one of several adapter heads that transmit light in a usable manner. Fiber Optic Light Guides offer the benefits of numerous illumination products with only one light source making them cheap, effective alternatives to many other illuminators.

We proceed to a design and manufacture of a custom fiber optic bundle with 22 tails. More specifically, the fiber bundle is comprising of 15 tails of 12 strand and 7 tails of 25 strands polymer fibre. All tails are 0,5m long, each one finished with an 8mm smooth brass ferrule. All tails are terminated in a polished 30mm common end. Each tail will be coupled with each LED and in the 30mm diameter common end we are going to have all available light wavelengths.

Figure 111 – Fiber Optic Bundle

4.2.4 LED board

LED board is the heart of our Incoherent Light Source. All twenty-two SMD LEDs are soldered on a PCB. PCB is the best way to arrange the LEDs because the location of the pads, where LEDs are soldered, is fixed and so we have high accuracy at the coordinates of each LED on the surface of the PCB. Also, we get rid of the chances of miswiring or short-circuited wiring.

The main concern is the spatial arrangement of the LEDs on the PCB considering the way we are going to couple each LED with a fiber optic tail. As mentioned in the previous paragraph, each fiber optic tail is finished with an 8mm smooth brass ferule. This means that the minimum distance between two fiber optic tails must be over 8mm. Also, the LEDs will be arranged in matrix of eleven columns and 2 rows.

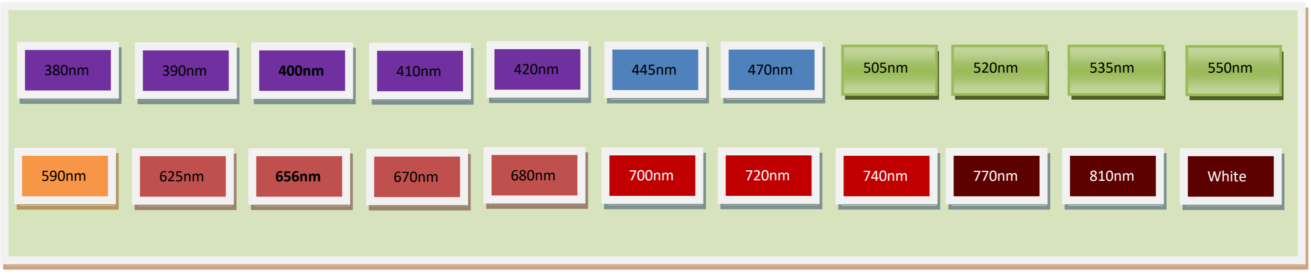


Figure 112 – Spatial arrangement of LEDs on the PCB

The first task is the designing of the PCB on an Electronic Design Automation software package. The program we used for this design is Altium Designer. Firstly, we design the footprints of the white and monochromatic LEDs. The footprints design was based on the manufacturer's recommended soldering pad pattern. The next step was to arrange in the best way the footprints on the PCB region and make the connections between the LEDs by placing conductive tracks.

Regarding the power supply of the LEDs, they divided into 3 groups with different forward voltages, i.e. some LEDs have common anode. The anode of each LED is connected to the appropriate pin of the 5-pin connector which is located to the left of the board. Using a cable, the 5-pins are connected to the LEDs power supply, which was presented before. The cathode of each LED is connected to one specific pin of the two 16-pin connectors. Using cables, the 32-pins are connected to the Driving board. After we have finished the design, we proceed to the printing process and LED soldering. The next figure illustrates the final board with the LEDs.

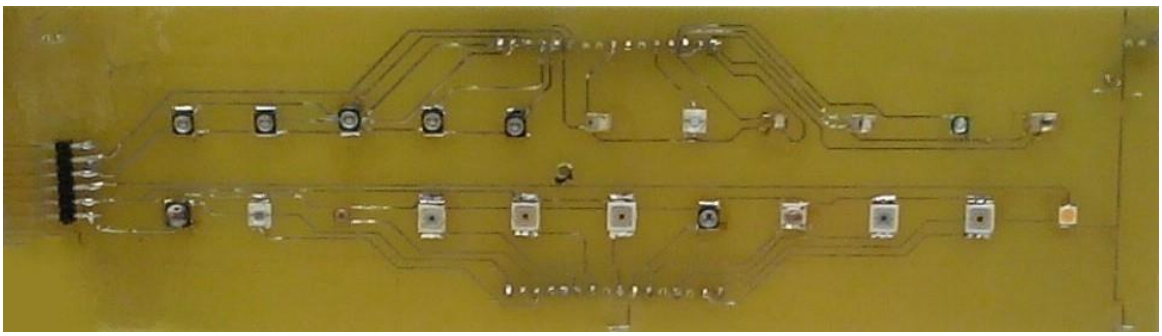


Figure 113 – LED Board

4.2.4 LED board and Fiber Optic Bundle Coupling

Considering the two previous paragraphs we proceed to a component design for coupling LEDs with fiber optic tails. We used SolidWorks to design the component and our 3d printer to print it. The component is rectangular with raised conical opening where the fiber tails will be plugged in. Then, the coupling component is fixed in the right place, on the LED board. The 3d printed component which couples the LED Board and the fiber optic bundle is illustrated below:

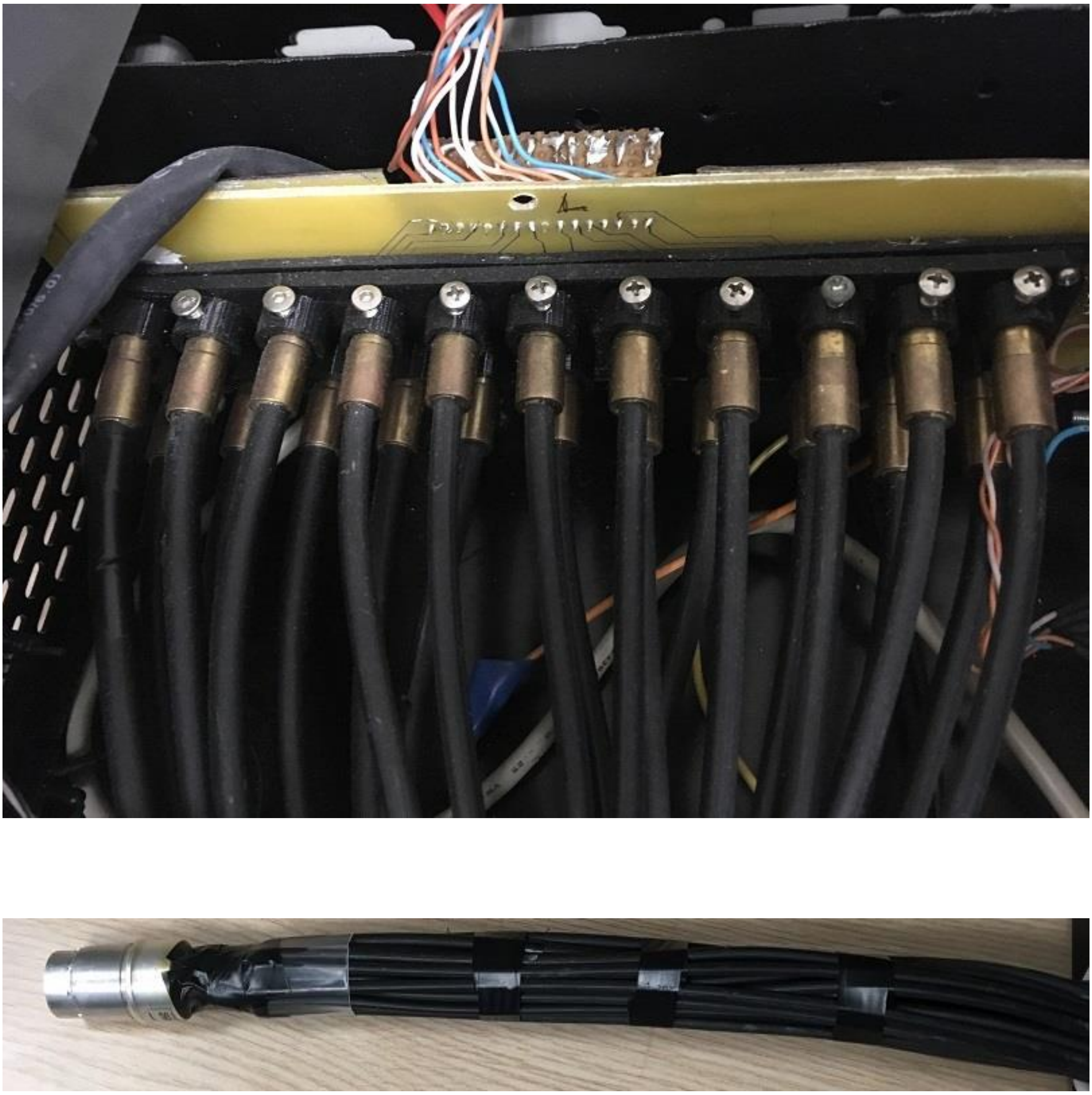


Figure 114 – Fiber Optic Bundle and LED Board Coupling

4.2.6 Connectivity and Assembly

After presenting all the parts of our device, let's present the parts all connected together. The block diagram of the final device is illustrated bellow:

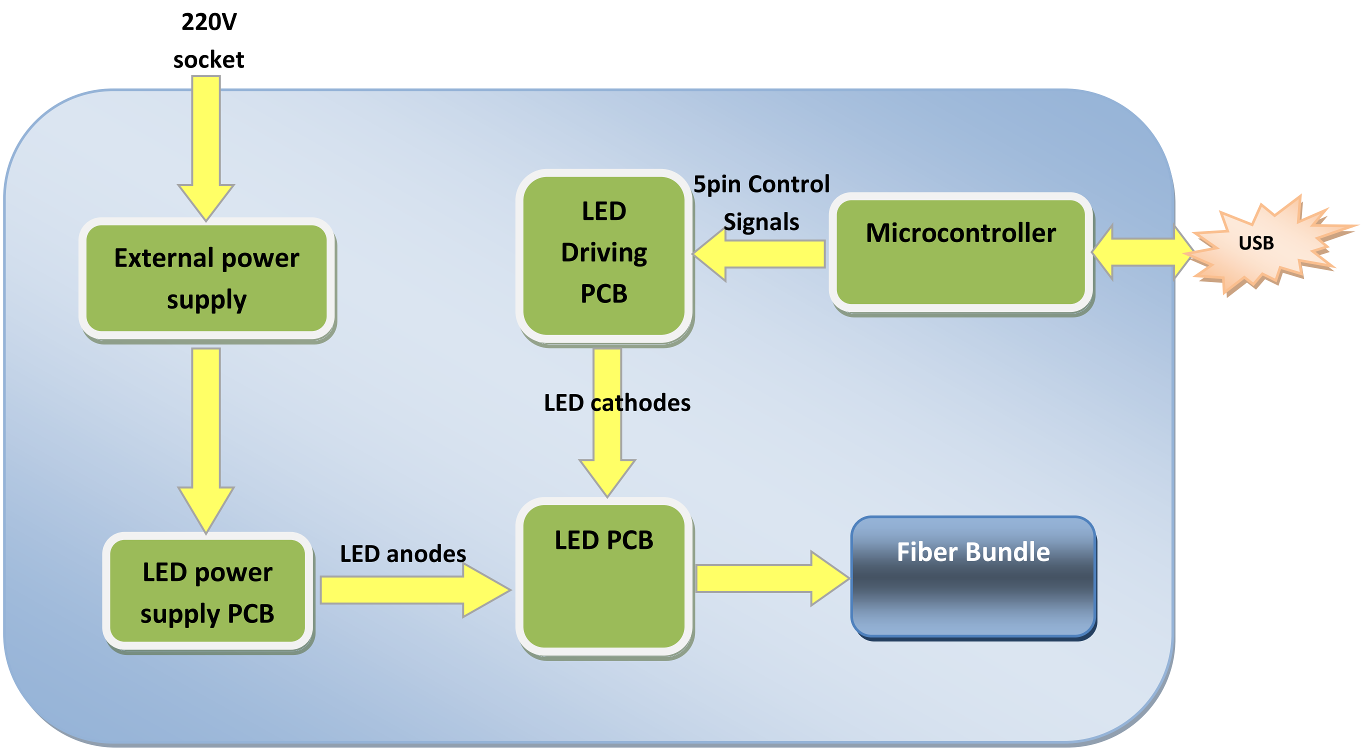


Figure 115 – Connectivity

According to the above diagram, the system has one input (220V socket) and one input/output (USB). Also, we recognize two circuit "paths" which end in the same board. So, we have External power supply→LED power supply→LED PCB and Microcontroller→LED driving board→LED PCB. The first "path" gives the appropriate power to LEDs and the second "path" controls the dimming of the LEDs via PWM pulses. All these components are enclosed in a box. The selection of the right box is very important as a way to have a compact, beautiful and charming device. The final device, after the connectivity setup is illustrated below:

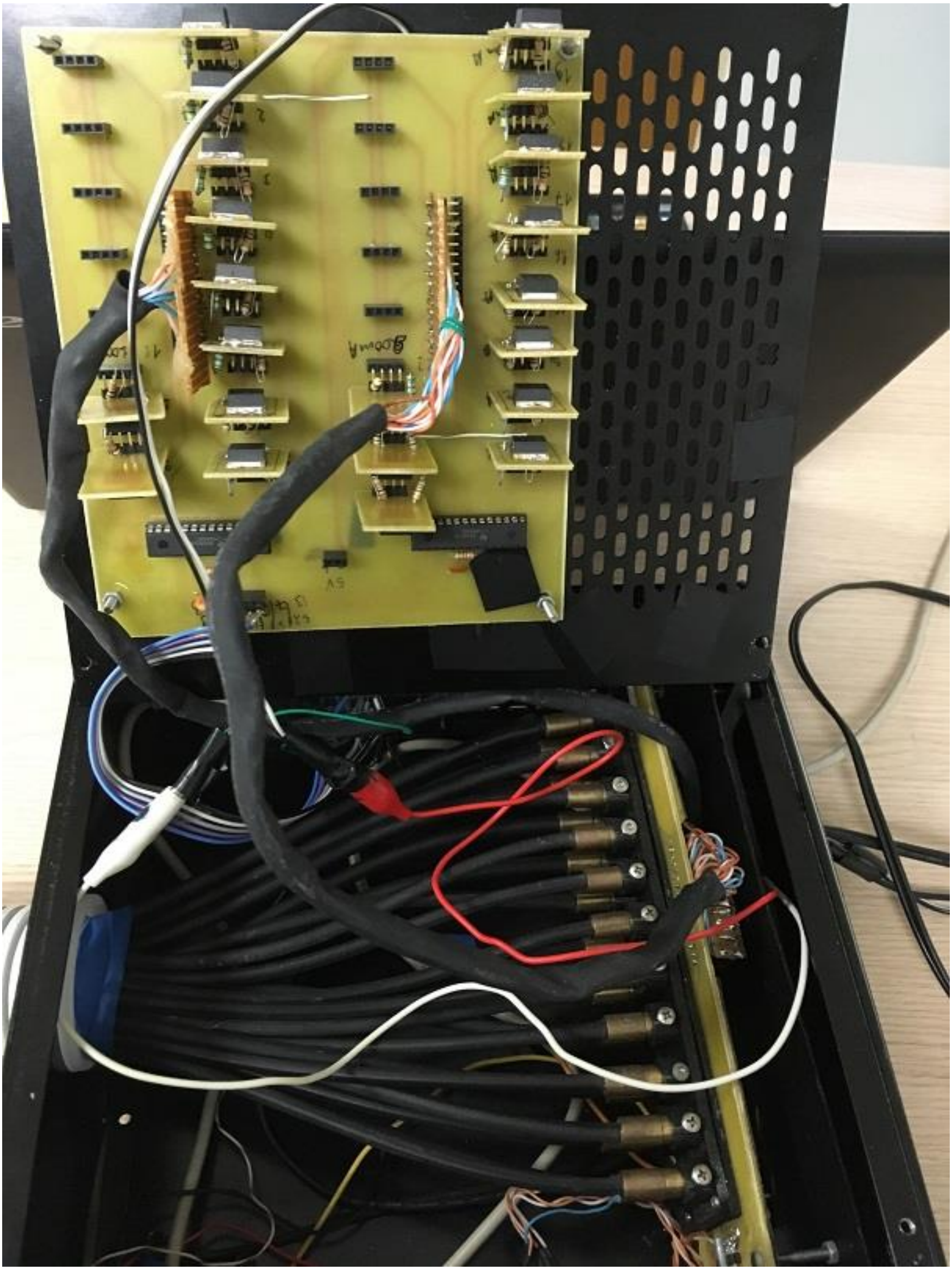


Figure 116 – Internal Connectivity

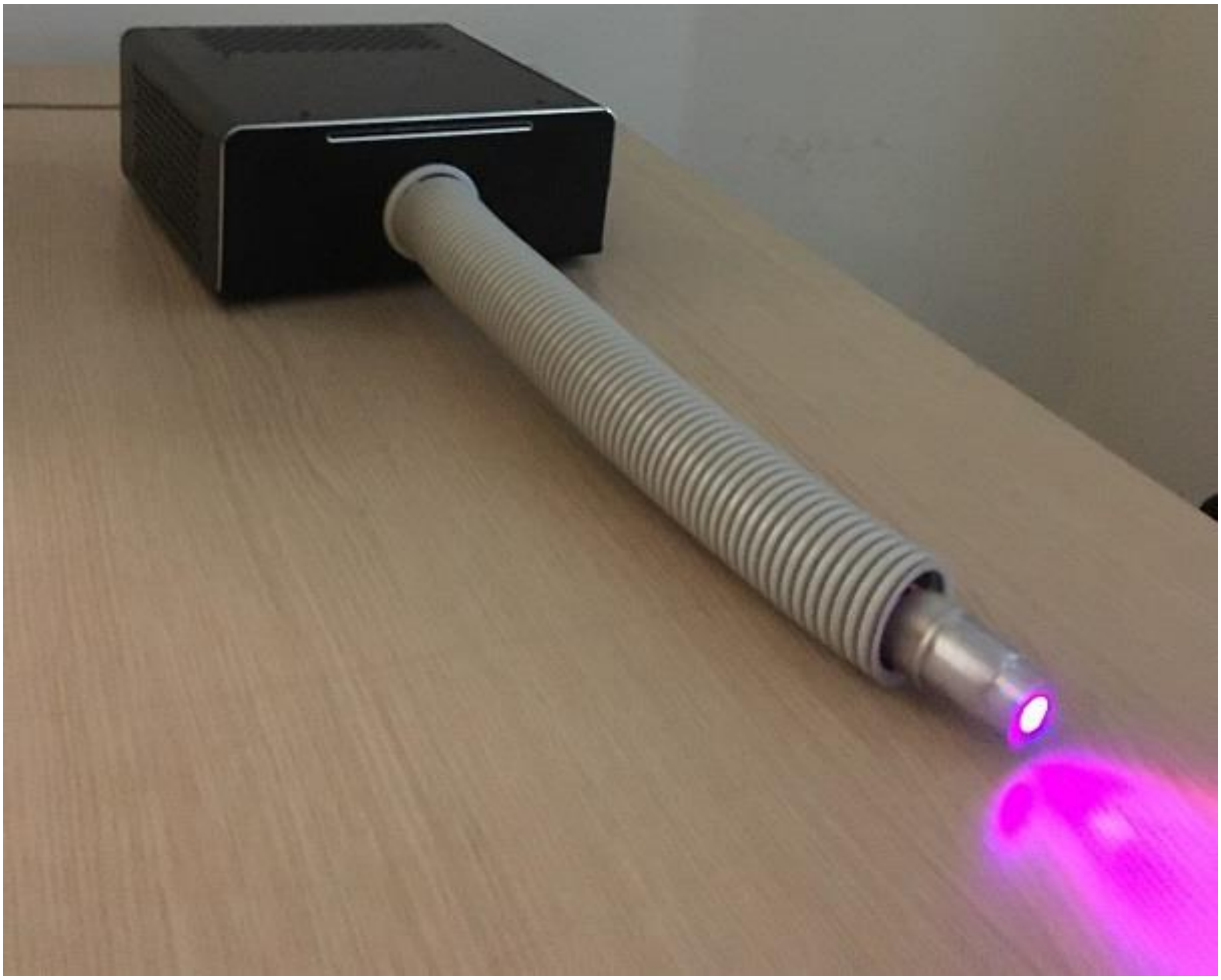


Figure 117 – The Incoherent Light Source Emitting a purple color light

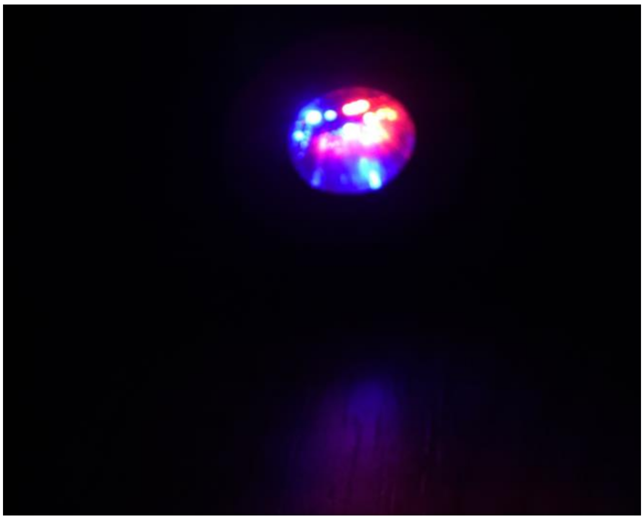


Figure 118 – Various LED Emission | The individual fiber optic strands are easy to be distinguished

4.2.7 Programming the microcontroller

The microcontroller used in this project is the Atmel AVR ATmega328 which is mounted and preassembled on a development board, as mentioned in the previous chapter.

The microcontroller executes two tasks. One task is the controlling of the TLC5940 LED drivers, which are responsible for the dimming of the LEDs, using PWM with 4096 steps. The second task is the setup of serial communication with the PC.

About the first task, we used the available Libraries for driving TLC5940. This library has several core functions which make our life easier in the control of the basic features of the TLC. The core functions that we used in our project are:

- Tlc.init(int initialValue (0-4095)) - Call this is to setup the timers before using any other Tlc functions. initialValue defaults to zero (all channels off).
- Tlc.clear() - Turns off all channels
- Tlc.set(uint8_t channel (0-(NUM_TLCS * 16 - 1)), int value (0-4095)) - sets the grayscale data for channel.
- Tlc.update() - Sends the changes from any Tlc.clear's, Tlc.set's, or Tlc.setAll's.

About the second task, the serial port is used to receive byte of data in ASCII code format. According to the character received via the serial port, the microcontroller commands TLC to execute different functions. To do this, we use the switch statement. Switch statement allows us to choose between several discrete options. So, we have a mini "Finite State Machine (FSM)".

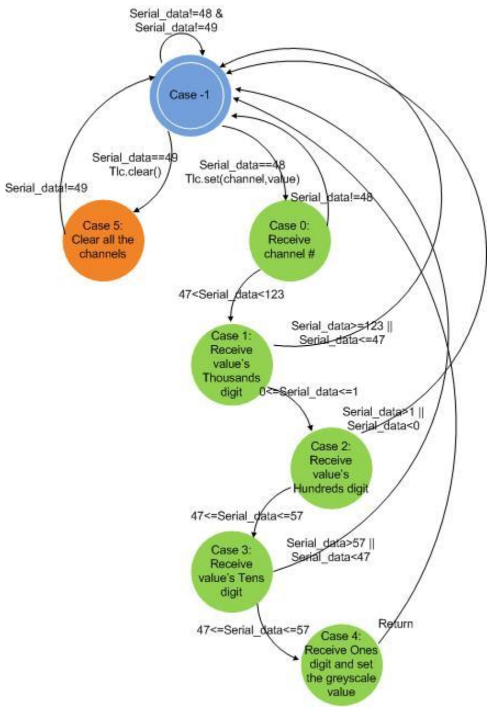


Figure 119 - Switch statement

After the setup of the serial communication, the switch statement takes place. Let us analyze the various cases, according to the above diagram:

Case -1: When we are in the case -1 the selection between three "path"options is done using if statement:

a) In the case, we have no data in the serial the next state is again -1, ie returns to itself.
b) In the case the value received is "48" (ASCII code) the next state is case 5.
c) In the case the value received is "49" (ASCII code) the program follows the green path and the next state is case 0.

Case 5: In this case, all the channels of the TLC turn off using the tlc.clear() core function. Program returns to case -1.

Case 0: Case 0 is the first state of the green path, which is illustrated in the above figure. This path is used as a way to set the step of the grayscale PWM brightness control in a channel and finally control the dimming of a LED. In case 0 the received value sets the channel of the TLC. This value must be greater than "47" and less than "123". If the value is within these limits the next state is case 1. Otherwise, the next state is case -1.

Case 1: In case 0, we get the channel of the TLC. What remains is the value of the step of the grayscale PWM brightness control, which sets the dimming of the LED. As mentioned in the previous chapter, the TLC5940 device has a 4096-step grayscale PWM brightness control. In our project, we considered excessive the 4096 steps, so we scaled them to 1024 steps. So, we have a 1024-step grayscale PWM brightness control. The received value of the step is divided into thousands, hundreds, tens and ones digits, i.e. each digit is a different received value. In case 1 the received value is the thousands digit. For example if we have the step 1022, in case 1 the received value will be number "49" in ASCII code (1_{DEC}). Also, the received value must be "48" (0_{DEC}) or "49" (1_{DEC}) and the next state is case 2. Otherwise, the next state is case -1.

Case 2: In this case, the hundreds digit of the step of the grayscale PWM brightness control is received. This value must be greater or equal than "47" (0_{DEC}) and less or equal than "57" (9_{DEC}). If the value is within these limits the next state is case 3. Otherwise, the next state is case -1.

Case 3: In this case, the tens digit of the step of the grayscale PWM brightness control is received. This value must be greater or equal than "47" (0_{DEC}) and less or equal than "57" (9_{DEC}). If the value is within these limits the next state is case 4. Otherwise, the next state is case -1.

Case 4: In this case, the ones digit of the step of the grayscale PWM brightness control is received. This value must be greater or equal than "47" (0_{DEC}) and less or equal than "57" (9_{DEC}). If the value is within these limits we proceed to the reformation of the value of the grayscale PWM brightness control step using the 4 digits which received in cases 2 to 4. After the reformation, we are ready to set the step of the grayscale PWM brightness control in the channel number received in case 1, using the core function tlc.set(channel, step_value). Finally, the program returns to case -1, where the program waits to receive new data.

4.2.8 Serial Communication with the microcontroller

In the previous paragraph, we analyze the program which is loaded to the microcontroller. We saw that the control to what function will be executed is done by sending data through the serial port of the microcontroller. Now let us analyze how the communication between the computer and the microcontroller is done. The interface with the computer is done through USB connection, which is downgraded to USB-to-serial, and supportive adapter chips on the board.

To send data to the microcontroller we wrote a script in Matlab. This script includes functions that perform several operations. The functions are:

- ✓ **function a=microctrl(comPort)**: This function is a **constructor**, which connects to the microcontroller board and creates an object. The checks are made through this functions are:
  - ➢ Check if the name of the port is correct. The name must be a string, e.g. 'COM8'
  - ➢ Check if we are already connected to a port.
  - ➢ Check whether serial port is currently used by Matlab.

  To proceed to the connection the first check must be true, the second must be false and the third must be false. After the checks, we define the serial object and we proceed to the connection. In a try-catch statement we open the port. If the port opens the connection established successfully.
- ✓ **function delete(a):** This function is a destructor which deletes the microcontroller object. If the serial is valid and open then close it and call the tlc_clear function, which turn off TLC channels.
- ✓ **function flush(a):** This function clears the serial port buffer of the computer. To do this, we read all the bytes available (if any) in the computer's serial port buffer, therefore clearing that buffer.
- ✓ **function tlc_clear(a) :** This function sends the value "48" (ASCII code) to the microcontroller via the serial port. As we mentioned in the previous paragraph, by sending the value "48" to the microcontroller all channels turn off.
- ✓ **function tlc_set(a,pin,val):** This function sets the step of the grayscale PWM brightness control in a TLC channel. To do this, we send the function code "49" (ASCII code), the channel number and the step value. To send the channel number, which is the argument "pin", the number 48 is added to the value of the argument. ASCII code 48 is the number 0 in decimal, so if the argument pin=1 then its ASCII code will be 48+pin=48+1=49. In the same manner, we add number 48 to the thousands, hundreds, tens and ones digits and finally we send them to the microcontroller via the serial.

The above functions are called in the GUI of this project, which will be presented in the next paragraph. This paragraph combined with the previous one is the back end programming of our project. All that remains now is to create a user-friendly interface called the front end of the software.

4.2.9 User interface

After we presented the back end application let us present the front end application of our software. The front end is an interface between the user and the back end. For that reason, the front end interface must be user-friendly with several features as a way to cover the whole functionality of the light source. In our case, a GUI application acts as a front end environment. GUIs provide point-and-click control of software applications, eliminating the need to learn a language or type commands in order to run the application. In this paragraph will present our GUI application and its basic features. Our GUI application has developed in Matlab environment, using a toolbox called GUIDE (GUI development environment). GUIDE toolbox contains controls such as menus, toolbars, buttons, and sliders. Using the GUIDE Layout Editor, you can graphically design your UI. GUIDE then automatically generates the MATLAB code for constructing the UI, which you can modify to program the behavior of your app. The next figure shows how our GUI application looks like. Also, it is depicted which are the main functionalities of the interface.

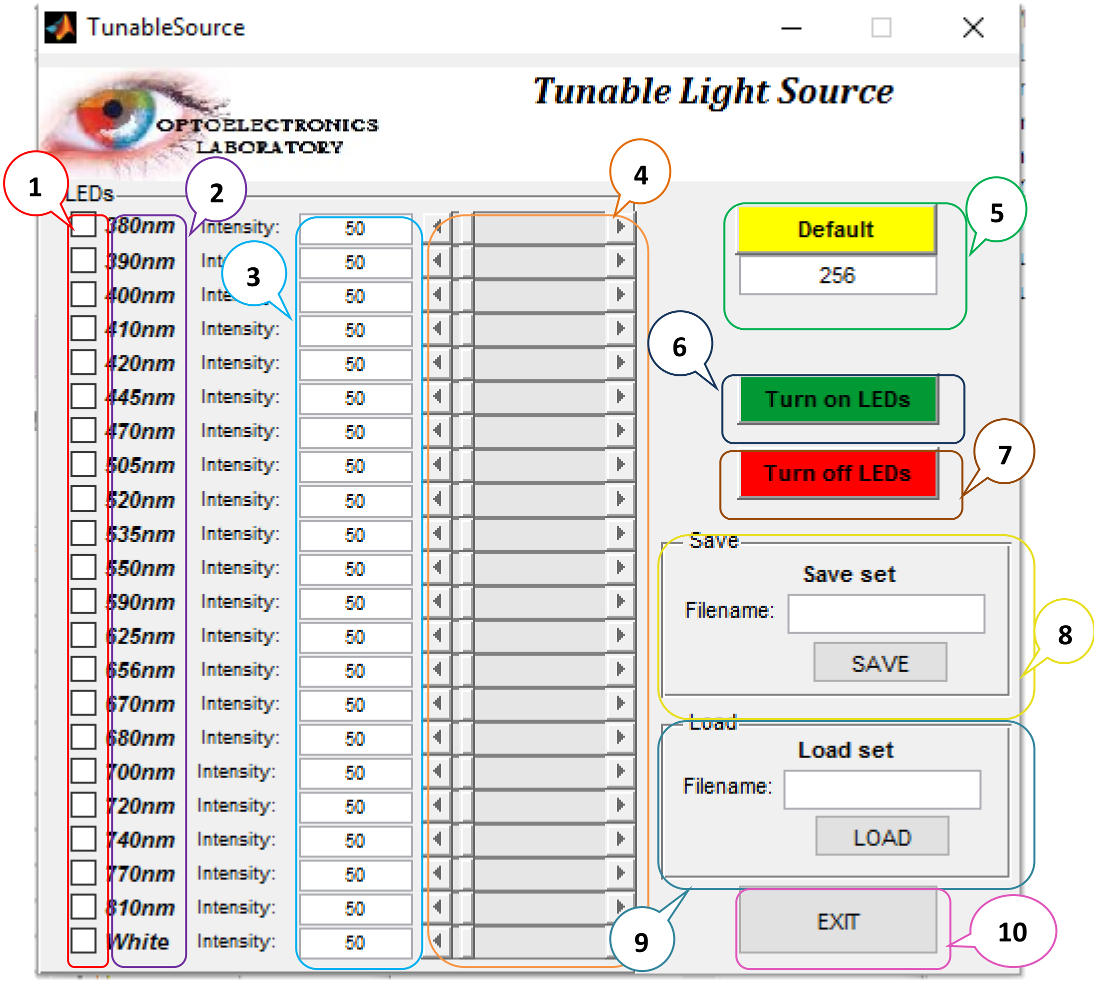


Figure 120 – GUI breakdown

GUI Breakdown

1) **Check boxes for enabling/disabling LEDs.** The user has to check the box to enable the PWM port of the current LED, i.e. the LED turns on. When unchecking the box the LED turns off.
2) **Static text with LED's transmitted wavelength:** Each static text informs the user about the wavelength transmitted if the current LED is turned on.
3) **Edit boxes for choosing intensity:** In the edit box user can type the values between 0 and 1023 (a total of 1024 steps) with 1 step. Entering the value 0 the LED is off, while entering the value 1023 the LED is on at its maximum intensity. In other words, the edit box adjusts the period of the PWM and therefore the dimming of the LED. Also, when assign a value to the edit box, the slider next to it (4) moves in the appropriate point.
4) **Sliders for choosing intensity:** The function of the slider is that when the user moves the slider, the dimming of the LED is adjusted. The slider executes the same function as the edit box, which described above. Its minimum value is 0 and the maximum is 1023. Also, when the user moves the slider, the intensity edit box's string changes to the current intensity value. In other words, slider and its fellow edit box perfectly synchronized with each other every time a change is made.
5) **Default intensity value:** The user can type a number between 0 and 1023 in the edit box. When pressing the Default button the intensity value in all the intensity edit boxes(3) and the sliders (4) changes to the intensity value the user typed.
6) **Turn on LEDs button:** When the user presses this button all the check boxes (1) are checked and all the LEDs turned on.
7) **Turn off LEDs button:** When the user presses the off button all the check boxes (1) are unchecked and all the LEDs turned off.
8) **Save set feature:** With this feature the user has the choice to save the intensity values of each LED in a excel datasheet. The user types the desired filename and clicks SAVE. This is very important because the user can save the desired configuration sets as a way to load them later without adjusting the values from scratch.
9) **Load set feature:** With this feature the user has the choice to load the intensity data set which saved with the above feature.
10) **Exit button:** When the user pushes this button the GUI and the connection between the microcontroller and Matlab are terminated.

The application analyzed above was the result of rapid prototyping procedure which led us to the final form of this software. Before creating the final form, there were prior forms of the GUI which was not as much user-friendly and beautifully designed as the final form. The purpose of the final design is to attract the user and make his life easier in handling the light source.

4.2.10 Need for homogenization

From the first moments of testing our incoherent light source we observed a phenomenon at the bundle output. The problem is that the light at the bundle output is not properly homogenized. This is easy to understand due to the fact that the fibers in the end of the fiber bundle are randomly distributed and not in homogenized way. Bellow, an image reflection of the fiber optic bundle output with one red, one green and one blue LED enabled, is illustrated:

Figure 121 – Image by reflection of three LEDs (RGB) at the fiber optic bundle end

It is obvious that the output light of the fiber bundle is not homogenized at all. There is no color mixing.

This problem lead us to think ways of homogenizing the light coming out from the fiber optic bundle. We ended up in a light homogenizing setup which includes a homogenizing rod and a diffuser.

Homogenizing rods, also known as Light pipes, are optical components designed for any application that requires homogenized light. Homogenizing rods utilize total internal reflection to homogenize non-uniform light sources, regardless of the light source's spectral characteristics.

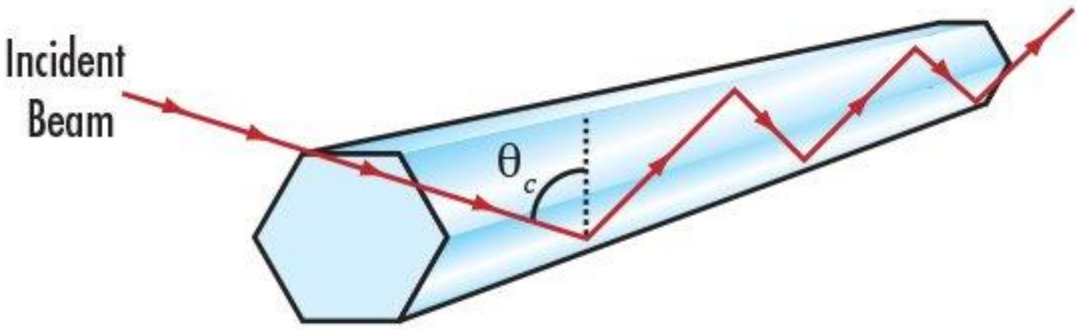


Figure 122 – Working principle of a homogenizing rod

This sounds a very good solution to our problem. So, we tested this solution by coupling the end of the fiber bundle with homogenizing rod. Then, we captured an image reflection at the rod output with the same LEDs enabled like these enabled in Figure 94.

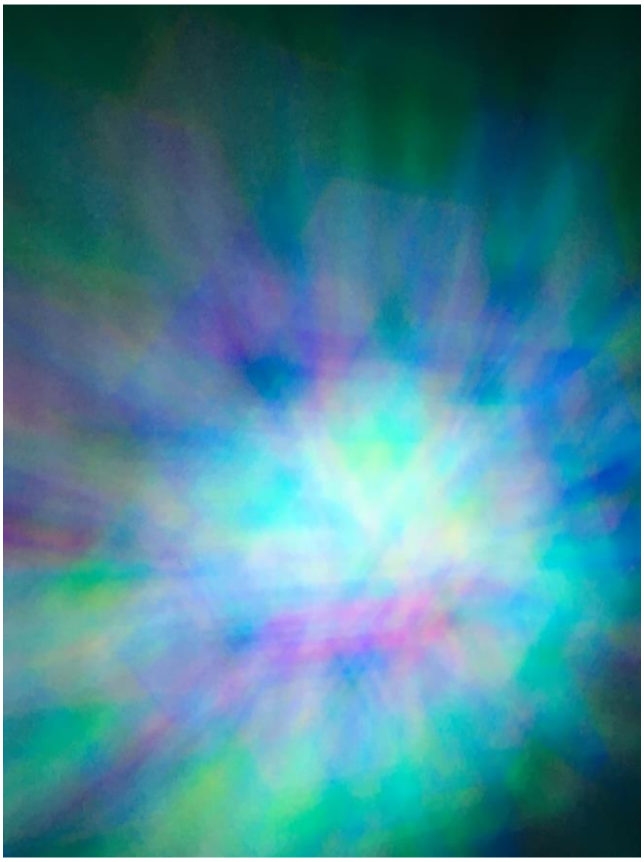


Figure 123 – Image by reflection of three LEDs (RGB) at the homogenizer's output

The output shows the multiple reflections that take place inside the homogenizing rod. But still, this is not the desired output. There is a last ingredient to be added to the recipe for being successful. It is called diffuser.

Diffusers are an optical component used to evenly distribute light from a source while eliminating bright spots. A perfected diffuser should create Lambertian scattering where the radiance is independent of angle.

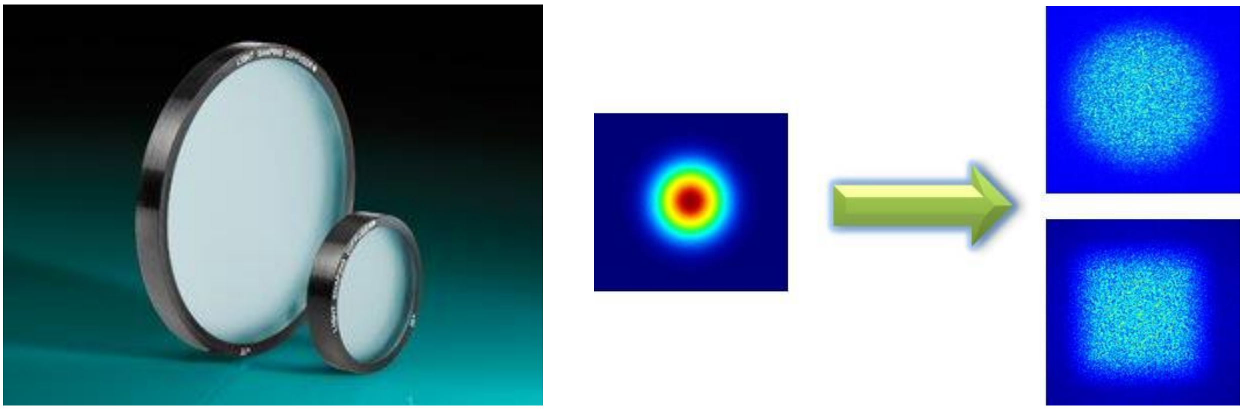


Figure 124 – Optical diffuser

So, we proceed to a homogenizing setup coupling the fiber bundle end with the homogenizing rod and the homogenizing rod with an optical diffuser. The setup is illustrated below:

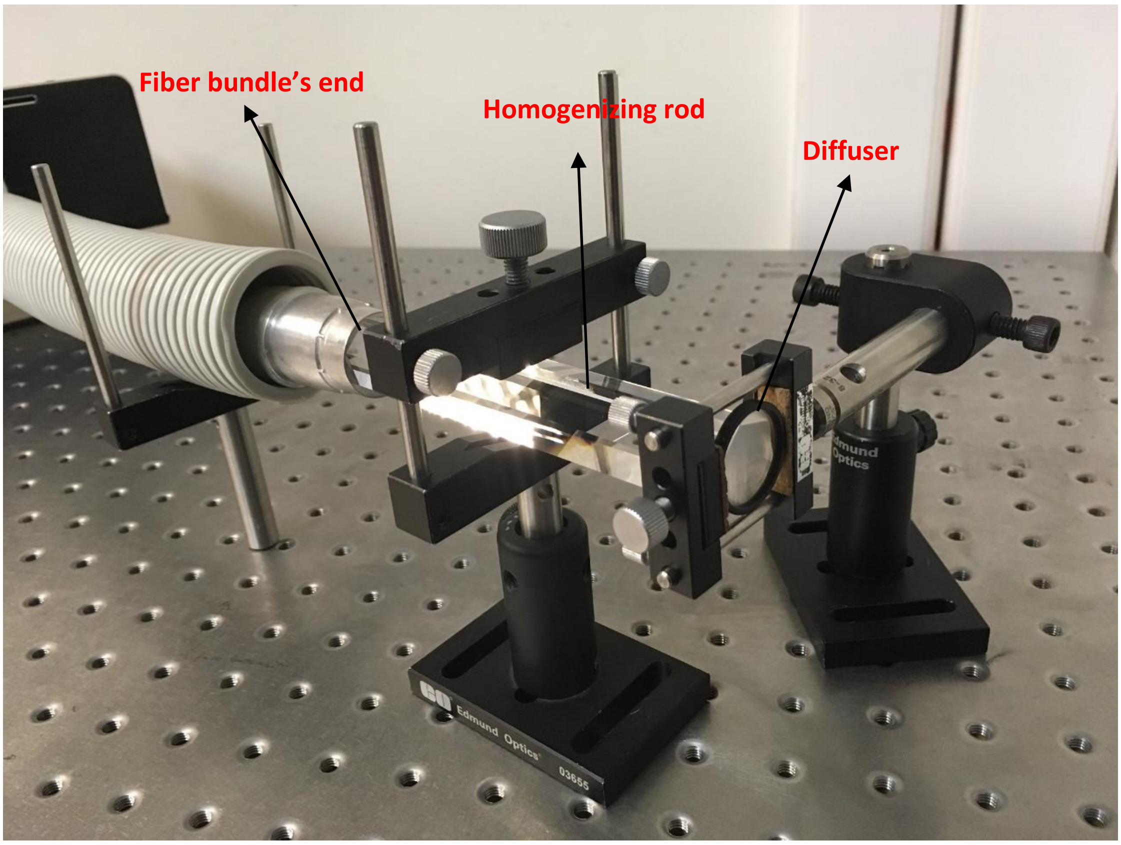


Figure 125 – Homogenizing setup

The next step is to capture the reflected emission image using the last homogenizing setup with the same LEDs enabled like the two previous captures. So, the result is illustrated bellow:

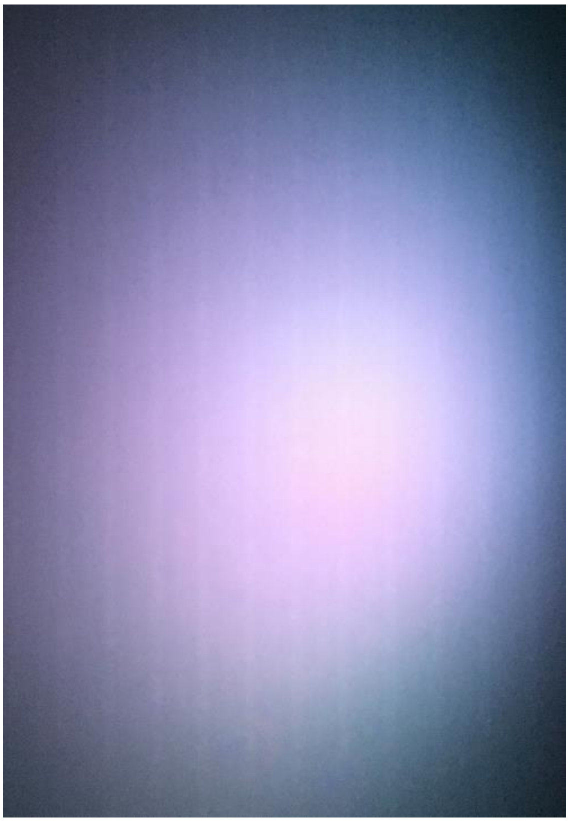


Figure 126 – Image by reflection of three LEDs (RGB) at the diffuser's output

Finally, this result is very suitable for our project. The LEDs' emissions are mixed in a perfect way, compared to Figures 94 and 96. The output is a perfect white, something that does not appear in Figures 94 and 96. Thus, we ended up in this homogenizing setup using a homogenizing rod and an optical diffuser.

.

4.3 Technical Evaluation

4.3.1 Switching speed of LEDs

One important part of the design is the ON/OFF speed of the LEDs. The speed depends mainly on the TLC5940 controller which has a delay between outputs. The TLC5940 has graduated delay circuits between outputs. The fixed delay time is about 20ns, OUT0 has no delay, OUT1 has 20ns delay, and OUT2 has 40ns delay etc. The maximum delay is 300ns from OUT0 to OUT15. The delay works during switch on and switch off of each output channel. Moreover, there is propagation delay time of the controlling signals of the TLC5940.

In our design, we used 2 TLC5940. As we mentioned in Chapter 4 the TLC5940 has 16 outputs and the design has 22 LEDs. So, all the outputs of the first TLC5940 are used for the first 16 LEDs and the first 6 outputs of the second TLC5940 are used for the 6 remaining LEDs. So, the maximum delay is 420nm from OUT0 to OUT21 (OUT5 of the second TLC5940) regarding that the TLCs are on cascade.

4.3.2 Stability of the Incoherent Light Source

Illumination sources based on plasma discharge (arc lamps), incandescence (tungsten-halogen lamps), or stimulated emission in a gaseous environment (gas lasers) require a considerable period after ignition to reach thermal equilibrium, a factor that can affect temporal, spatial, and spectral stability. In many cases, a period of up to one hour is required until the illumination source is sufficiently stable to enable reproducible measurements or to record time-lapse video sequences without significant temporal variations in intensity. In many cases, a period of up to one hour is required until the illumination source is sufficiently stable to enable reproducible measurements or to record time-lapse video sequences without significant temporal variations in intensity. Once the proper operating temperature has been reached, the tungsten-halogen lamp is the most stable conventional light source over time periods of a few milliseconds due to the high thermal of the tungsten filament.

As described in previous paragraphs, our assembly has monochromatic and white LEDs. LEDs are capable of reacting extremely fast, within a few microseconds, and feature the lowest operating temperatures of all light sources and are among the most stable in temporal and spatial terms. However, the LEDs we used in this thesis are miniature high-power LEDs. This means that without an efficient heat sink the LEDs will be overheated and the whole system will become unstable.

As a way to test out Light Source's stability, we power on the LEDs in the typical forward voltage and we take the spectrum curves using the spectrometer. After some minutes we take the spectrum again and compare with the first spectrum. In the figure below compared spectrums of some LEDs are presented:

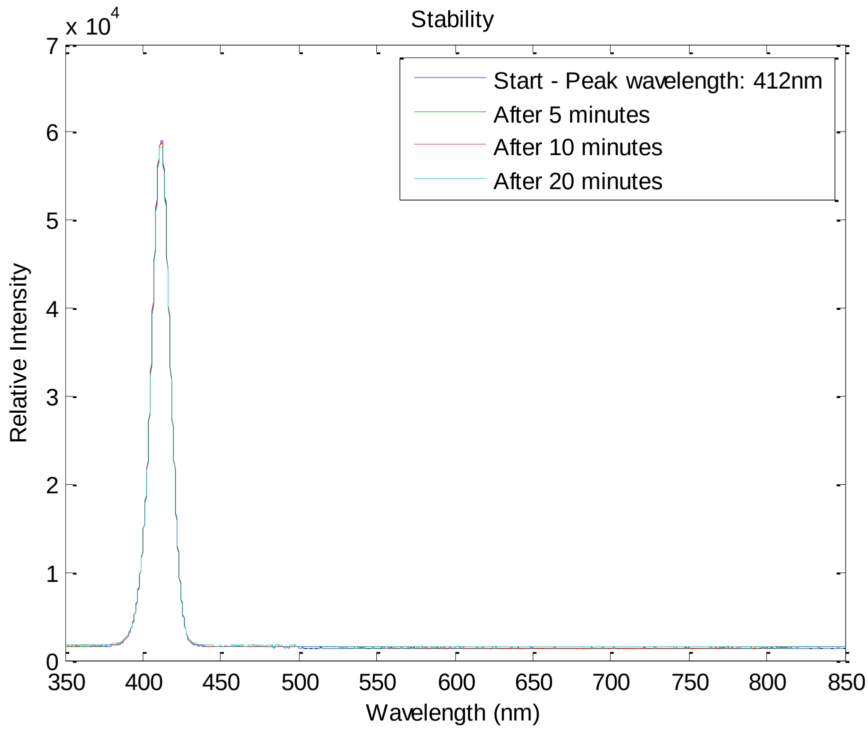


Figure 127 – Stability test, LED_peak=412nm

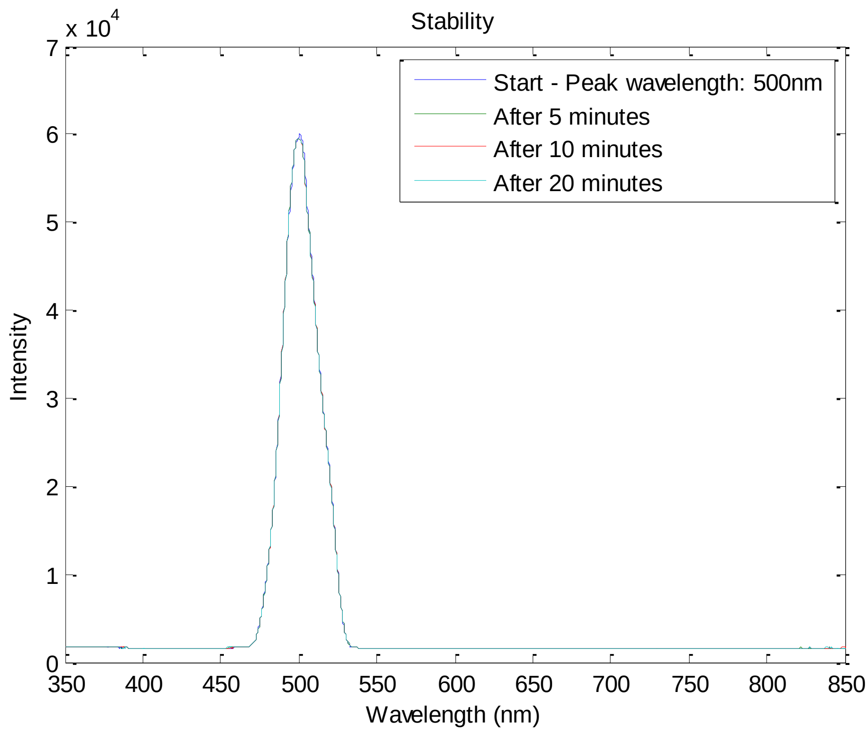


Figure 128 – Stability test, LED_peak=500nm

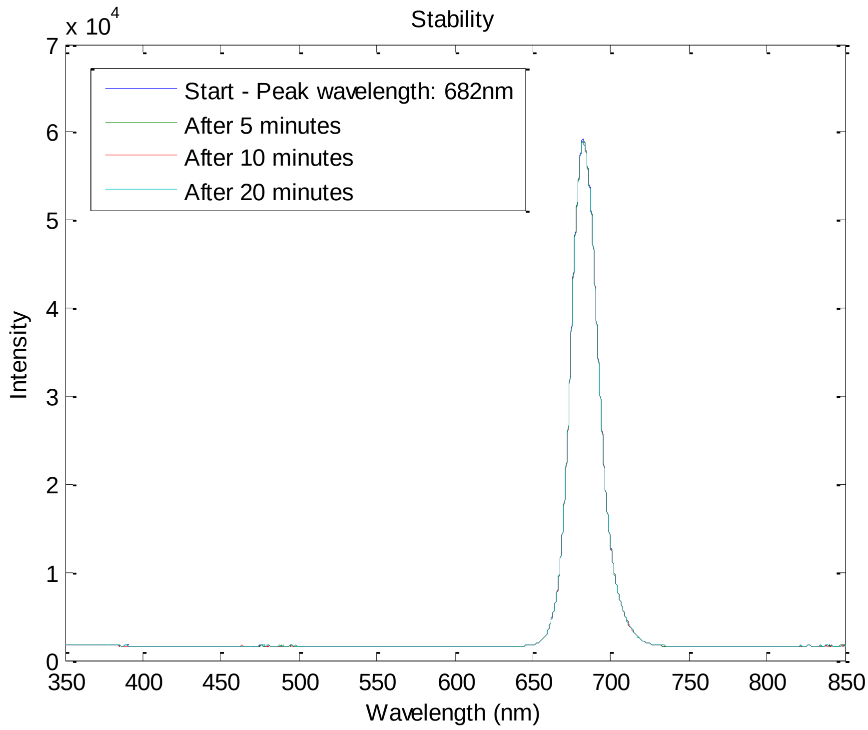


Figure 129 – Stability test, LED_peak=682nm

As shown in the above figures there is no shifting of the spectrum and the intensity of each LED. This means that Light Source has great stability and needs short ignition time.

4.3.3 Lifespan of the Incoherent Light Source

Mercury and xenon arc lamps have a lifespan of 200 to 400 hours, whereas metal halide sources last 2,000 hours or more. Tungsten-halogen incandescent lamps have lifetimes ranging from 500 to 2,000 hours, depending on the operating voltage. In contrast, many LED sources exhibit lifetimes exceeding 10,000 hours without a significant loss of intensity, and some manufacturers guarantee a lifetime of 100,000 hours before the source intensity drops to 70 percent of the initial value.

Because of LED's used in this project, our Light Source has great stability, reliability and lifetime. Also, the great lifetime provides economy because there is no need for changing expensive lamps, like the lamp in Xenon light source.

4.3.4 Emulation of a Flat Line Response Source

As we mentioned in previous paragraphs, the user of the Incoherent Light Source can adjust the intensity of each LED in 1024 steps. So, by powering on all monochromatic LEDs and adjusting each LED's spectrum to have the same intensity, we have a continuous spectrum flat response light source. For measuring the spectra we used a spectrometer and its relative software.

We can tune available wavelengths of the Light Source for having flat response.

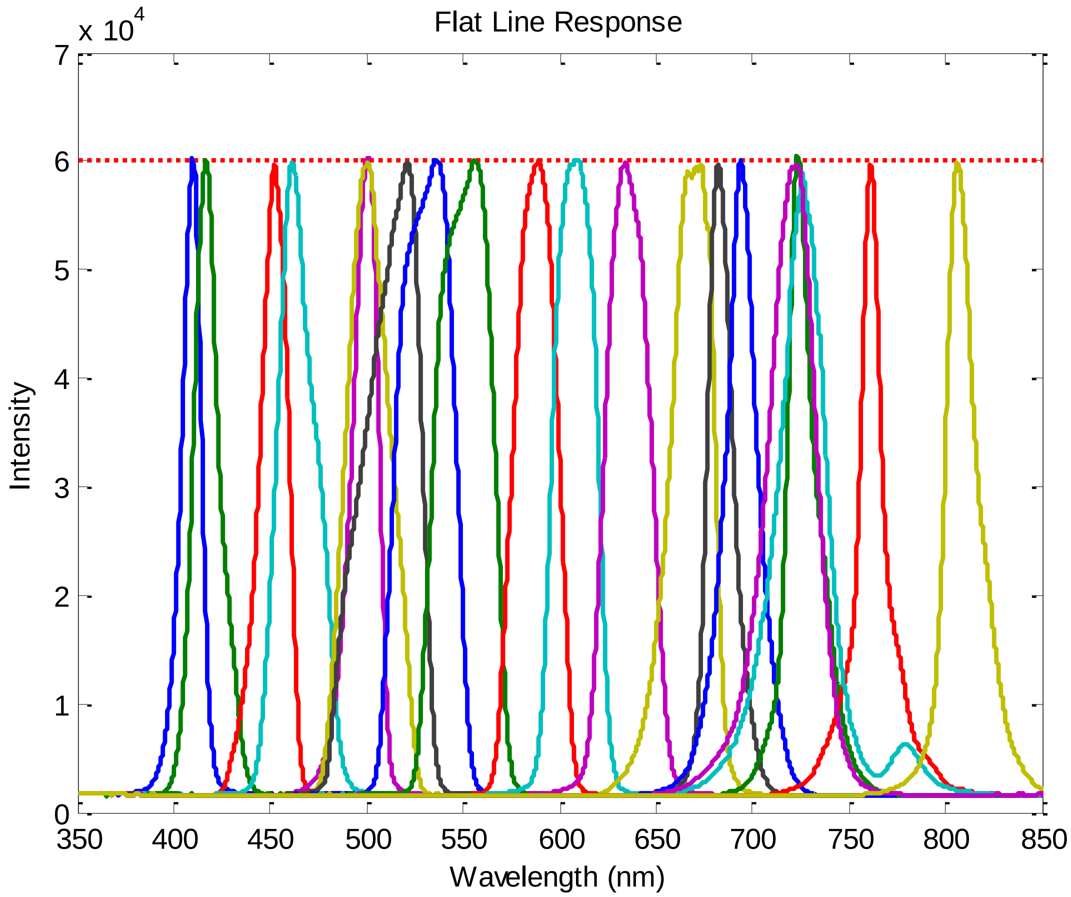


Figure 130 – Flat Line Response

Flat light sources are of great importance because we have an accurate flat line response which is necessary for calibration purposes. Also, there is no conventional light source which has flat response.

4.3.5 Emulation of Curves on Demand

Suppose we want to emulate a random source, as shown below. This means that the experimental points, which are the peaks of the spectrum of each LED, should fit on the curve of the random source's spectrum. To do this we adjust the height of each curve manipulating current LED's intensity.

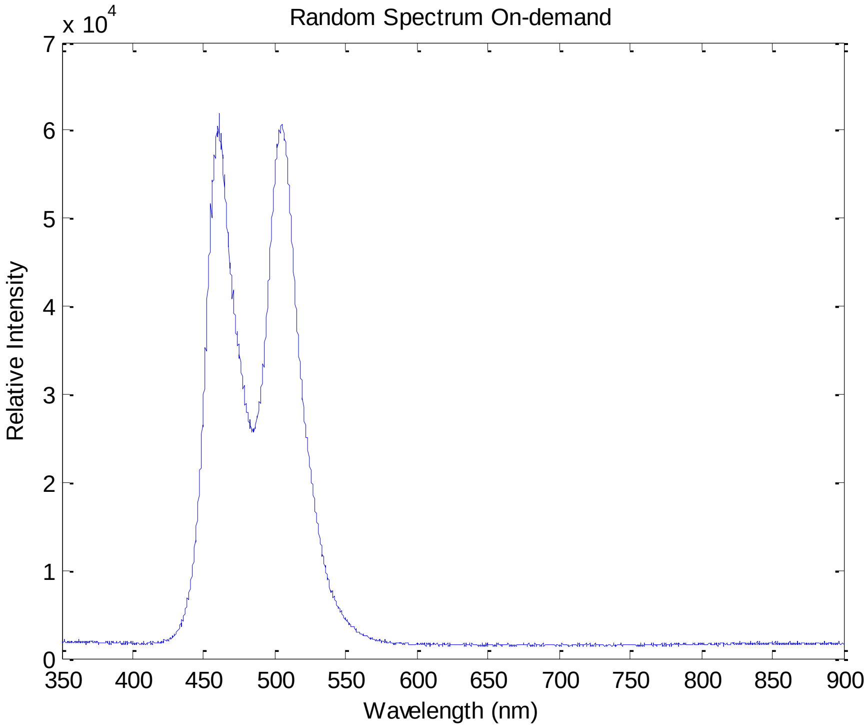
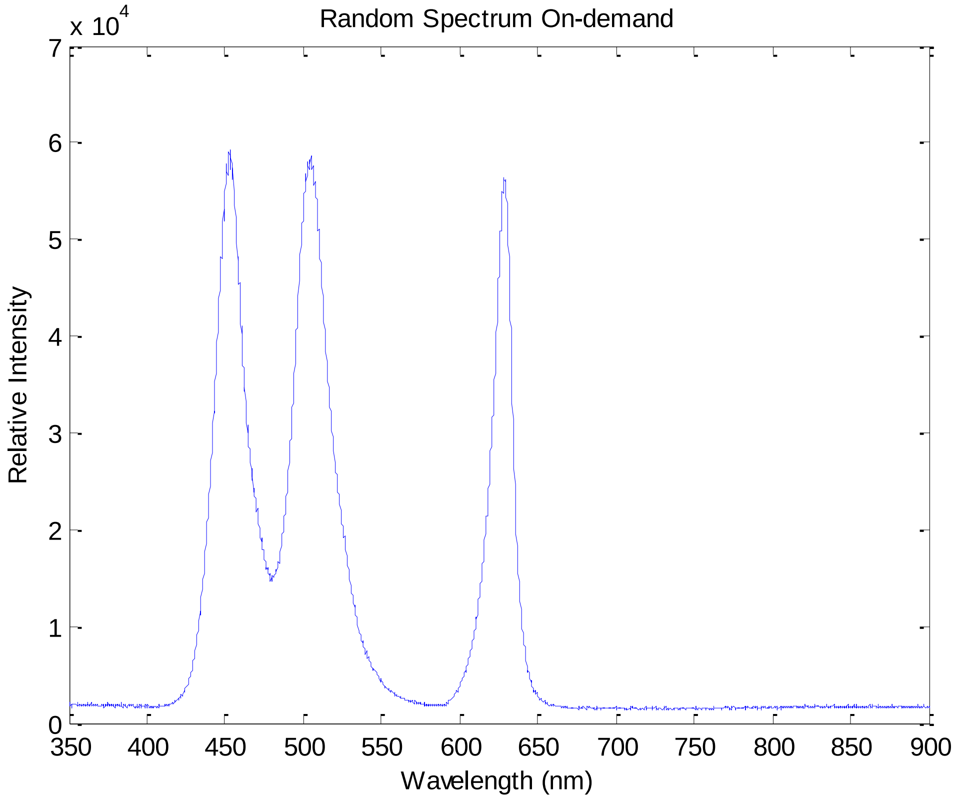


Figure 131 – On demand spectrum 1 | Blue-green color



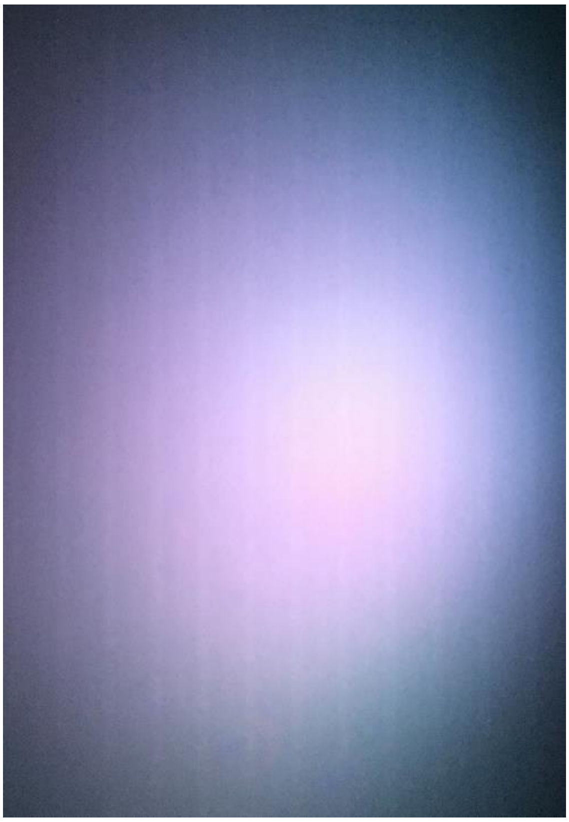
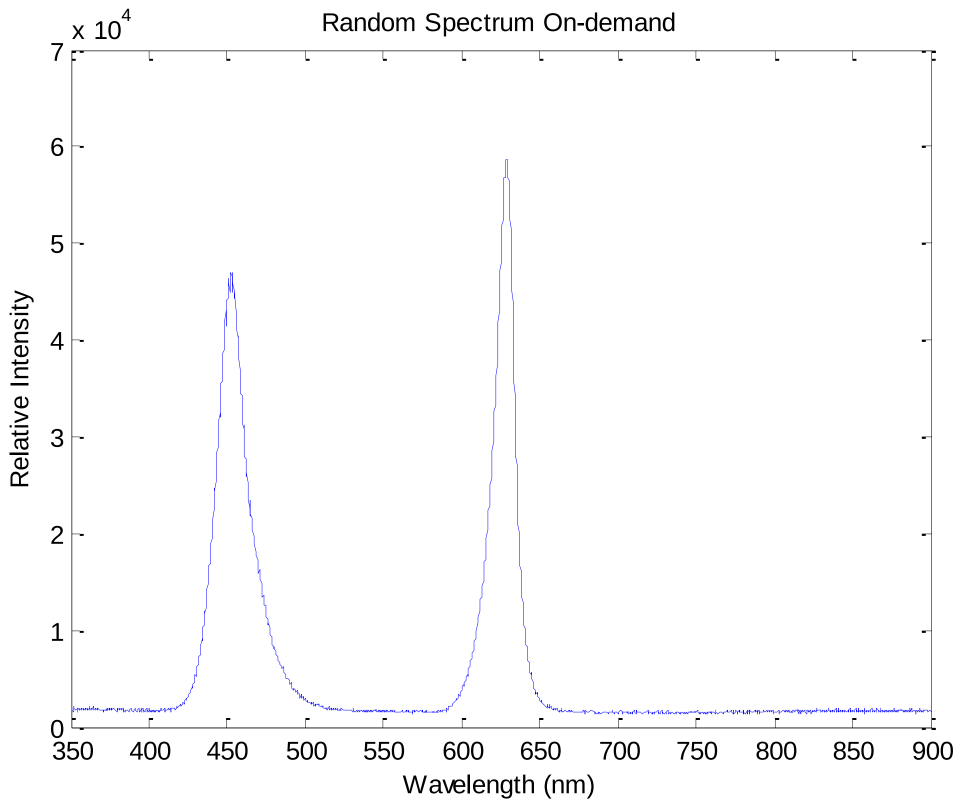


Figure 132 – On demand spectrum 2 | White Light emitted by 1 green, 1 red and 1 blue LED



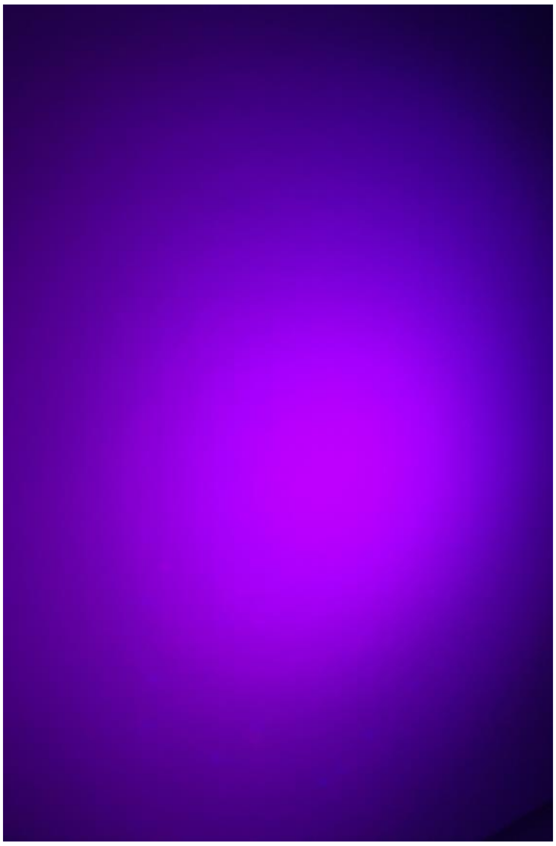
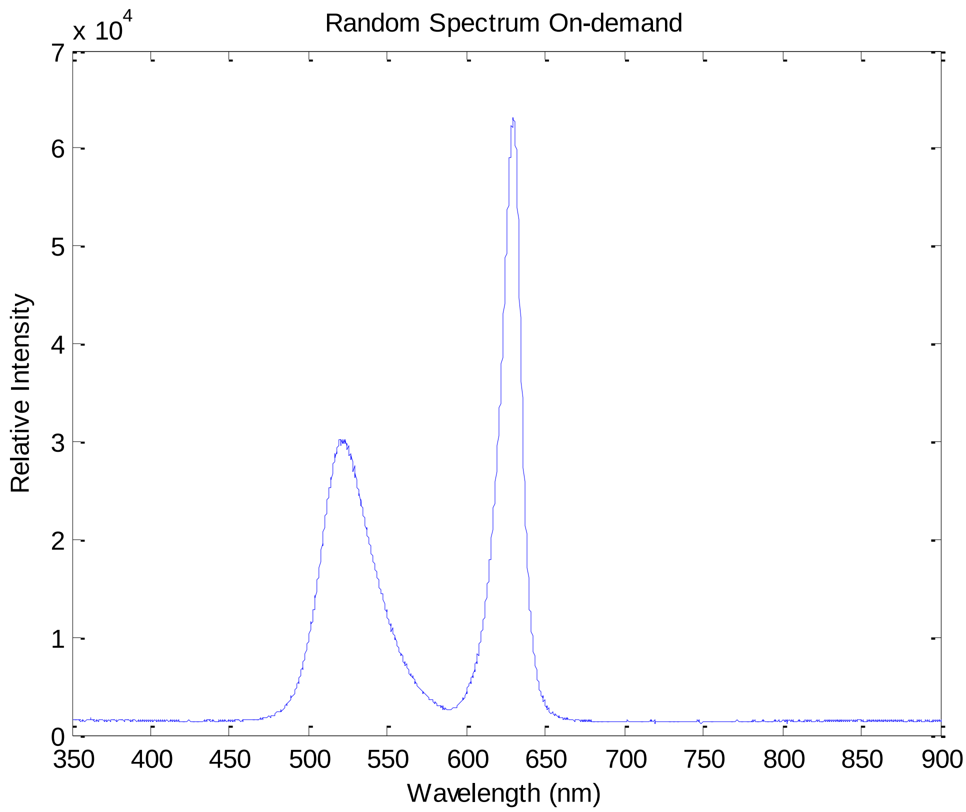


Figure 133 – On demand spectrum 2 | Purple color



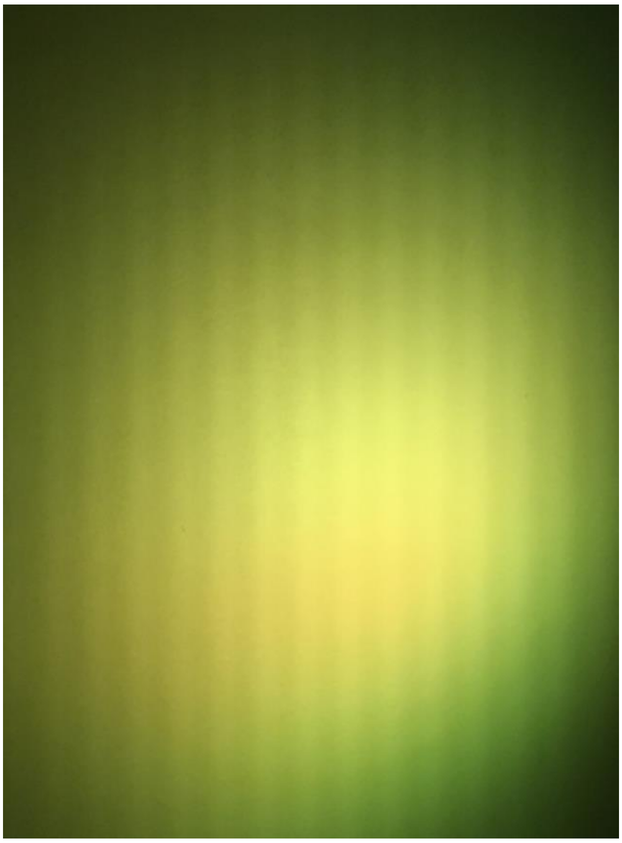


Figure 134 – On demand spectrum 3 | Yellow color

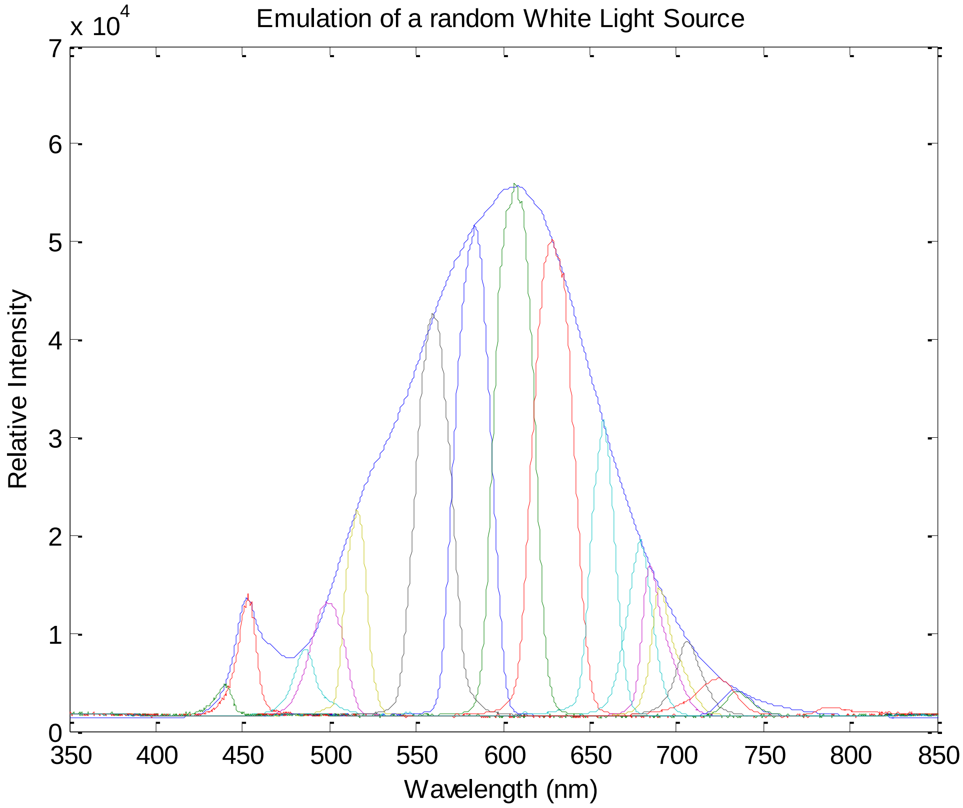


Figure 135 – On demand spectrum 4 | Emulating a White LED manipulating the intensities of the Monochromatic LEDs

4.4 Applications

There are several applications in which, our innovative Incoherent Light Source could be very useful. It could be an incredible instrument for various medical and non-medical applications, some of them are depicted below:

- Medical Applications
    - Endoscopy lightning
    - Microscopy lightning
    - Fluorescence microscopy lightning
    - Surgical and examination lightning
    - Medical analysis
    - Pupillary motor reflex excitation source
    - Checking human vision spectral limits
- Non-Medical Applications
    - Hyperspectral Imaging
    - Art Restoration
    - Calibrating Optical Systems
    - Characterizing Imaging Sensors
    - Characterizing Optical Filters

5

COHERENT LIGHT SOURCE

The goal of this thesis is the development of an incoherent and a coherent light source for various applications including biomedical applications. In the previous chapter our Incoherent Light Source has been presented. In this chapter the development of the coherent LASER light source will be presented. Lasers combine some of the best aspects of arc lamps and LEDs. As with lamps, they provide intense light, but because the light is focused on a point rather than over the whole field, the high intensity isn't as damaging to a living cell. And as with LEDs, lasers are long-lasting and provide light in a specific wavelength range, negating the need for filters.

Our goal is to design a compact device with great optical power. The major challenge is the LASER beams' multiplexing as well as the beams homogenization. A major challenge is the reduction of the so-called 'speckle' effect. This effect introduced fixed random pattern noise effects in imaging applications due to the local interference of the coherent LASER Light. Finally, another challenge is the developing of the right hardware to control the LASER diodes.

Design specifications will be discussed. Also, implementation procedure including electronic design, software interface, light multiplexing method will be presented in detail. In the end, technical validation of the coherent light source will be presented including stability of the source, spectral emission and intensity control of the laser via PWM without losing lasing. Also, several applications in which the light source could be used will be depicted.

The following figure illustrates a general overview of the device. Components and analysis will be the subject of this chapter and the following paragraphs.

Figure 136 – The Incoherent Light Source

5.1 Design Specifications

There is a huge technology gap in coherent light sources designed for medical applications like microscopy and endoscopy. In previous chapter, various coherent light sources were presented which are used in several medical, scientific or general applications. These coherent light sources haven't got the best balance of simultaneously emitted wavelengths, high optical power and low cost. For example, super continuum laser, which is a gas laser, has got a broadband emission spectrum and with various optical filters, several wavelengths could be transmitted. But its drawbacks are that several wavelengths could not emitted simultaneously without expensive and complicated modules and they cost a lot for just a few milliwatts.

Our goal is to develop a coherent light source for scientific and medical applications having laser modules with selected emission wavelengths that could be useful for various applications for example exciting as much as possible Alex Fluor family of fluorescent dyes (Alexa Fluor is a family of fluorescent dyes that used as cell and tissue labels in fluorescence microscopy and cell biology).

Nevertheless, someone might say why you develop a coherent light source after you already developed an incoherent light source which easily could emit the same and more wavelengths. There are several reasons a coherent light source is a must be device for a medical or general scientific lab. For example, in bioinstrumentation, the requisite spot size for optimum operation depends on the type of instrument and then the specifics of the particular model. It can range from tens of microns in diameter, to several millimeters in size. Probably the most significant inherent difference between lasers and LEDs is in their ability to efficiently collect and focus their outputs to attain these desired spot sizes. This is because the output of a typical laser is a well-behaved, narrow, low-divergence beam. Such a beam behaves like an ideal, true point source. This means that all the source output can be collected and focused into the precise spot size needed by the application, minus, of course, any small losses due to scattering or reflection by the system optics. The only true limit on the minimum focused spot size of such a source is diffraction, which prevents a laser from being concentrated to a spot diameter that is much smaller than the laser wavelength. The ability to easily focus a laser beam to a small spot delivers the advantages of high intensity and high optical efficiency (lower cost per watt). It also enables the use of lower cost focusing optics. Moreover, the monochromaticity of lasers is a characteristic that is very important for several applications. In other words, lasers have spectral clearance. In general, they generate light in a very narrow band around a single central wavelength. Monochromatic output is of great important for lasers being used in interferometric measurements, remote sensing for specific chemical constituents or in high resolution spectroscopy to observe specific transitions in a molecule. Also, an application in which spectral clearance is of great importance is fluorescence. In fluorescence, excitation and emission spectra of several fluorescent dyes are often overlapping. So, we need very narrow spectral band excitation light as a way to be sure that what we see in the examination is emission and not the excitation itself. In these conditions, LEDs are not applicable even more with the narrowest optical filters. Great optical power is needed and spectral clearance. Thus, the most sure and right way are lasers.

Considering all the above factors, our overall goal is to develop a computer controlled Coherent Light Source emitting multiple application targeted narrow-band wavelengths simultaneously, having high optical power and the lower cost possible.

Thus, the design specifications of our incoherent light source are the following:

- Laser module optical power up to 1Watt
- Designing high efficiency Laser drivers
- Light multiplexing using a liquid light guide
- Selected Wavelengths: The most challenging part of the design is the available laser wavelengths we are going to choose for the Light Source. The purpose is developing a device that has got the minimum number of available wavelengths that cover several fluorophores because this source is targeted mostly in fluorescence. Firstly, we need to cover the most famous fluorophores that used in our projects. The fluorophores we would like to cover are four. DAPI (excitation peak at 350nm), FITC (excitation peak at 490nm), Alexa 555 (excitation peak at 555nm) and Alexa 633 (excitation peak at 633nm). After searching for diode lasers that have got a good ratio of optical power to cost and they could excite the above fluorophores, we finally ended up in four laser diodes with 405nm, 450nm, 532nm and 635nm emission wavelengths respectively. Bellow five graphs are presented, each for one of the lasers we selected and some common fluorophores that they could excite.

405nm Laser diode

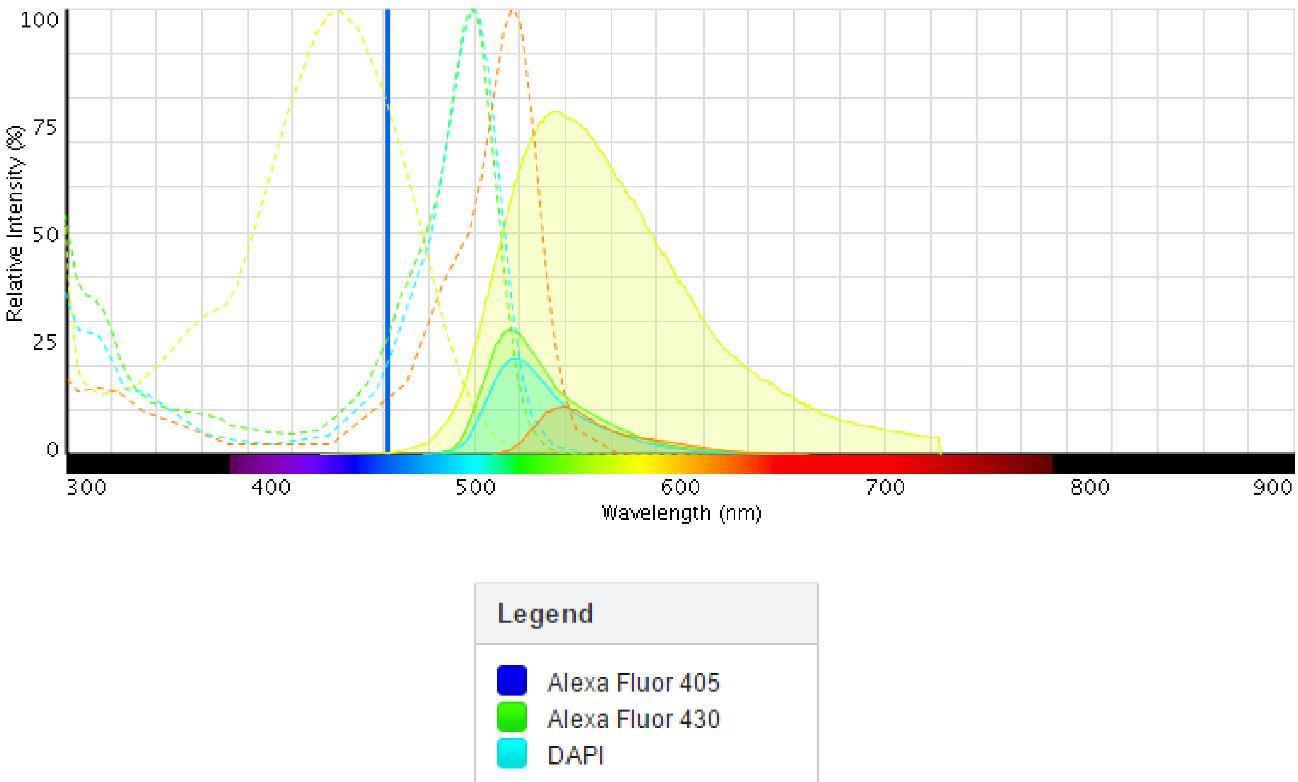


Figure 137 – Fluorophores excited by 405nm laser diode

450nm Laser diode

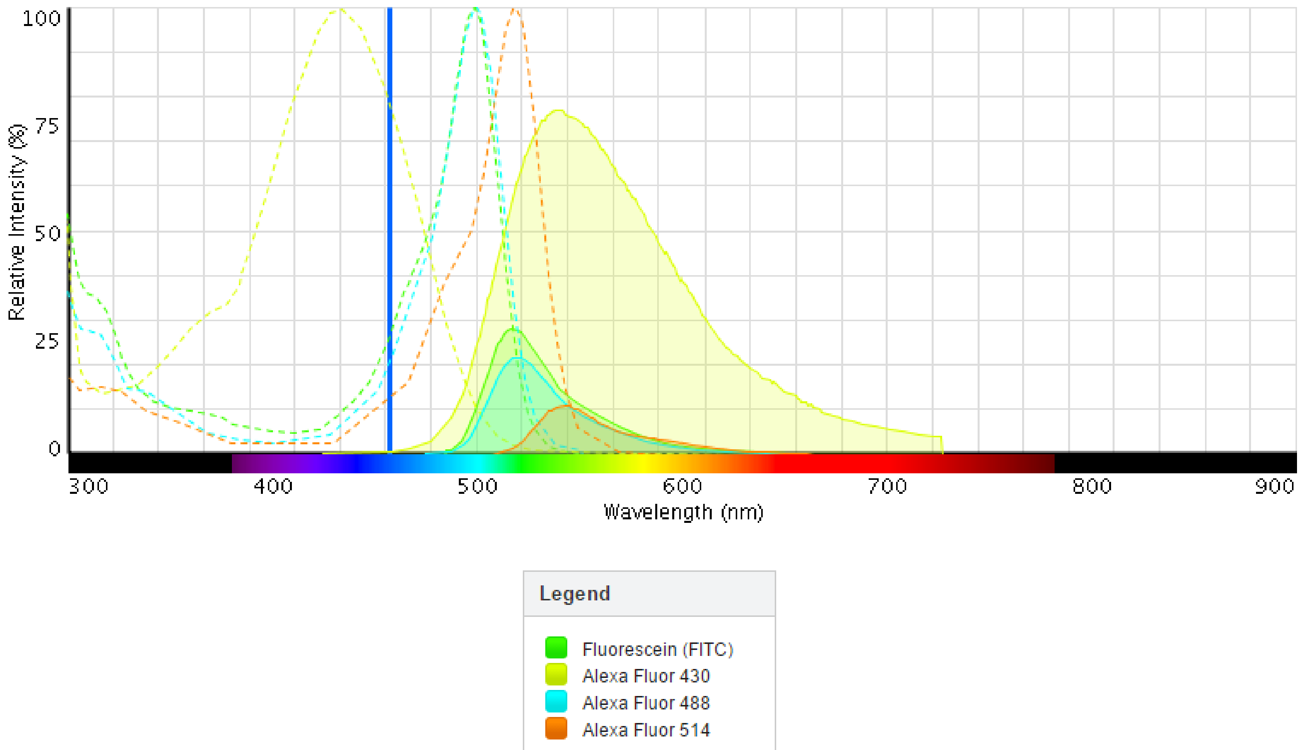


Figure 138 – Fluorophores excited by 450nm laser diode

532nm Laser diode

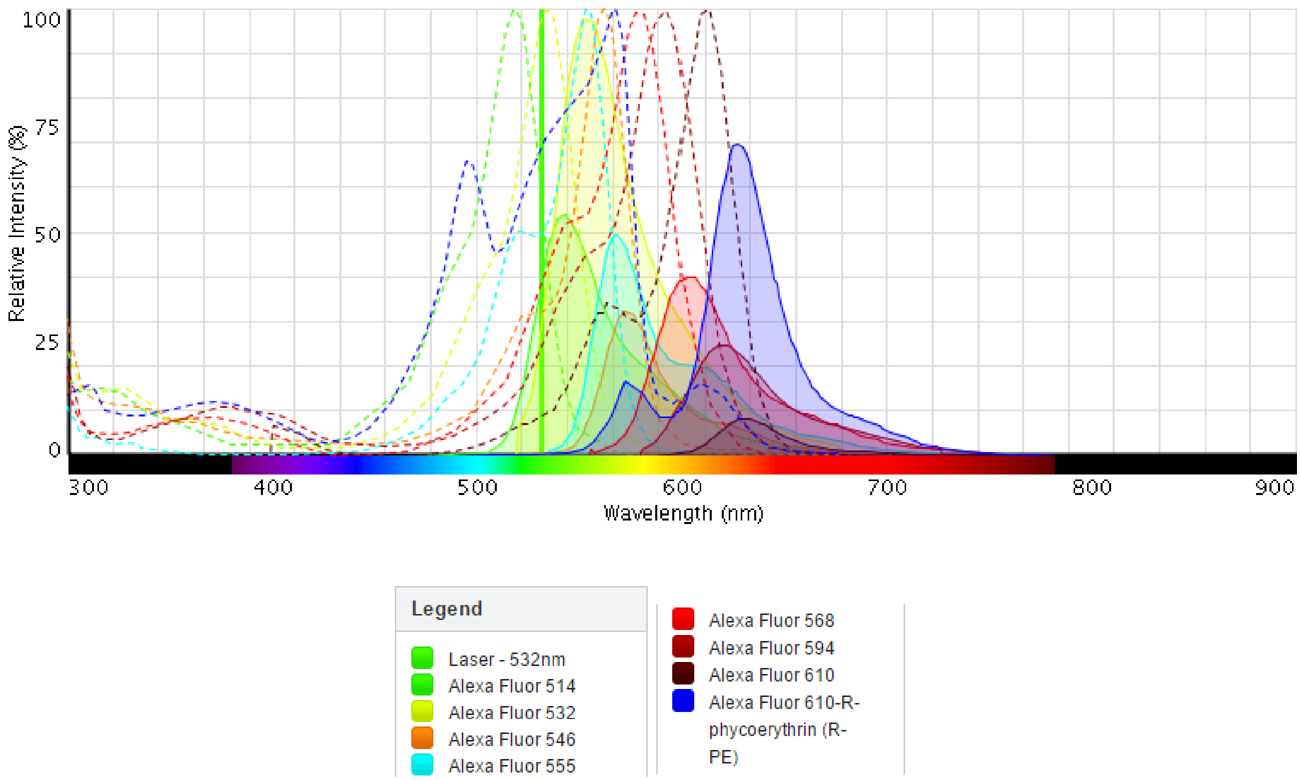


Figure 139 – Fluorophores excited by 532nm laser diode

635nm Laser diode

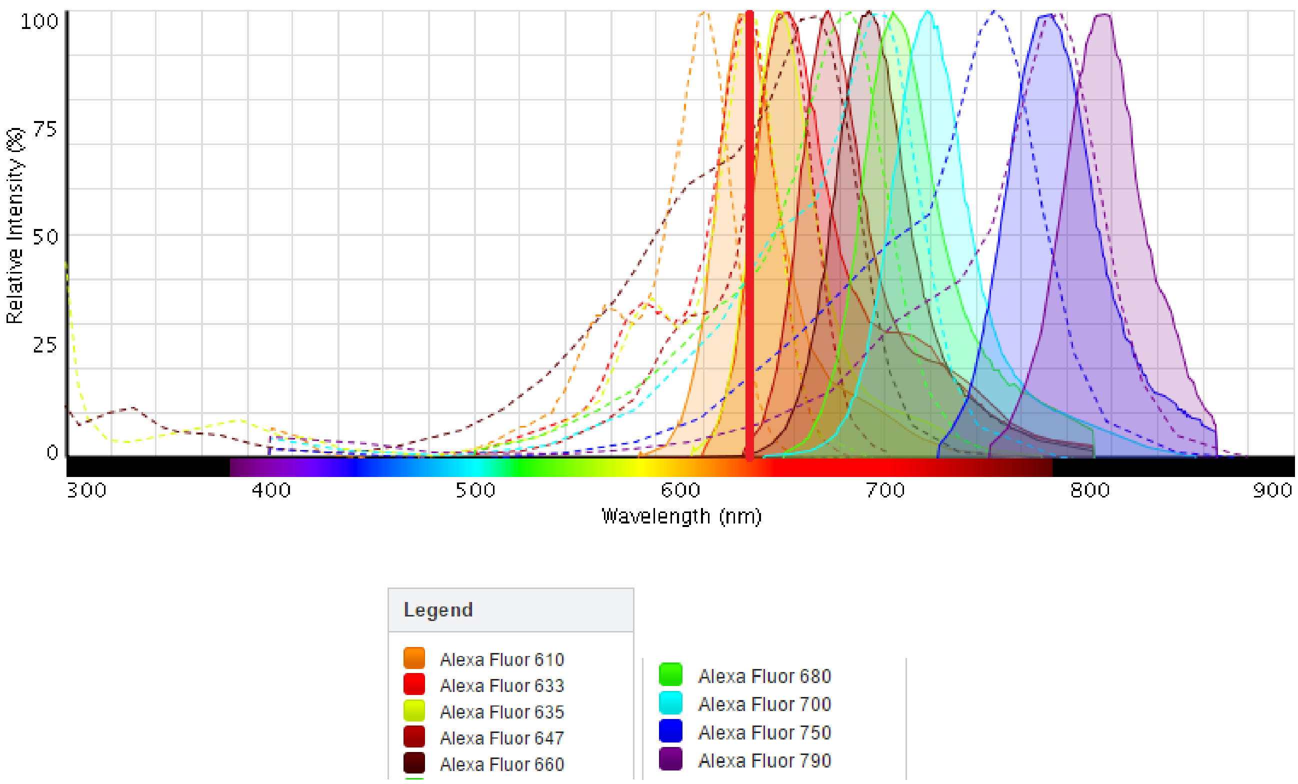


Figure 140 – Fluorophores excited by 635nm laser diode

5.2 Implementation

5.2.1 Laser components

In the previous paragraph, we analyzed the factors that lead us to select 405nm, 450nm, 473nm and 635nm laser light wavelengths. What remains is to choose the type of Laser we are going to use in the development of the Coherent Light Source.

As mentioned in a previous chapter, there are several types of lasers available like solid-state, gas, dye and diode lasers. The types of lasers we are going to use us diode lasers because compared to most laser types, diode lasers are less expensive and more compact making them ideal for small electronic devices. Using another type of laser for example helium-neon lasers or another type of gas laser increases the size of these devices by as much as five times. Diode lasers use much less power than most types of lasers. While gas and solid-state lasers require a power supply in kilo-volts, diode lasers typically run on small voltage. Nevertheless, due to continuous development in laser diode technology, laser diodes have been developed that have got high optical power. So, the diode lasers chosen are the following:

5.2.1.1 405nm Laser Diode

The Sony SLD3237VF continuous wave laser diode is very efficient and has a 200mW optical output power. The diode structural material is the gallium nitride crystal. Also, it's guaranteed high-temperature operation up to 85^{o} C assures reliability at high temperature operation. Its operating voltage is 5V and operating max current is 260mA. The package of the laser diode is the TO-38 (5.6mm). It's working life is more than 10000 hours.

Figure 141 – Sony SLD3237VF Laser Diode

5.2.1.2 450nm Laser Diode

The LD-450-1600MG by Roithner is a continuous wave laser diode is very efficient and has a 1600mW optical output power. The diode structural material is the gallium nitride crystal. Also, it's guaranteed high-temperature operation up to 70° C assures reliability at high temperature operation. Its operating voltage is 4.8V and operating max current is 1.5A. The package of the laser diode is the TO-38 (5.6mm). It's working life is more than 10000 hours.

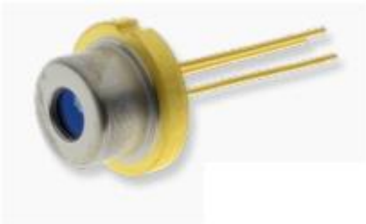


Figure 142 – Roithner LD-450-1600MG Laser Diode

5.2.1.4 532nm Laser Diode

The HK-E03421 by Laserpointerpro is a continuous wave laser diode and has a 200mW optical output power. The diode structural material is YGA. Also, it's guaranteed high-temperature operation up to 40° C assures reliability at high temperature operation. Its operating voltage is 3V and operating max current is 1A. The package of the laser diode is a laser pointer package. The laser pointer disassembled in our lab and only the laser diode package left TO-38 (5.6mm). It's working life is more than 10000 hours.

Figure 143 – Laserpointerpro HK-E03421

5.2.1.5 635nm Laser Diode

The RTL635-150-TO3 by Roithner is a continuous wave laser diode, is very efficient and has a 150mW optical output power. The diode structural material is AlGalnP. In contrast to the other diode lasers which could operate in high temperatures, RTL635-150-TO3 laser diode cannot operate in high temperatures and the diode must have a temperature between 10° C and 25° C. When operating over the temperature range there is a loss of 20% in optical output power. For this reason, we must keep the laser module temperature in the operating temperatures that manufacturer suggests. The expected lifetime is the half of the laser diode's lifetime and it is expected at

10000 hours but it can be shortened by high temperatures. The operating voltage is 2.3V and operating max current is 650mA. The package of the laser is TO3.

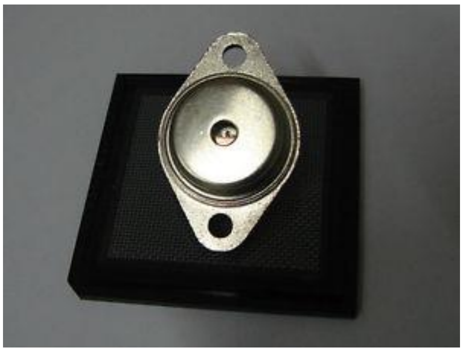


Figure 144 – Roithner RTL635-150-TO3 Laser Diode

5.2.2 Laser Driving Board Implementation

Laser driving board is the main control board of the device. Its purpose is enabling/disabling the laser components of the system. Laser driving board is the most important part of the hardware assembly. Laser components must be supplied with the correct voltage and current at a constant flow.

The specifications of the Laser Driving board are:

- Input Voltage Vin=12V
- Four (4) outputs for Laser components power supply
- Four (4) inputs for manual enabling/disabling Lasers using push buttons (located in the front panel of the case)
- One (1) input for selecting manual (via front panel push buttons) or computer control of Lasers using a rocket switch which is located in the rear panel of the case

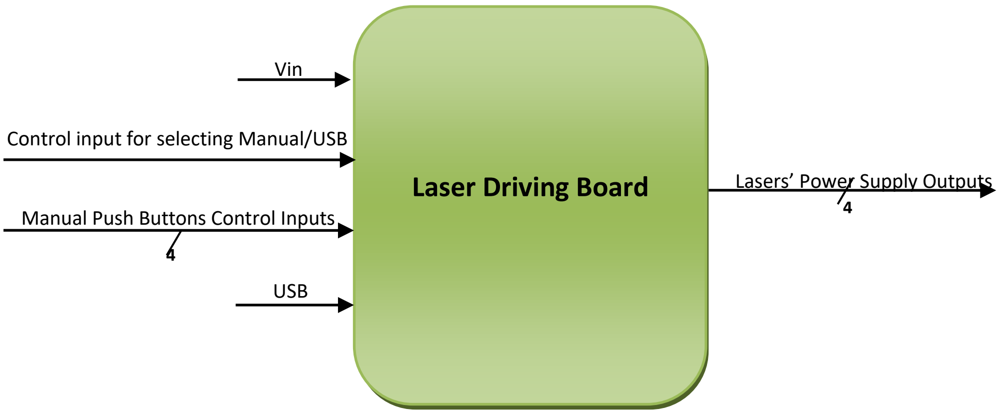


Figure 145 – Laser Driving Board - Black Box

The most important part of the laser driving board circuit is the power supply and control of the Laser components. The power supply must be very accurate, very efficiency with low working operation temperatures. What we need for this circuit is a voltage regulator and an electronic switch that will power on and power off the laser according to the command sent by the microcontroller. This electronic switch will be a very efficient power MOSFET. It's time to present the electronic components that we choose for developing the Lasers' power supply and control circuit. The selection on the following components was based on high quality, high efficiency, high accuracy and small dimensions.

Voltage Regulator PTN78000WAH by Texas Instruments

Figure 146 – Voltage regulator PTN78000 series

The PTN78000WAH is a wide input adjustable switching regulator. The PTN78000W is a series of high efficiency, step down integrated switching regulators. Operating from a wide input voltage range, the PTN78000 provides high-efficiency, step-down voltage conversion for loads up to 1,5A. The output voltage is set using a single external resistor within the range 2,5V to 12,6V. The PTN78000 has undervoltage lockout and an integral on/off inhibit. The modules are suited to a wide variety of general-purpose applications that operate off 12-V, 24-V, or 28-VDC power. Also, PTN78000W does not develop high temperatures during operation like the linear voltage regulators, so does not need any heat dissipation assembly due to switching technology.

Voltage Regulator PTN78020WAH by Texas Instruments

Figure 147 – Voltage regulator PTN78020 series

The PTN780020WAH is a wide input adjustable switching regulator. It's in the same family with the PTN78000WAH. The PTN78020WAH is a high efficiency, step down integrated switching regulators. Operating from a wide-input voltage range, the PTN78020 provides high-efficiency, step-down voltage conversion for loads of up to 6 A. The output voltage is set using a single, external resistor. The PTN78020W may be set to any value within the range, 2.5 V to 12.6 V. The output voltage of the PTN78020W can be as little as 2 V lower than the input, allowing operation down to 7 V, with an output voltage of 5 V. Also, PTN78060W does not develop high temperatures during operation like the linear voltage regulators, so does not need any heat dissipation assembly due to switching technology.

Power NPN MOSFET IRFZ44N by Infineon Technologies

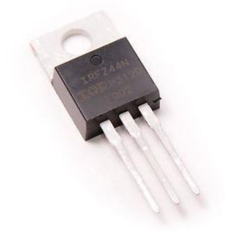


Figure 148 – Power MOSFET IRFZ44N

The IRFZ44N by Infineon Technologies utilize advanced processing techniques to achieve extremely low on-resistance per silicon area. This benefit, combined with the fast switching speed and ruggedized device design that HEXFET power MOSFETs are well known for, provides the designer with an extremely efficient and reliable device for use in a wide variety of applications. The TO-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry. About absolute maximum ratings V_{DSS}=55V, $R_{DS(on)}$=17.8mΩ and I_D=49A. Finally, as a way to make the MOSFETs more efficient TO-220 heatsinks it is preferred to be used.

Combining PTNs and MOSFET for a constant high efficient Laser driver

The combination of a PTN module and a MOSFET leads to an ultimate Laser driver with high efficiency, great stability and low operation temperatures.

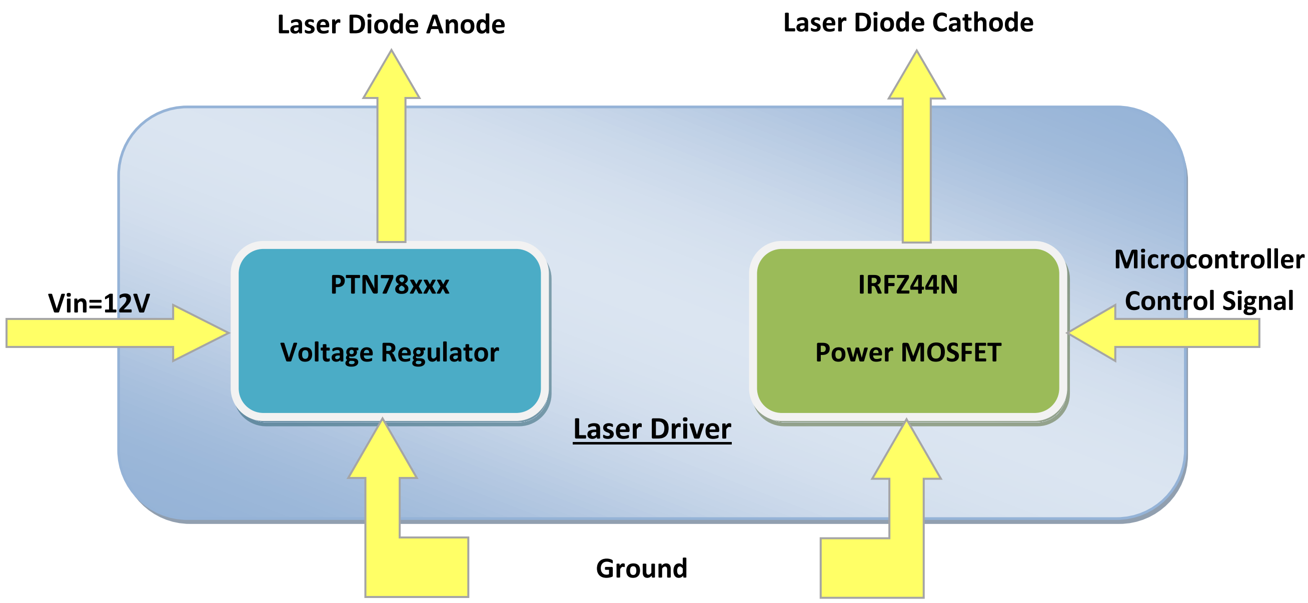


Figure 149 – Basic structure of Laser driver

With the above configuration, we cover the need in voltages and currents that each laser component consumes. The procedure of driving a Laser is as follows:

1. The microcontroller controls the Gate of the MOSFET (5V->ON, 0V-> OFF).
2. The Output of the MOSFET is connected with the Cathode of the Laser Diode.
3. The PTN78xxx voltage regulator is connected to the common input voltage of 12V.
4. The output of the voltage regulator is connected with the Anode of the Laser Diode.

5. Both components are connected to Ground.

In our project as already presented in the previous paragraph we are going to use four (4) Laser Diodes. Two of them, 405nm and 450nm laser diodes, have got the same forward voltage (V_F). So, for saving space and reduce cost one voltage regulator will be used for both 405nm and 450nm laser diodes. Thus, the circuit will be comprised of three (3) voltage regulators, 2xPTN78000WAH and 1xPTN78020WAH, and four (4) MOSFETs. The PTN78020WAH (6A max) will be used for powering the two common voltage laser diodes.

Microcontroller

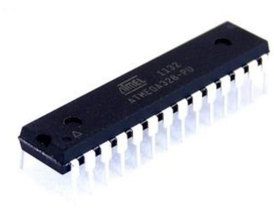


Figure 150 – ATmega328

A microcontroller is needed to control and synchronize all the signals of the system. Its goal is to control directly the power MOSFETs and indirectly the laser diodes.

The model used is the Atmel AVR ATmega328, 8-bit microcontroller, which covers the needs sufficiently. The microcontroller was mounted and preassembled on a development board. A development board also consists of complementary components to facilitate programming and incorporation into other circuits. The board includes a 5-volt linear regulator and a 16MHz crystal oscillator. The microcontroller is pre-programmed with a bootloader so that an external programmer is not necessary. The interface with the computer is done through USB connection, which is downgraded to USB-to-serial, and supportive adapter chips on the board.

Additional features of the board

Front Panel Push Buttons

We choose two ways of controlling the laser diodes. One way is via USB connection to a PC using a software that we developed. The second way gives the ability to the user to enable or disable the lasers using push buttons. Push buttons will be fixed in the front panel of the case. The push buttons are connected as inputs to the microcontroller. The microcontroller reads the button's state and enables or disable the current laser. Each time only one way could be enabled due to safety reasons.

Rear Panel Rocket Switch

Regarding the two ways of controlling the laser diodes as presented in the previous paragraph, the microcontroller must know which way has been chosen by the user, so as to run the correct commands. The solution to this problem is a rocket switch that is connected as input to the microcontroller. Depending on the state of the rocket switch the USB or push button control way is enabled or disabled.

PCB Design

Combining all the above designs and features we proceed to the schematic design of the driving board, using the program for PCB design that is called Altium Designer. Also, we designed the footprints of all electronic components. The footprint design of each component was based on the manufacturer's recommended soldering pad pattern.

Immediately after completion of the schematic design of the driving boards we proceed to the PCB design of the driving board. The PCB design is the most important step. Many features and techniques must be kept in mind while designing. From conductive track's width to the best arrangements of electronics on the board.

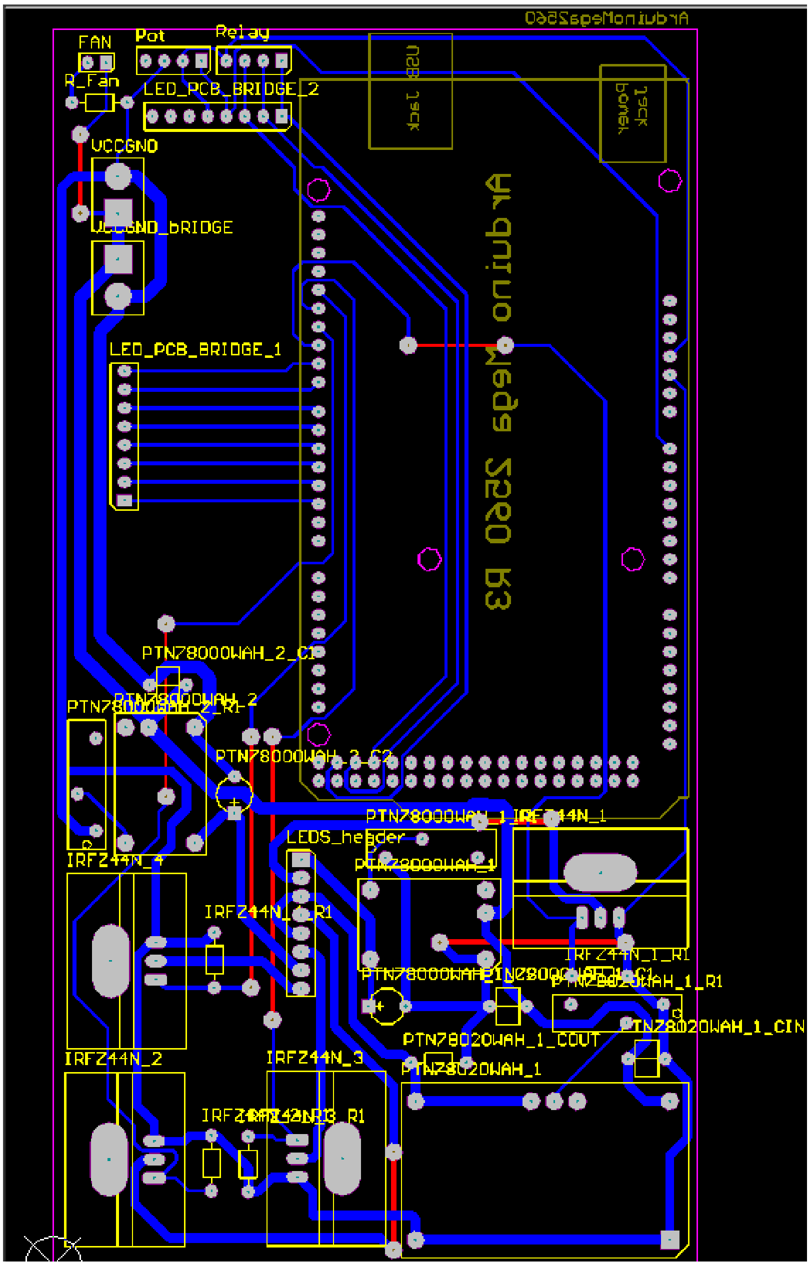


Figure 151 – Laser Driver PCB Design

After the completion of th PCB device the next step is printing the circuit board. Then, the printed board is drilled where it needs and components are soldered on the board. The driving board after all steps completed, is the following:

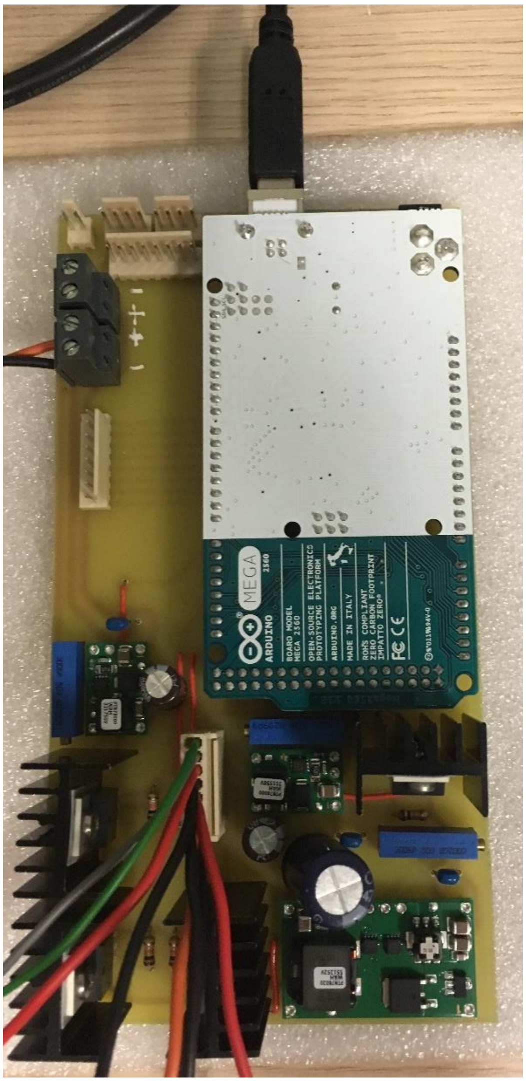


Figure 152 – Laser Driving Board

5.2.3 Programming the microcontroller

The microcontroller used in the development of the Coherent Light Source is the Atmel AVR ATmega328 which is mounted and preassembled on a development board. In few words, microcontroller executes the following tasks. At first, the microcontroller sets all the outputs and inputs. Next, microcontroller reads the Rocket Switch's state. If the state is HIGH then we are in USB control mode, else if the state is LOW then we are in PushButton control mode. While in USB control mode, microcontroller waits to receive via serial characters that are the commands which enable or disable the current laser. Then the program goes to the start again. While in Push Button control mode, microcontroller read the states of each pushbutton and enables or disables the current LED. All the above are nicely illustrated in the following flow chart:

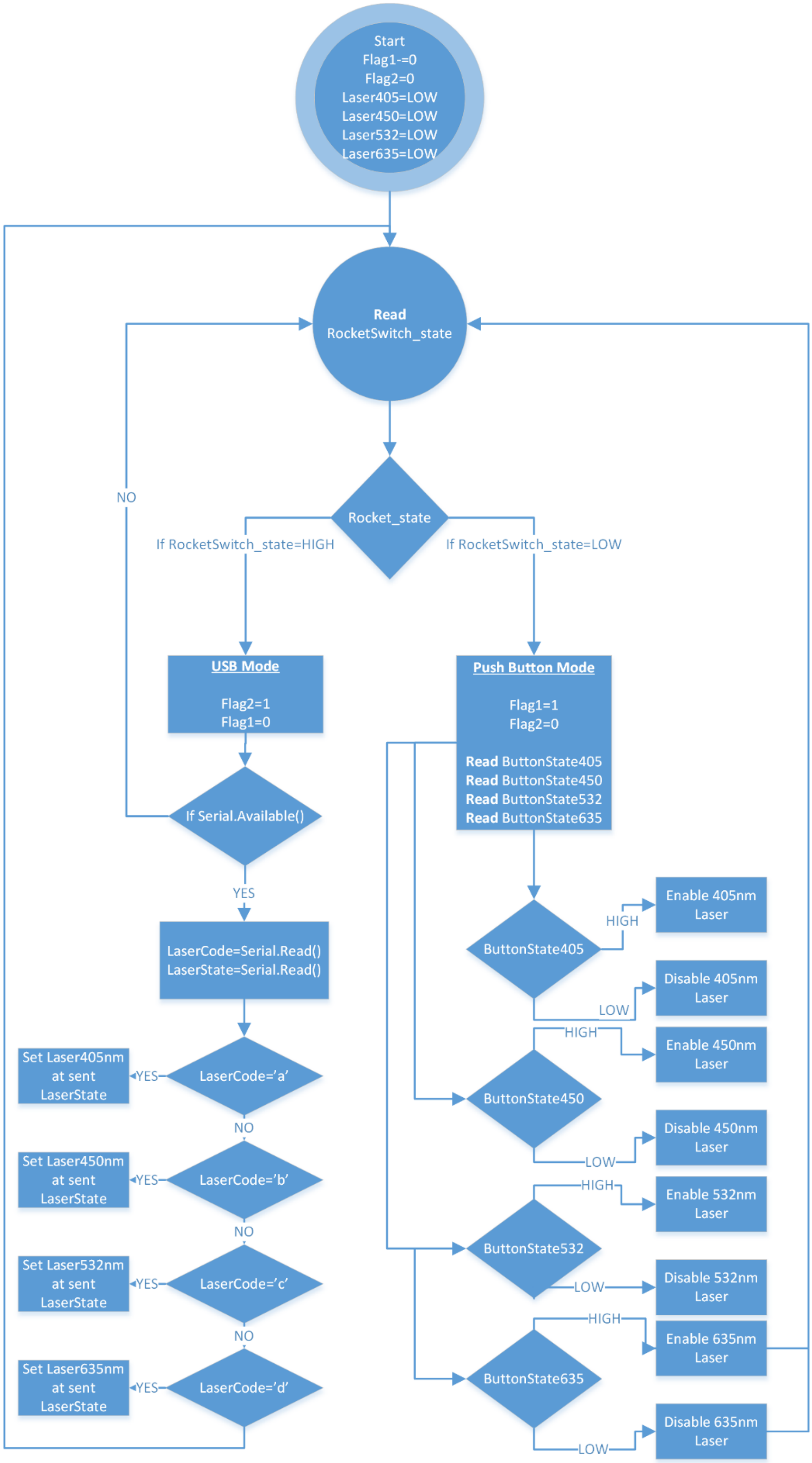


Figure 153 – Flowchart of microcontroller program

5.2.4 Software interface via USB

While the device is in USB control mode, the device communicates with a PC via USB cable. For this reason, a simple Graphical User Interface (GUI) has been developed. While designing the GUI we had in mind that the interface should be user-friendly while keeping the whole functionality of the light source. GUIs provide point-and-click control of software applications, eliminating the need to learn a language or type commands in order to run the application.

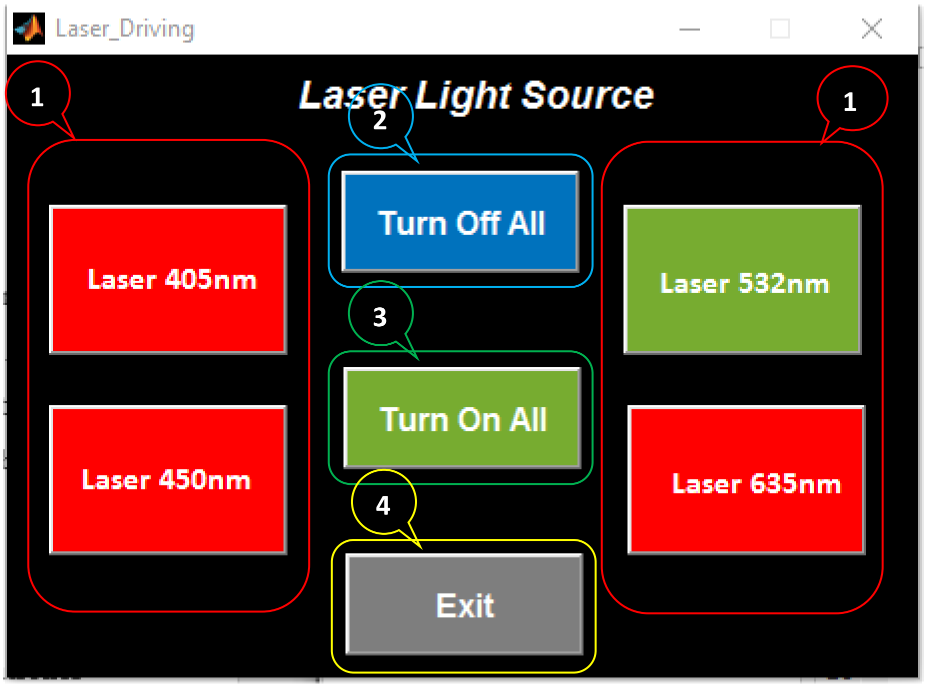


Figure 154 – GUI of Coherent Light Source

GUI Breakdown

1. **Laser Control Buttons**: When the user pushes the button the GUI the current LED is enabled or disabled. If its previous state is off (red button filling) when pushing button the button turns green and the current laser is enabled. Similarly, if the previous state is on (green button filling) when pushing button, the button turns red and the current laser is disabled.
2. **Turn off All Lasers button**: When the user presses this button all the lasers are disabled and the Laser button fillings get red.
3. **Turn on All Lasers button**: When the user presses this button all the lasers are enabled and the Laser button fillings get green.
4. **Exit button**: When the user pushes this button the GUI and the connection between the microcontroller are terminated.

5.2.3 Laser components' spatial arrangement and light multiplexing

Another important part of the development of our coherent light source is how the four laser beams will be multiplexed. First of all, one challenge is the laser beam manipulation as a way all the four laser beams to fall into the same point in space. The second challenge is how the laser beams will be transmitted together out of the device enclosure. The thirds challenge is developing a compact design that will help to keep the portability of the light source.

About the manipulation of the laser beams as a way to fall on the same point in space we developed a mechanical part for fixing the laser components on it. This mechanical part has been fully designed and constructed in our lab. This mechanical part is cyclic with a hole in the center and seven bases on the perimeter of the semicircular course. In this version of the light source only the three bases will be occupied. The green laser at 532nm will be fixed in the center hole. The other three lasers will be fixed in the three bases over a kinematic mount. Kinematic mounts offer an angular displacement range of ±4°. The lasers' spots will fall in the same point about 20cm away from the cyclic mechanical component, its center will be collinear with the green laser component 532nm and its diameter will be no more than 10mm. So, the laser diode 532nm hits the center of the common point. To manipulate the other three laser beams, because the laser components are fixed vertical to the straight line that passes through the common point, we must bend them so as to fall in the common point. The bending is accomplished using right angle prisms and the kinematic mount. Miniature Right Angle Prisms are typically used to bend image paths or for redirecting light at 90°. The right-angle prisms are fixed as close around the hole where 532nm laser diode is fixed with the hypotenuse of each right-angle prism looking at the current laser diode beam spot. Kinematic mount denotes the indent angle of each laser beam on each prism's hypotenuse.

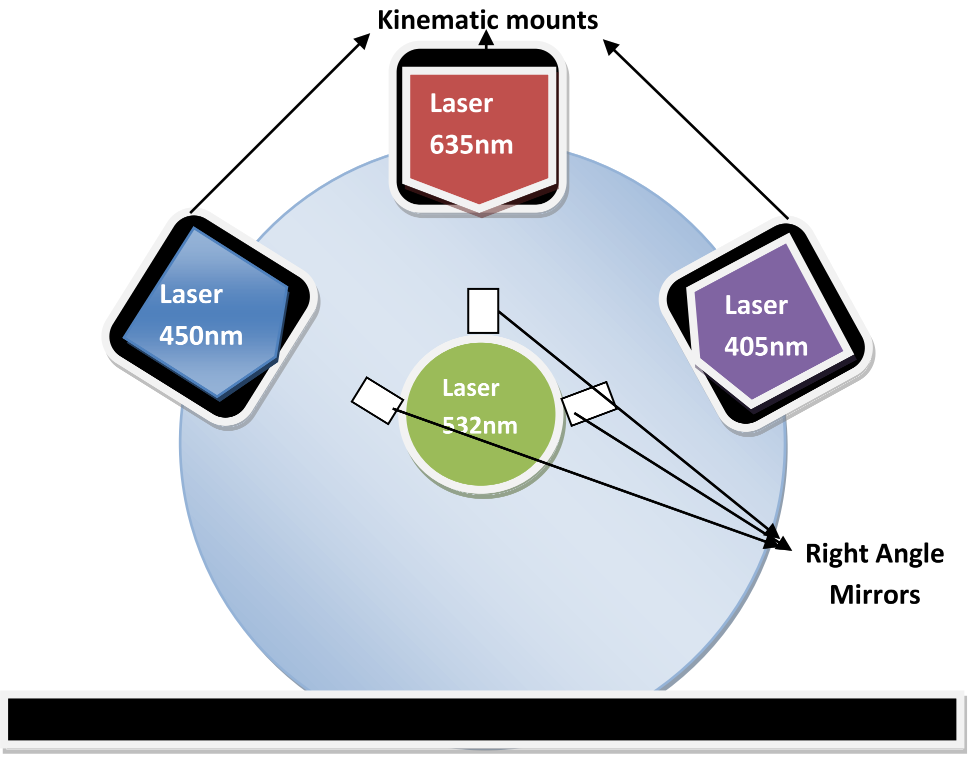


Figure 155 – Front of the mechanical part.

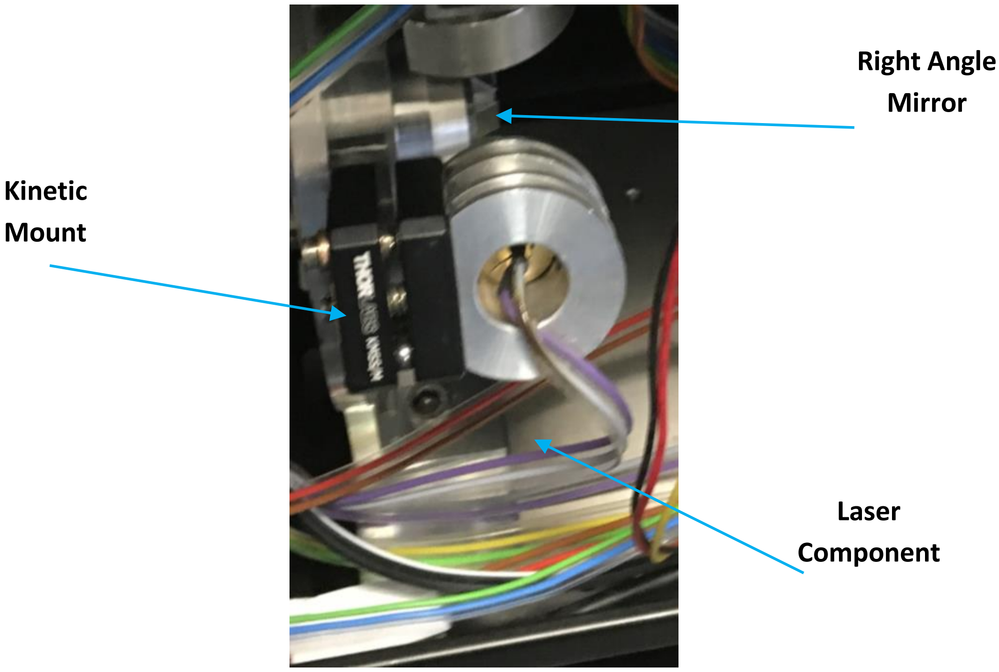


Figure 156 – Laser beam manipulation mechanism.

Using the two adjusters of the kinematic mount we adjust current laser's spot to fall with the correct incident angle on the hypotenuse of the prism, so as the spot of the laser to fall on the common point on which all laser's spots must fall.

In the common spot point liquid light guide is fixed with a diameter of 10mm. So, the lasers' spots will fall on the liquid's light guide tip. Thus, the light will be transmitted to the other tip of the liquid light guide with a touch of homogenization. We used a liquid light guide become due its technology the different laser light wavelengths are homogenized at the end tip and the light guide itself is easy to manipulate and coupled in various devices and applications, like microscopy. Bellow the whole assembly of multiplexing the laser beams is illustrated:

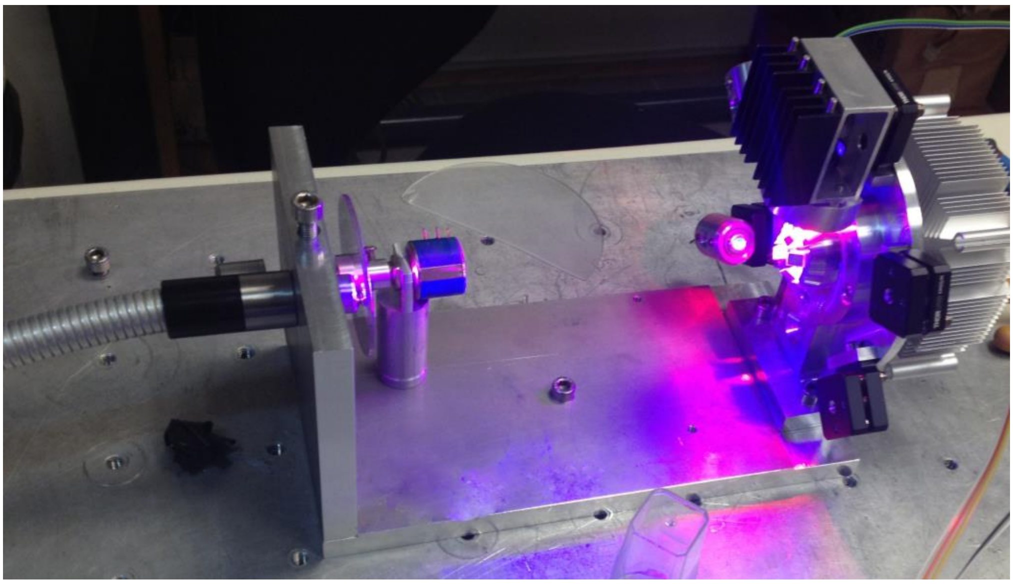


Figure 157 – Laser beam manipulation assembly.

Figure 158 – Liquid Light Guide

5.2.4 Speckle Reduction

Speckle is a random granular pattern which observed when a highly coherent light beam is diffusely reflected at a surface with a complicated (rough) structure such as a piece of paper. Our Coherent Light Source because is coherent suffers from this phenomenon. Before presenting our solution for speckle reduction a short description of the speckle phenomenon is presented.

Temporal and Spatial Coherence [30, 31]

The study of the physics of coherent properties of light is a fascinating topic with many surprises and unexpected behavior. In the previous chapters, coherent and incoherent light sources presented and the distinction between coherence and incoherence has been mentioned. However, coherence is never absolute. There is no such thing as completely coherent or incoherent light source. For example, incandescent light bulb has residual coherences on short time and space scales. Even black body radiation, if it passed through a narrow-bank filter, has coherence properties. Similarly, laser light, though highly coherent, has space and times beyond which its coherence properties fade.

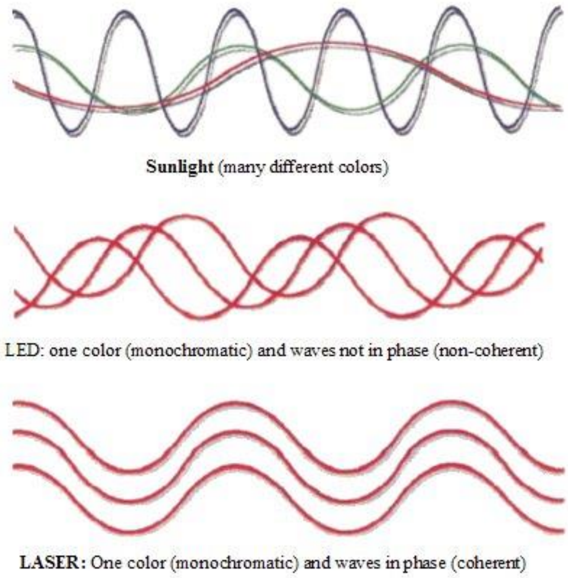


Figure 159 - Coherent and Incoherent light waves

In chapter 1, coherence has been presented in a very generic way and understandable way. Now coherence is time to presented in detail.

All light is partially coherent, which is to say that there are characteristic time and length scales within which interference effects occur and outside of which they do not. These scales are called coherence times and coherence lengths. The more coherent a light source is, the longer the coherence times or lengths. What determines the degree of coherence of a light source is the range of different waves that add through superposition to make up the light wave. This range of different waves is called bandwidth. If light is made up of waves of different colors, then this bandwidth is called spectral bandwidth. If light is made up of different k-vectors of different directions, then this bandwidth is called angular bandwidth or spatial bandwidth. Spectral bandwidth determines the temporal coherence, while angular bandwidth determines spatial coherence. Temporal coherence describes the time scale over which interference effects can be observed, and spatial coherence describes the length scale over which interference effects can be observed.

Consider a light source that has a complex-valued frequency spectrum s(ω). The field from this source is

$$E(t) = \int_{-\infty}^{\infty} s(\omega) e^{-i\omega t} d\omega$$

The above equation is just a Fourier transform between E(t) and s(ω). The temporal coherence time of a pulse is related to the spectral bandwidth of the spectrum and the spatial coherence is related to the angular distribution of the field.

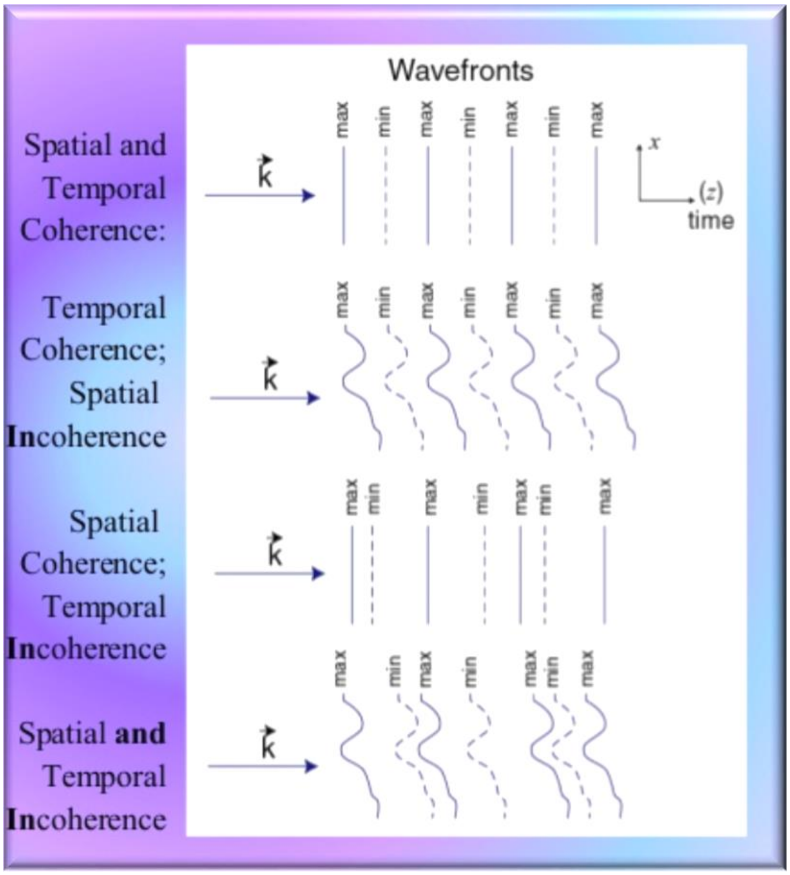


Figure 160 – Spatial and Temporal Coherence & Incoherence examples.

In other words:

- Spatial coherence is a measure of the correlation between the phases of a light wave at different points at right angles to the direction of propagation. Spatial coherence tells us how uniform the phase of the wave front is. It describes the correlation between signals at different points in space. Spatial coherence means a strong correlation (fixed phase relationship) between the electric fields at different locations. For example, within a cross section of a beam from a laser with diffraction-limited beam quality, the electric fields at different positions oscillate in a totally correlated way, even if the temporal structure is complicated by a superposition of different frequency components. **Spatial coherence is the essential prerequisite of the strong directionality of laser beams.**
- Temporal coherence is a measure of the correlation between the phases of a wave at different points along the direction of propagation or the predictable relationship between signals observed at different moments in time. Temporal coherence tells us how monochromatic a source is. Temporal coherence

means a strong correlation between the electric fields at one location but different times. For example, **the output of a single-frequency laser can exhibit a very high temporal coherence, as the electric field temporally evolves in a highly predictable fashion.**

Speckle phenomenon [31, 32, 33]

Speckle was discovered as an unexpected phenomenon when the first lasers were in operation, around 1960. It is a random intensity pattern that is produced by the mutual interference of a set of wave fronts.

Speckle patterns typically occur in diffuse reflections of monochromatic light such as laser light. Such reflections may occur on materials such as paper, white paint, rough surfaces, or in media with a large number of scattering particles in space, such as airborne dust or in cloudy liquids.

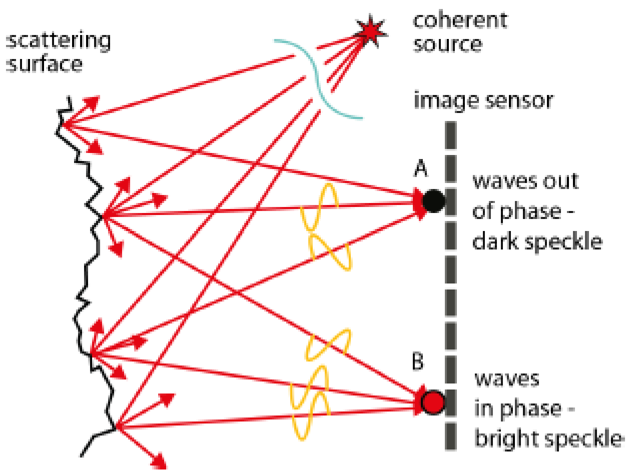


Figure 161 - The laser speckle phenomena. Light from a coherent light source scatter on a surface's microstructure and the resulting reflected waves reach an image sensor in different phases, due to differences in their travel paths.

The speckle effect is a result of the interference of many waves of the same frequency, having different phases and amplitudes, which add together to give a resultant wave whose amplitude, and therefore intensity, varies randomly. If each wave is modelled by a vector, then it can be seen that if a number of vectors with random angles are added together, the length of the resulting vector can be anything from zero to the sum of the individual vector lengths—a 2-dimensional random walk, sometimes known as a drunkard's walk. If the relative average group velocities change with time, the speckle pattern will also change with time. According to **diffraction theory**, each point on an illuminated surface acts as a source of secondary spherical waves. The light at any point in the scattered light field is made up of waves which have been scattered from each point on the illuminated surface. Speckle pattern is produced when the surface is rough enough to create path differences. If the surface is rough enough to create path-length differences exceeding one wavelength, giving rise to phase changes greater than 2π, the amplitude, and hence the intensity, of the resultant light varies randomly. If light of low coherence (i.e., made up of many wavelengths) is used, a speckle pattern will not normally be observed, because the speckle patterns produced by individual wavelengths have different dimensions and will normally average one another out. However, speckle patterns can be observed in polychromatic light in some conditions.

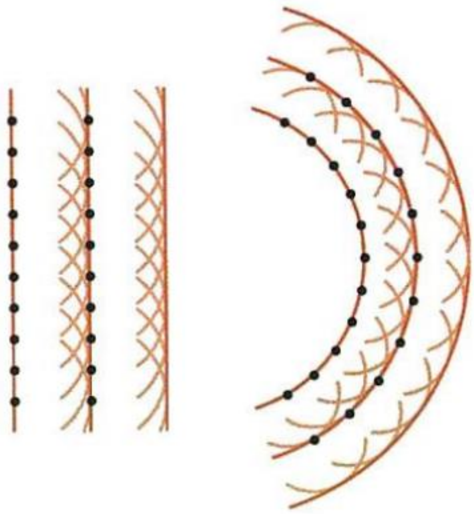


Figure 162 - Wave diffraction in the manner of Huygen's principle as modified by Fresnel: "Every unobstructed point on a wavefront acts, at a given instant, as a source of outgoing secondary spherical waves. The resulting net light amplitude at any position in the scattered light field is the vector sum of the amplitudes of all the individual waves."

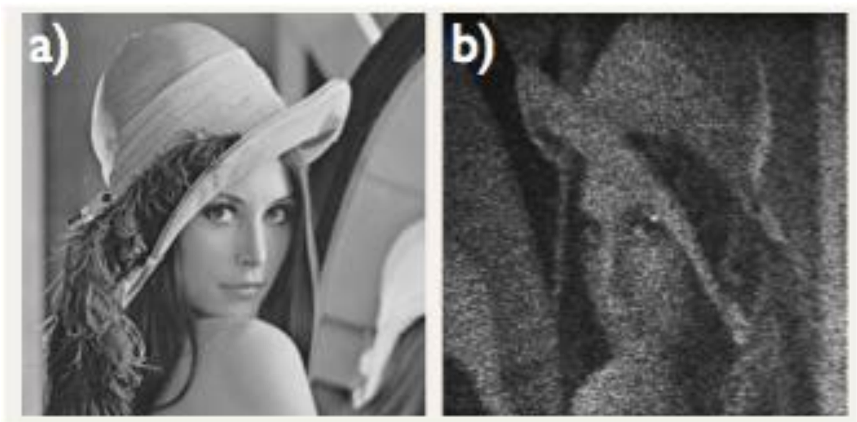


Figure 163 - a) Input image is fed into a display system b) Image with laser speckle noise, which could be an image that is displayed by a laser projector.

Subjective Speckles

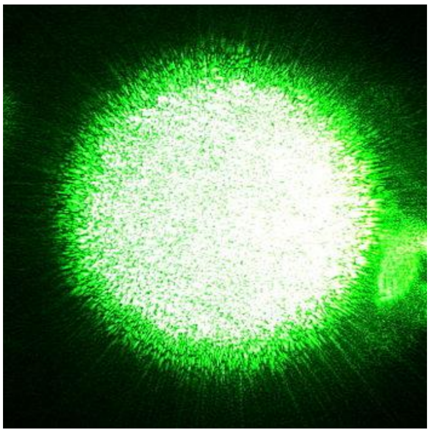


Figure 164 – Subjective Speckle Example

When a rough surface which is illuminated by a coherent light is imaged, a speckle pattern is observed in the image plane; this is called a “subjective speckle pattern” – see image above. It is called "subjective" because the detailed structure of the speckle pattern depends on the viewing system parameters; for instance, if the size of the lens aperture changes, the size of the speckles change. If the position of the imaging system is altered, the pattern will gradually change and will eventually be unrelated to the original speckle pattern. Also, each point of the image is illuminated by finite area in the object. The size of this area is determined by the lens which is given by the Airy disk whose diameter is 2.4λu/D (u is distance between the object and the lens and D is the Diameter of the lens aperture). The resolutions of the lens is limited by the diffraction. The change in speckle size with lens aperture can be observed by looking at a laser spot on the wall directly and then through a very small hole. The speckles will be seen to increase significantly in size.

Objective Speckles

When laser light which has been scattered off a rough surface falls on another surface, it forms an “objective speckle pattern”. If a photographic plate or another 2-D optical sensor is located within the scattered light field without a lens, a speckle pattern is obtained whose characteristics depend on the geometry of the system and the wavelength of the laser. The speckle pattern in the figure was obtained by pointing a laser beam at the surface of a mobile phone so that the scattered light fell onto an adjacent wall. A photograph was then taken of the speckle pattern formed on the wall. The light at a given point in the speckle pattern is made up of contributions from the whole of the scattering surface. The relative phases of these waves vary across the surface, so that the sum of the individual waves varies randomly. The size of the speckles is a function of the wavelength of the light, the size of the laser beam which illuminates the first surface and the distance between this surface and the surface where the speckle pattern is formed.

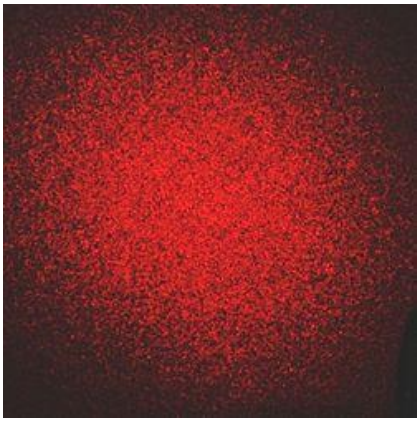


Figure 165 – Objective Speckle Example

Speckle contrast

The most popular method of speckle quantification is the speckle contrast (defined as the ratio of the standard deviation to the mean intensity) is an inherently pixel-centric method.

$$C_{speckle} = \frac{\sigma}{< I >} \leq 1$$

Ideal case = 1 | Completed blurred=0

Speckle reduction techniques

Speckle is considered to be a problem in laser based display systems like the Laser TV, laser confocal microscopy and in other scientific applications. As it is already mentioned before, speckle is usually quantified by the speckle contrast. Speckle contrast reduction is essentially the creation of many independent speckle patterns, so that they average out on the detector. There are several ways that this could be achieved like:

- Angle diversity: illumination from different angles
- Polarization diversity: use of different polarization states
- Wavelength diversity: use of laser sources which differ in wavelength by a small amount

Rotating diffusers could also be used to reduce the speckle. This technique destroys the spatial coherence of the laser light. Moving/vibrating screens may also be solutions. Also in scientific applications, spatial filters could be used or some special laser speckle reducers which dynamically diffusing the laser beam. The above techniques use very expensive parts.

Speckle reduction in our Coherent Light Source

The above speckle reduction techniques that presented are very expensive to get them. In our Coherence Light Source, a new simple method using vibrating diffuser interposed in the laser beam's path is introduced with terrific results with a very low cost. The vibrating diffuser destroys partially the coherent nature of the laser beam, thus minimizing interference effects and reduce the speckle phenomena. The cost of the vibrating diffuser, which is consisted of a diffuser and a vibration motor, is under 100 euros, in contrast to several speckle reduction products which cost over 600 euros. The results are excellent and a strong speckle reduction takes place. These results will be presented in detail in next subsection.

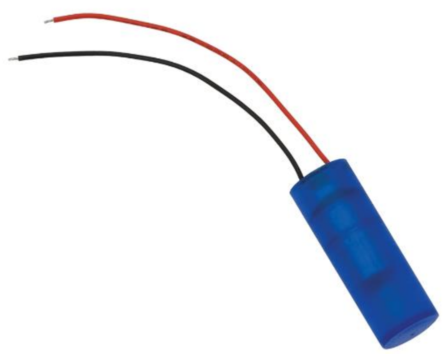


Figure 166 – Vibration Motor

5.2.5 Light Source Enclosure

After the completion of the hardware implementation, all the parts must be enclosed in a case that has the available space for the various components to fit in and is designed to impress. Bellow there are some photos from the final device where the case wins the impressions.

Figure 167 – The Coherent Source Emitting

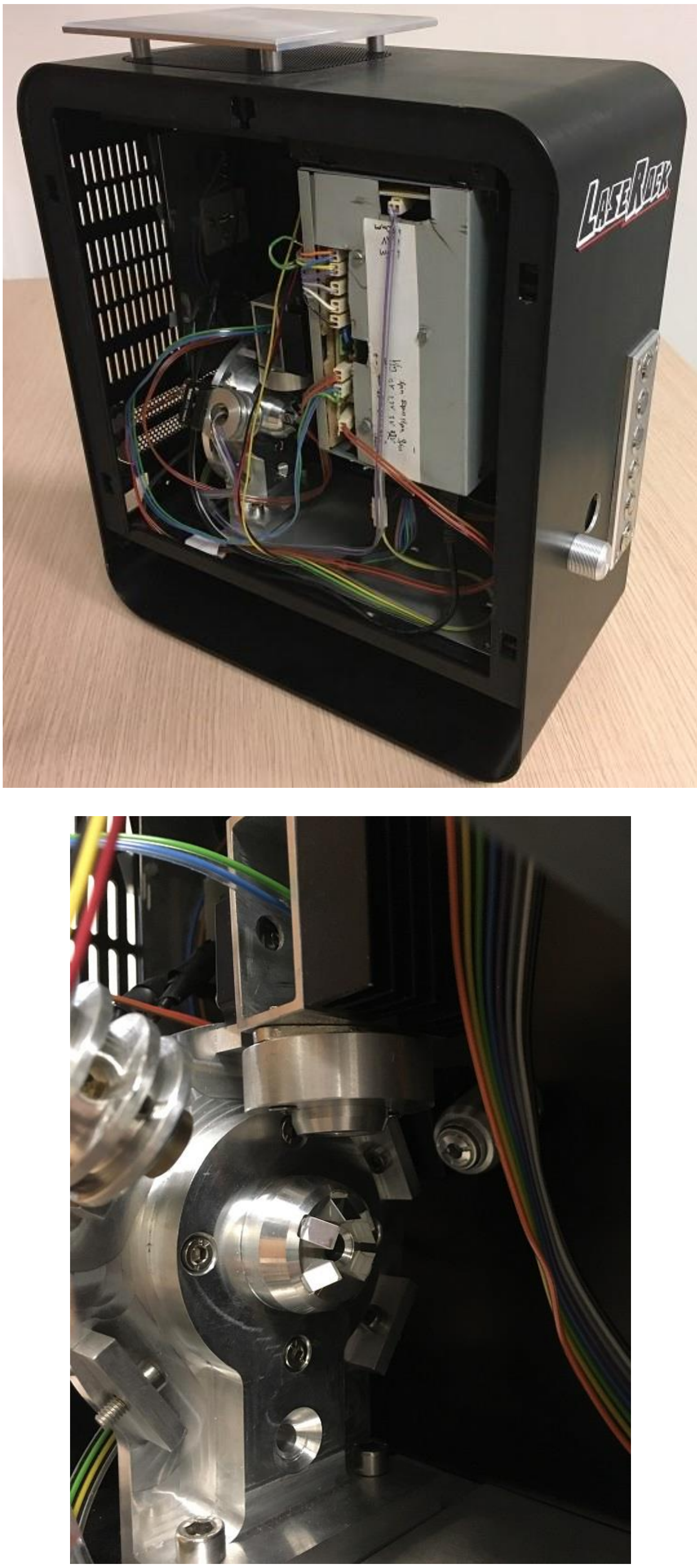


Figure 168 – Internal Structure

Figure 169 – Front panel and Rear panel. In the front panel the push buttons that control the laser diodes in non-USB mode are located. Looking at the rear panel, there is the central switch, the USB port for connecting with the PC, the rocket switch with which push button control or USB control of the laser diodes is selected, and the power jack.

5.3 Technical Evaluation

5.3.1 Laser spectra

Using the spectrometer, the four lasers' emission spectrum has been measures and it is illustrated bellow in the same plot:

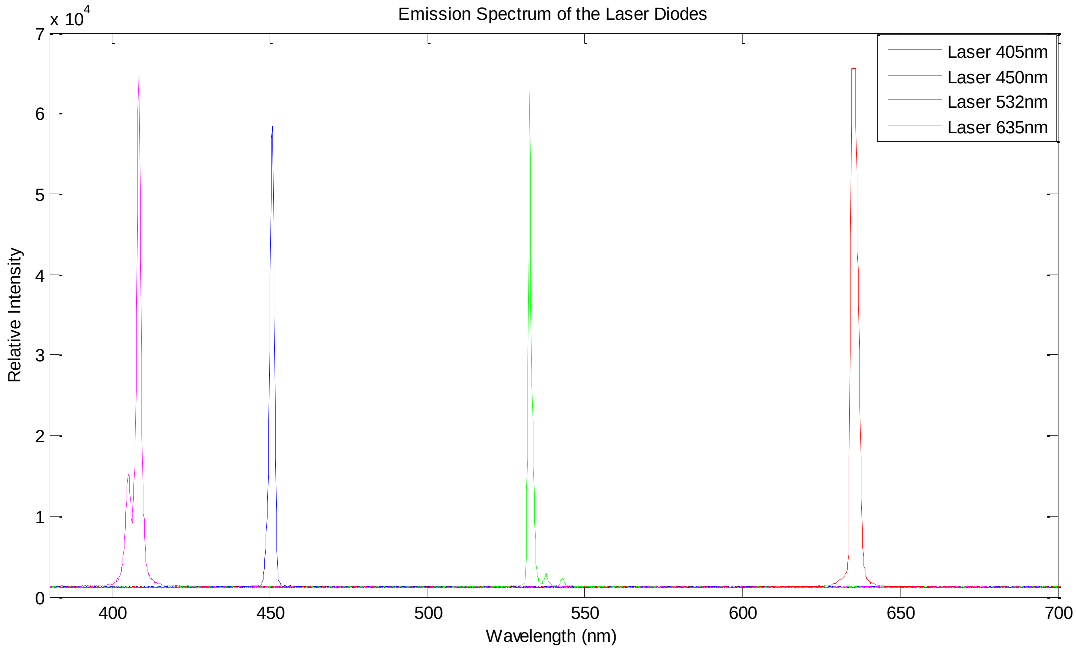


Figure 170 – Lasers' Emission Spectra

The emission spectra of the laser diodes are very narrow as expected.

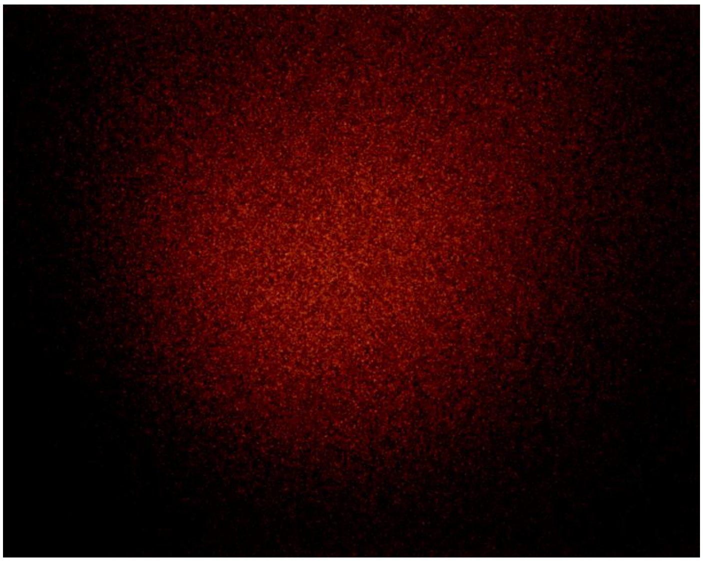
5.3.2 Lifespan of the Coherent Light Source

According to each laser diode's datasheet, the laser diodes have a lifespan of about 10.000 hours. The lifespan is the same with Incoherent Light Source whose emitting elements are LEDs. However, the lifespan could be reduced significantly if the datasheet's operation temperatures for each laser diode is not respected. For this reason, we received serious consideration for maintaining each laser diode's temperature within the permitted values.

5.3.1 Speckle Reduction

As mentioned in the previous subsection our Coherent Light Source due to the fact that is coherent, presents speckle phenomena. So, a new simple method using only vibration motor is introduced. In this paragraph, speckle reduction measurements will be presented. Applying vibration to the laser diode via the vibration motor we captured the laser's spot on a white paper by reflection, in various vibration frequencies (the laser light is transmitted though the liquid light guide). Vibration frequency gets higher when we grow the vibration motor's voltage from 0V (off) to 2V (maximum vibration frequency). We take measurements starting from 0V to 2V with a 100mV voltage step. From the captured image, laser profile is exported and plotted in the same graph with the laser profile when the vibration motor is off. Also, contrast ratio, which is the most famous speckle quantification method, will be calculated.

Vibration Motor's Voltage=0 V / $C_{Speckle}$=0.73



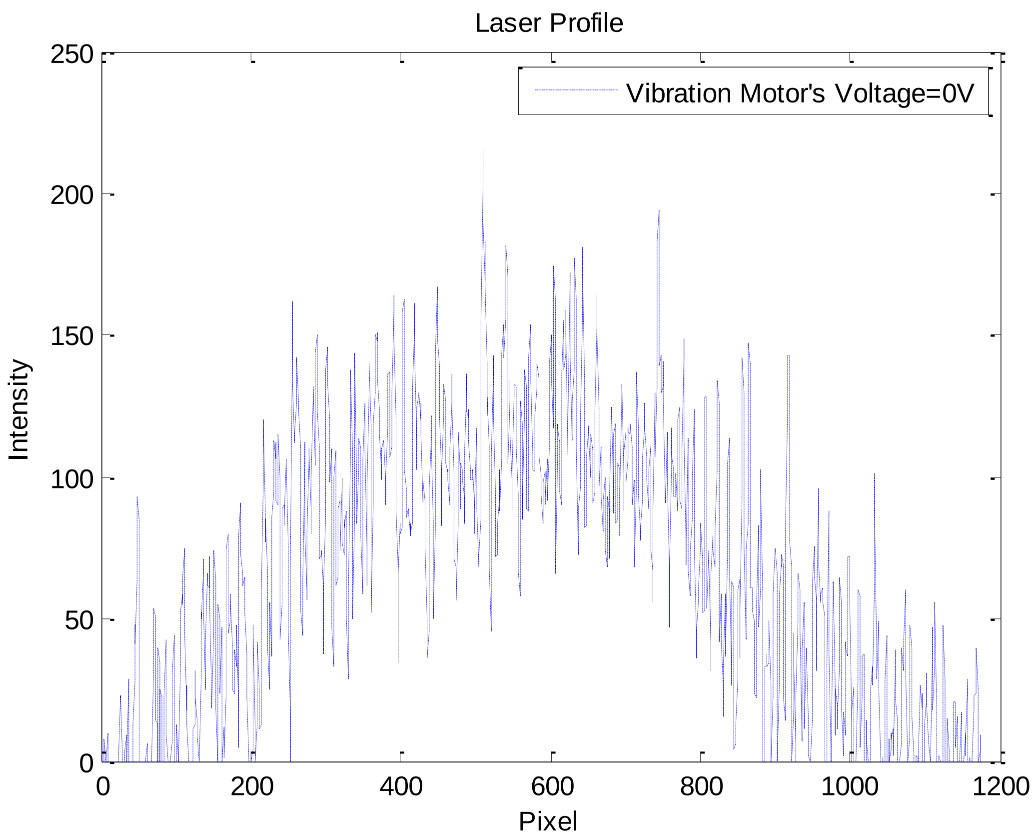
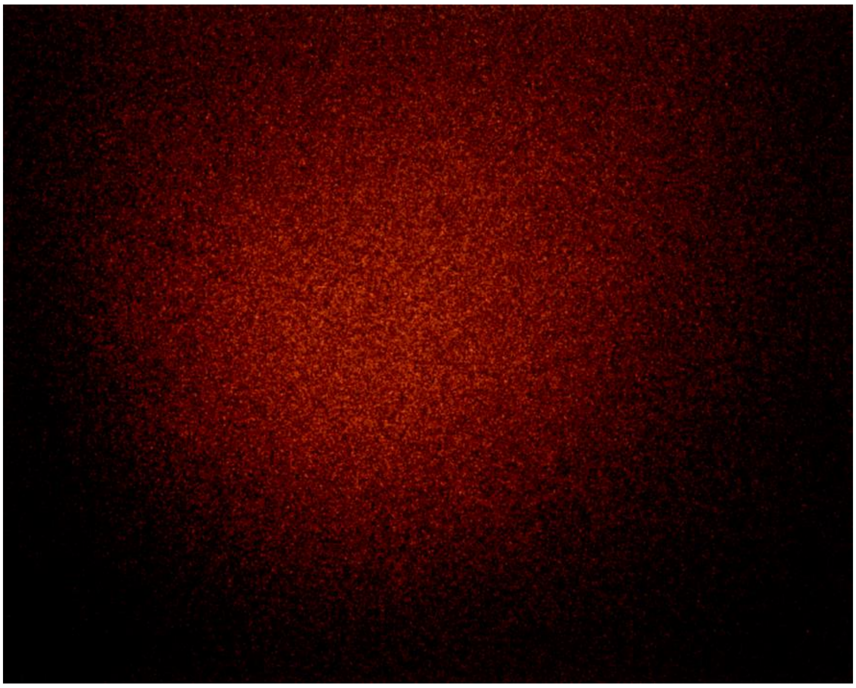


Figure 171 – Spot capture and Laser Profile at 0V

Vibration Motor's Voltage → 100 mV | $C_{Speckle}$=0.70



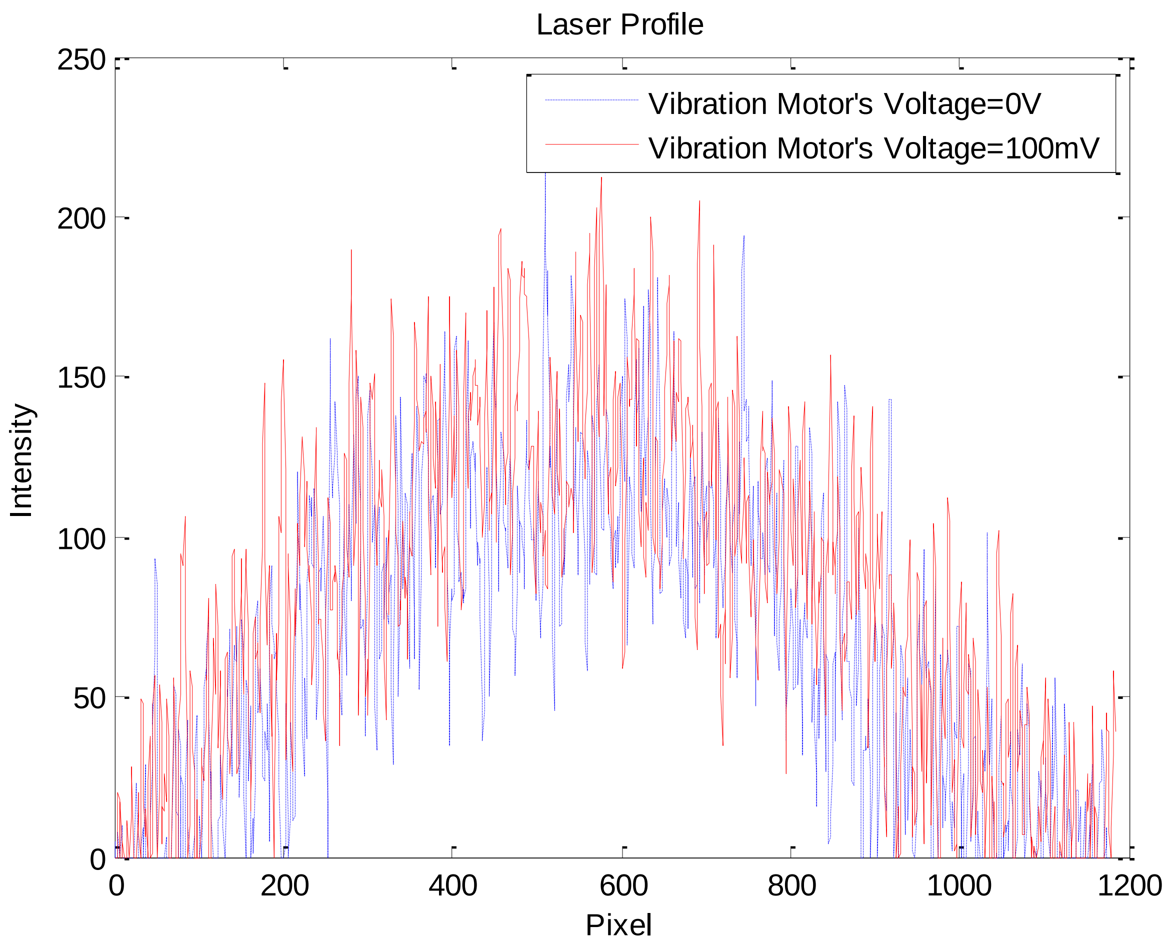
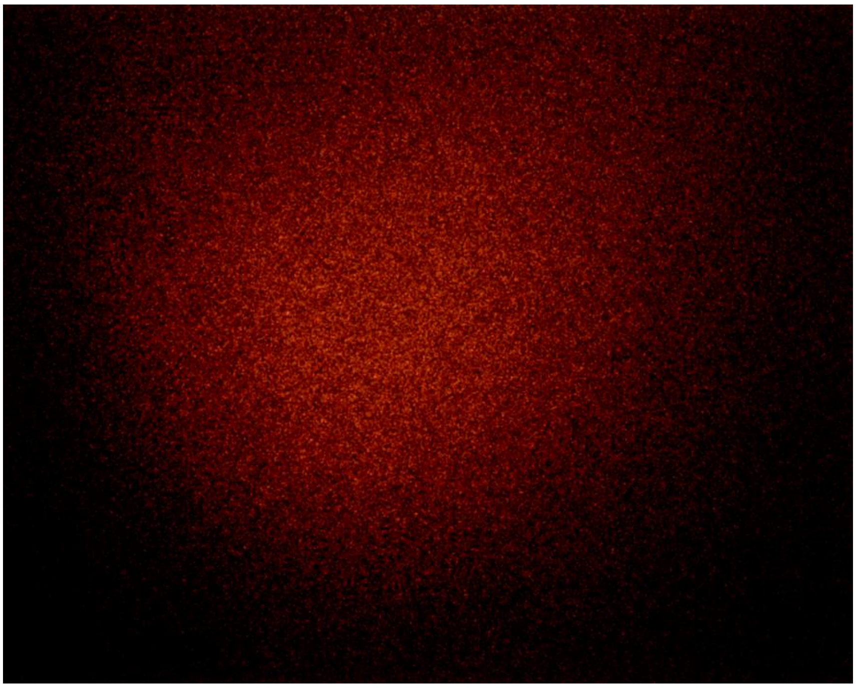


Figure 172 – Spot capture and Laser Profile at 100mV compared with non-vibrated graph

Vibration Motor's Voltage → 200 mV | $C_{Speckle}$=0.69



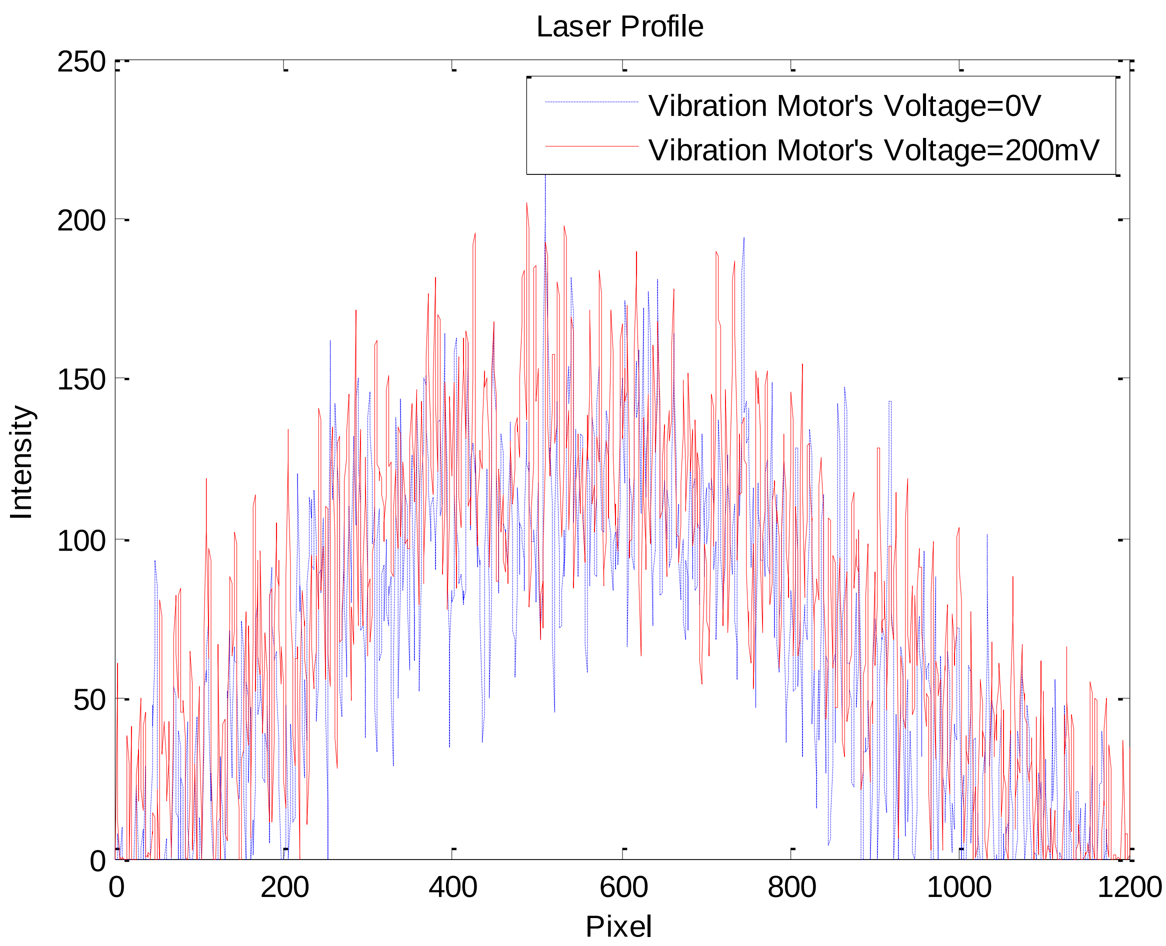
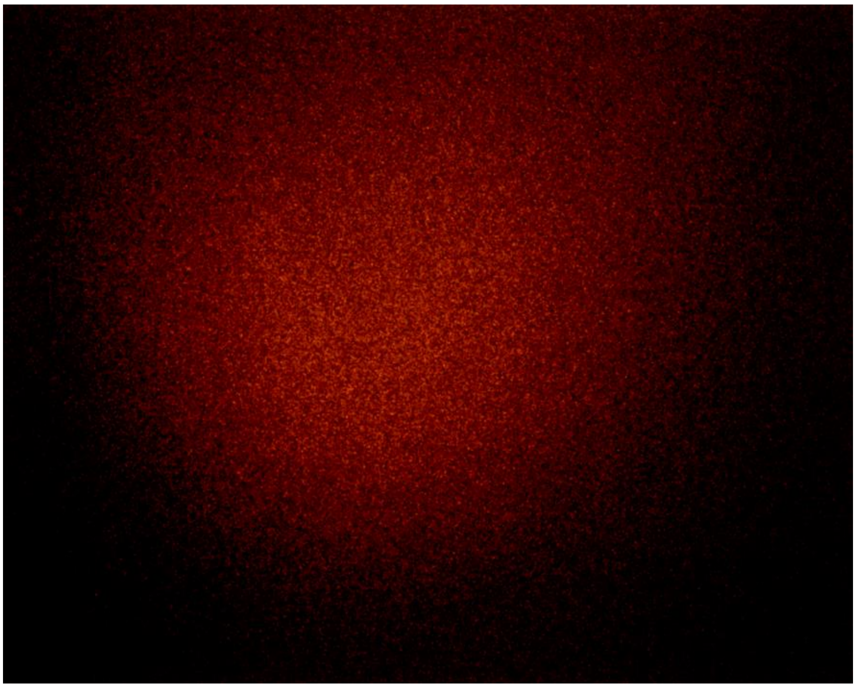


Figure 173 – Spot capture and Laser Profile at 200mV compared with non-vibrated graph

Vibration Motor's Voltage → 300 mV | $C_{Speckle}$=0.68



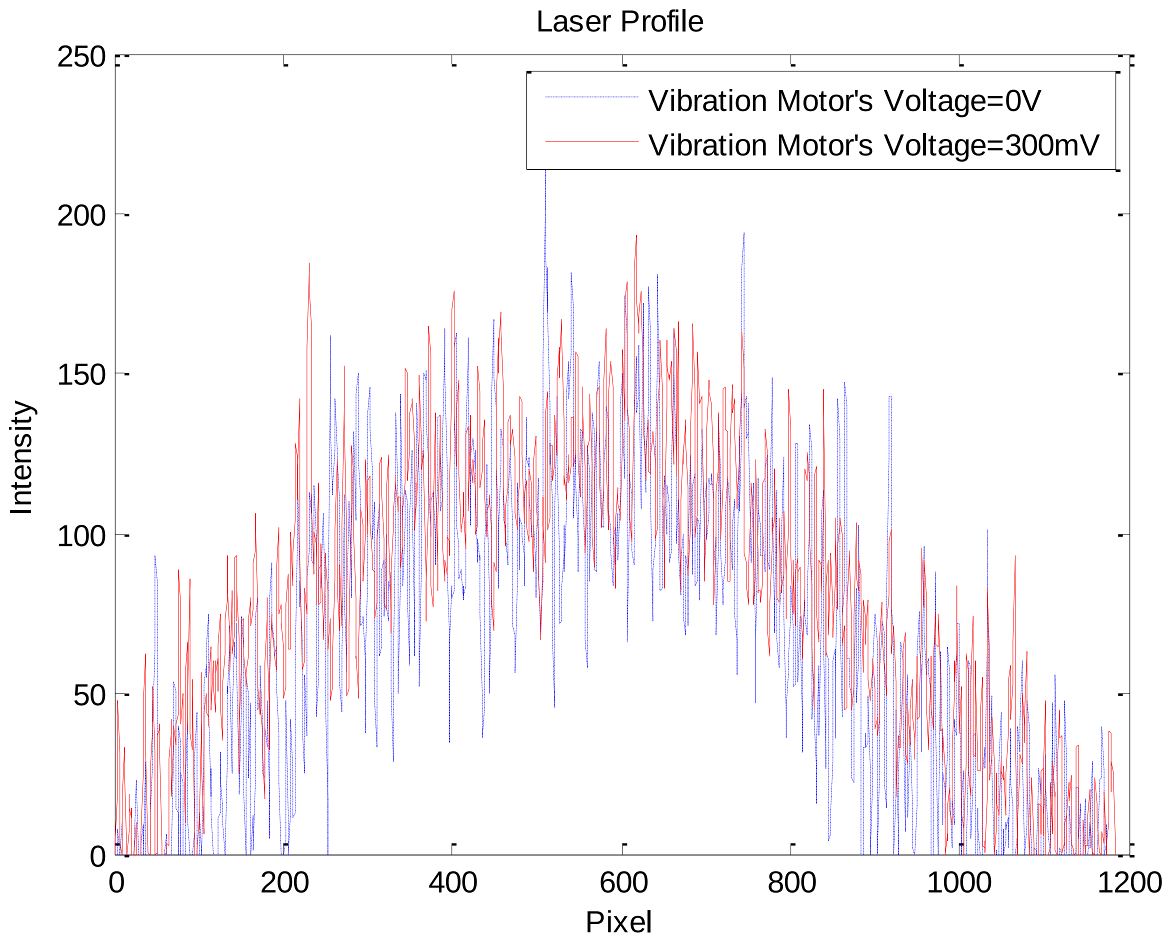
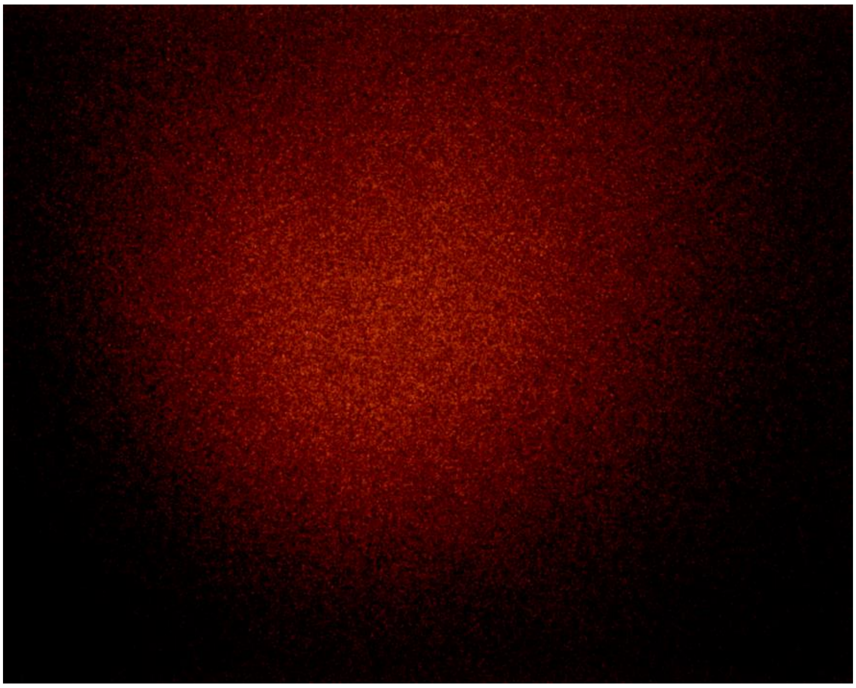


Figure 174 – Spot capture and Laser Profile at 300mV compared with non-vibrated graph

Vibration Motor's Voltage → 400 mV | $C_{Speckle}$=0.67



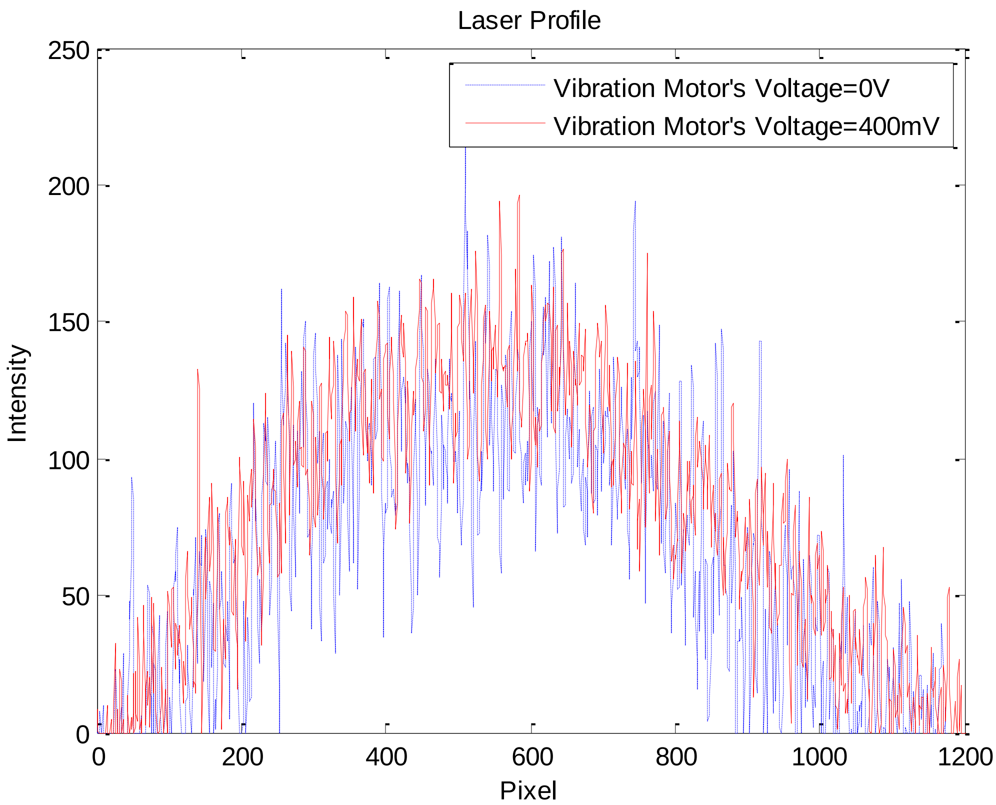
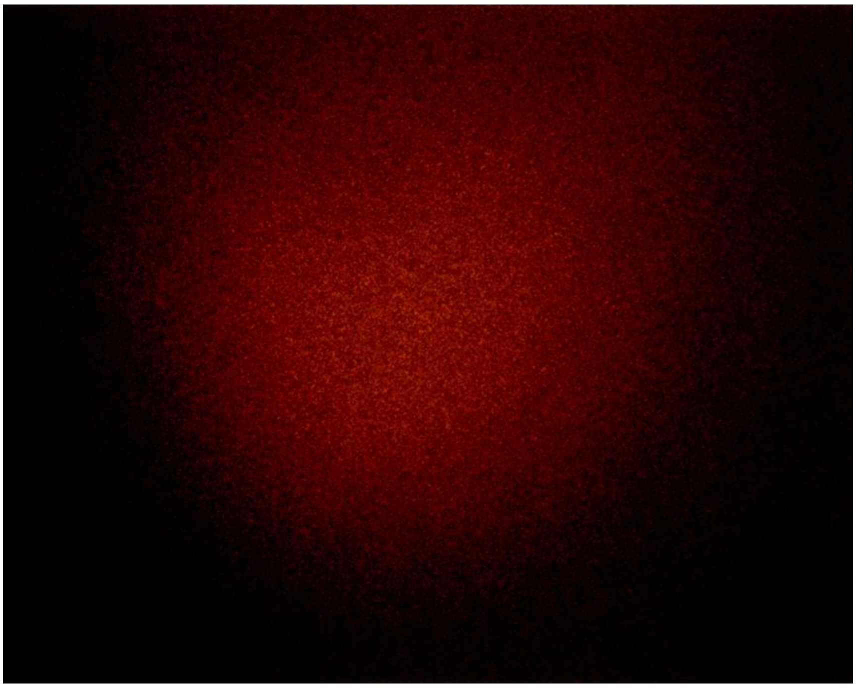


Figure 175 – Spot capture and Laser Profile at 400mV compared with non-vibrated graph

Vibration Motor's Voltage → 600 mV | $C_{Speckle}$=0.57



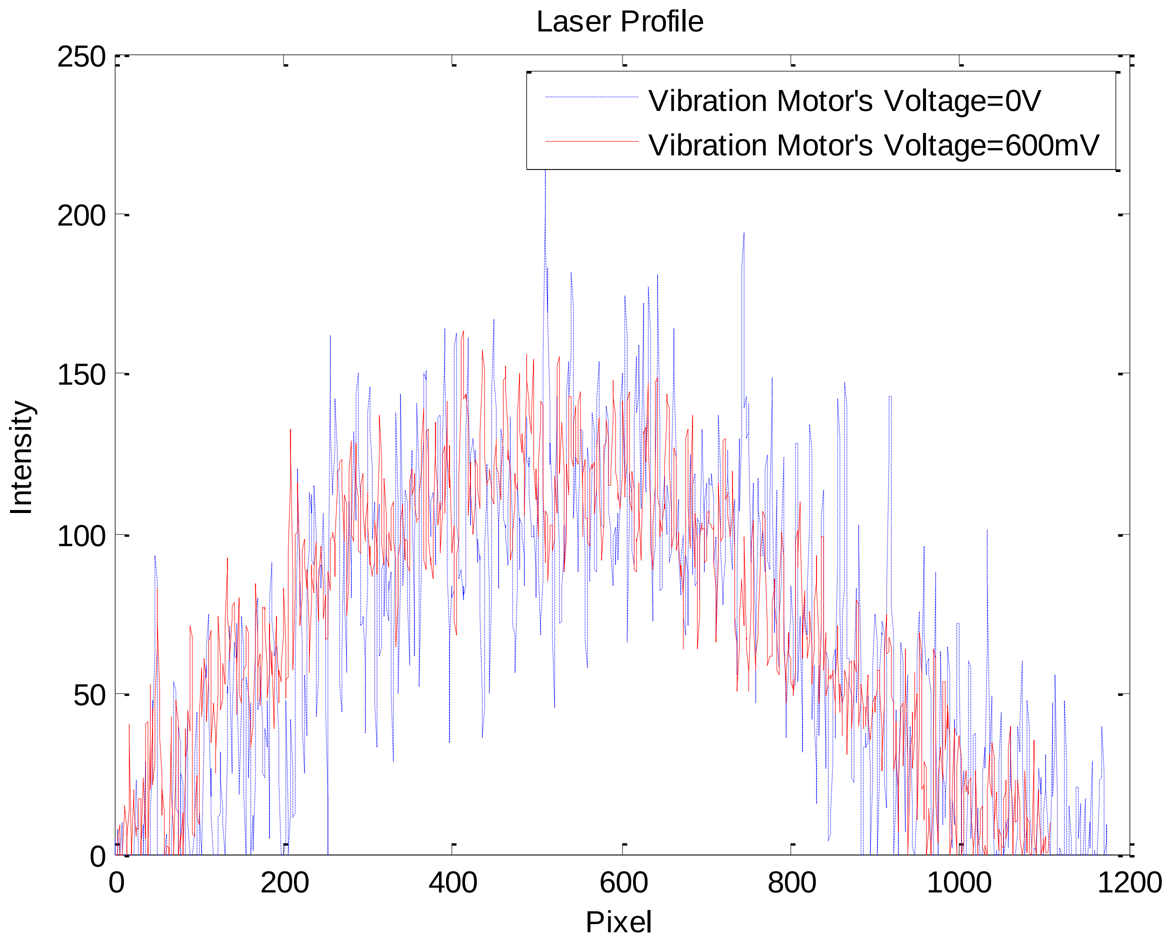
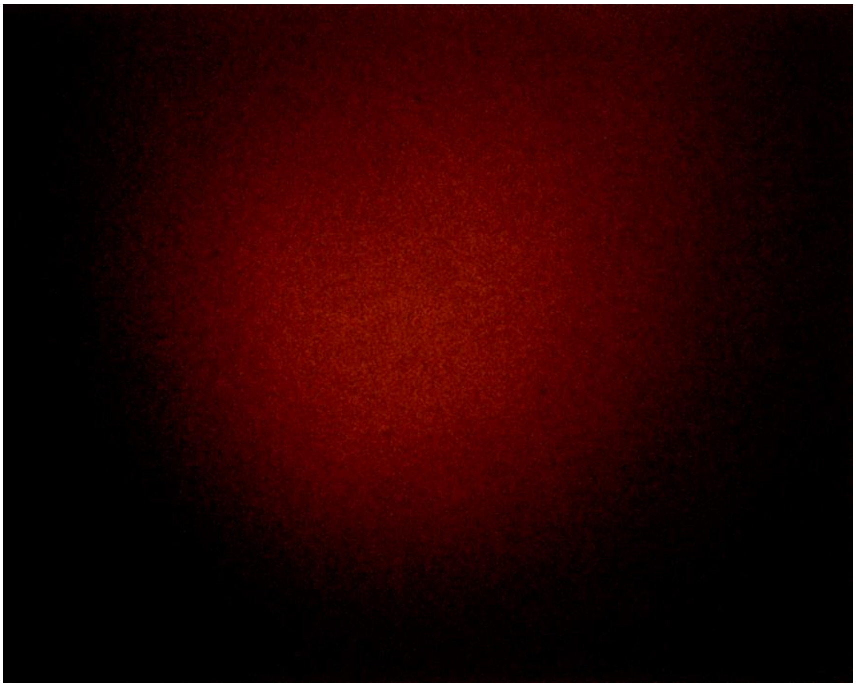


Figure 176 – Spot capture and Laser Profile at 600mV compared with non-vibrated graph

Vibration Motor's Voltage → 700 mV | $C_{Speckle}$=0.52



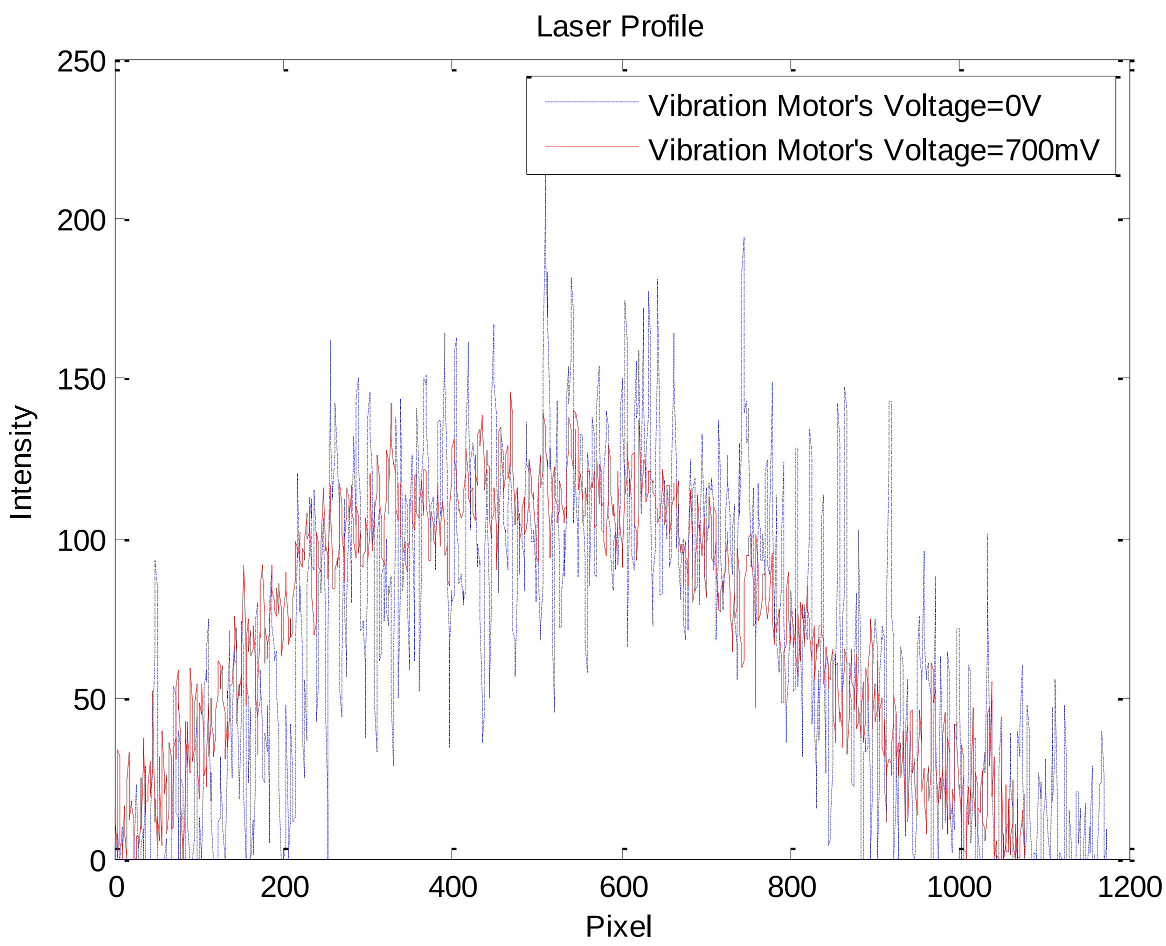
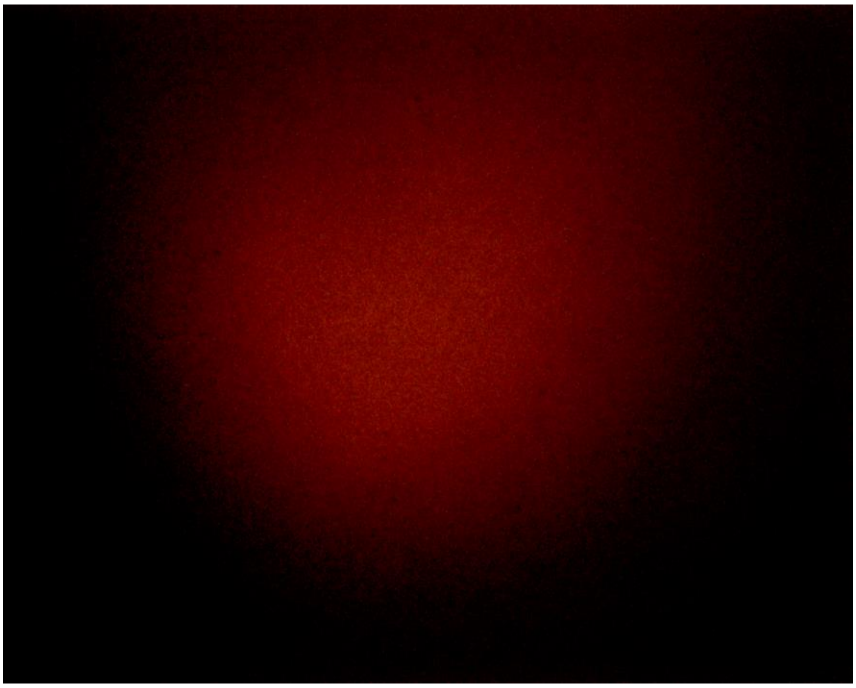


Figure 177 – Spot capture and Laser Profile at 700mV compared with non-vibrated graph

Vibration Motor's Voltage → 800 mV | $C_{Speckle}$=0.50



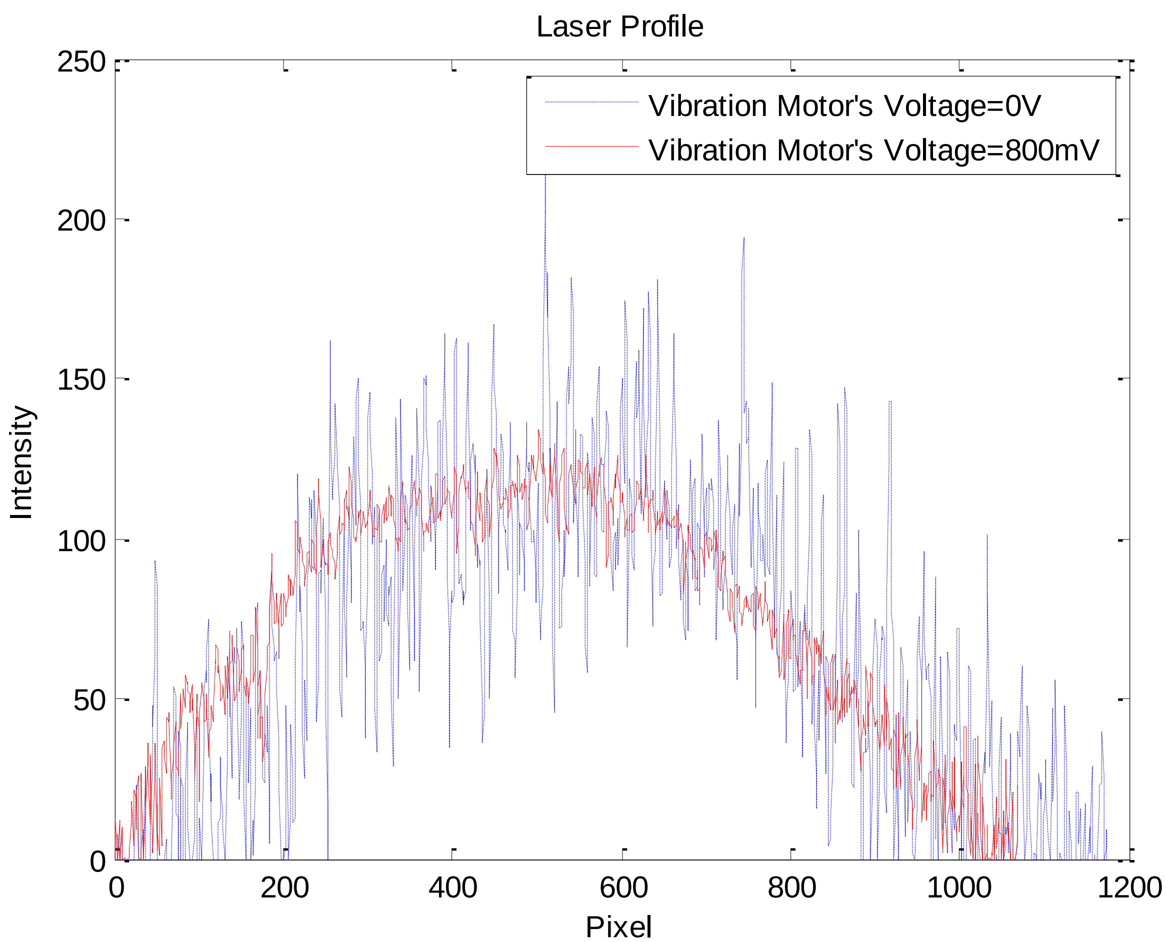


Figure 178 – Spot capture and Laser Profile at 800mV compared with non-vibrated graph

Vibration Motor's Voltage → 900 mV | $C_{Speckle}$=0.49

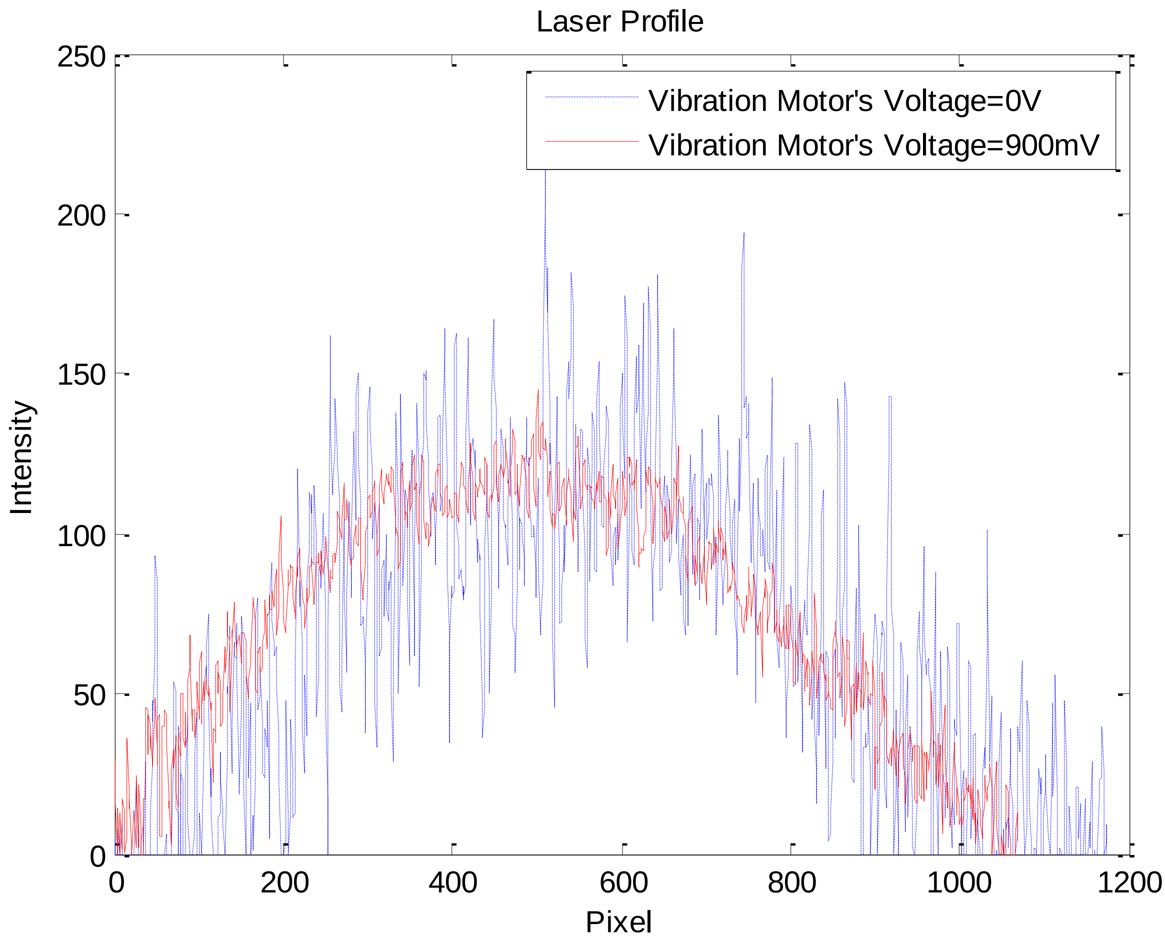
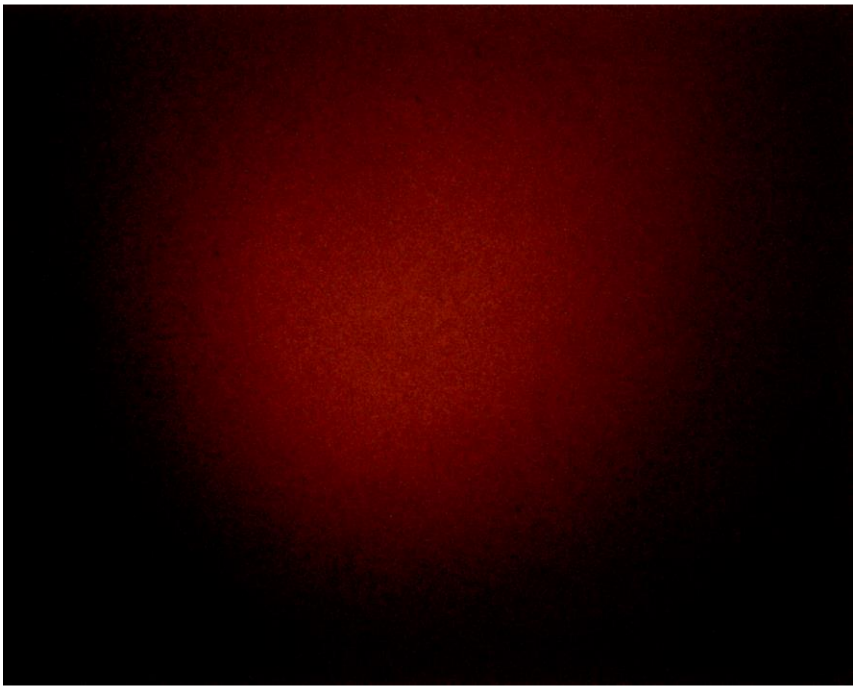


Figure 179 – Spot capture and Laser Profile at 900mV compared with non-vibrated graph

Vibration Motor's Voltage → 1 V / $C_{Speckle}$=0.45



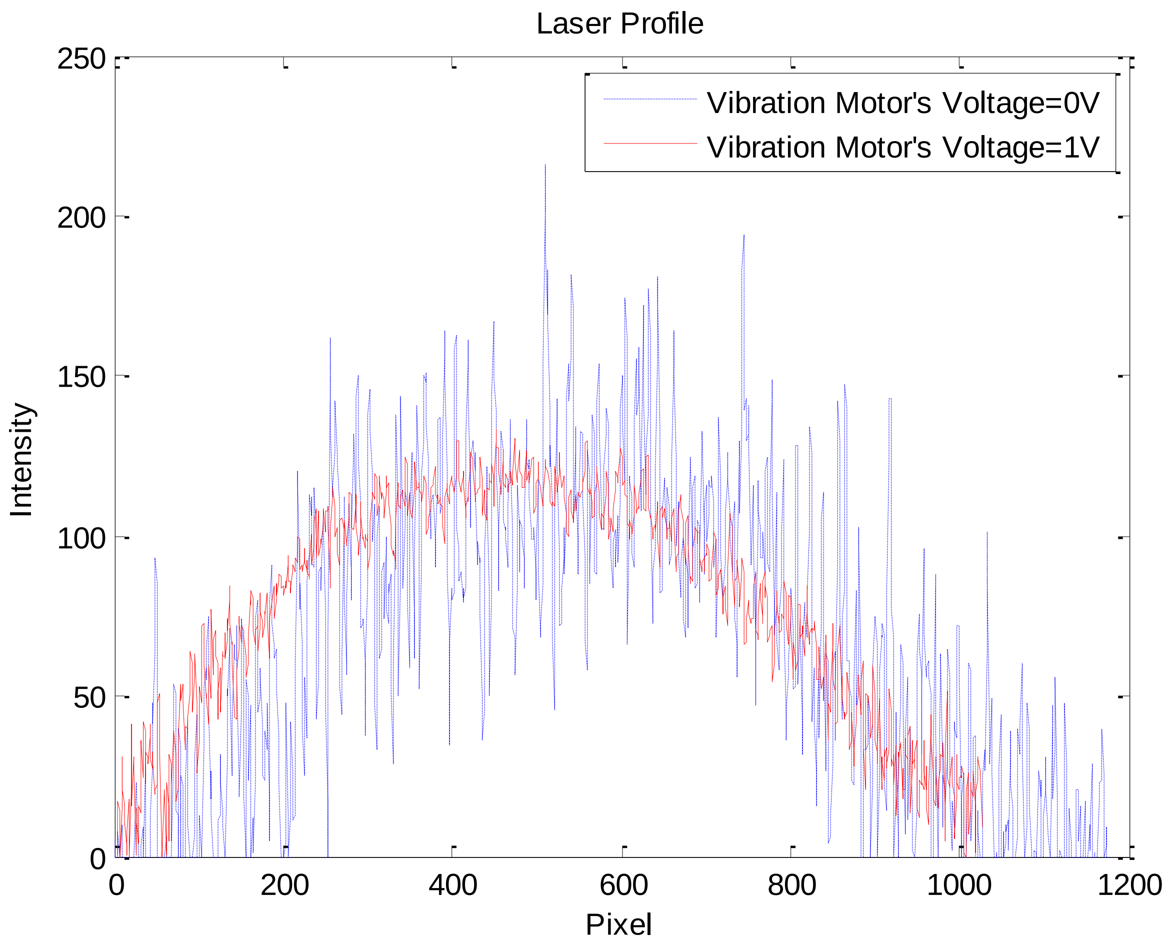


Figure 180 – Spot capture and Laser Profile at 1V compared with non-vibrated graph

Vibration Motor's Voltage → 1,1 V / $C_{Speckle}$=0.44

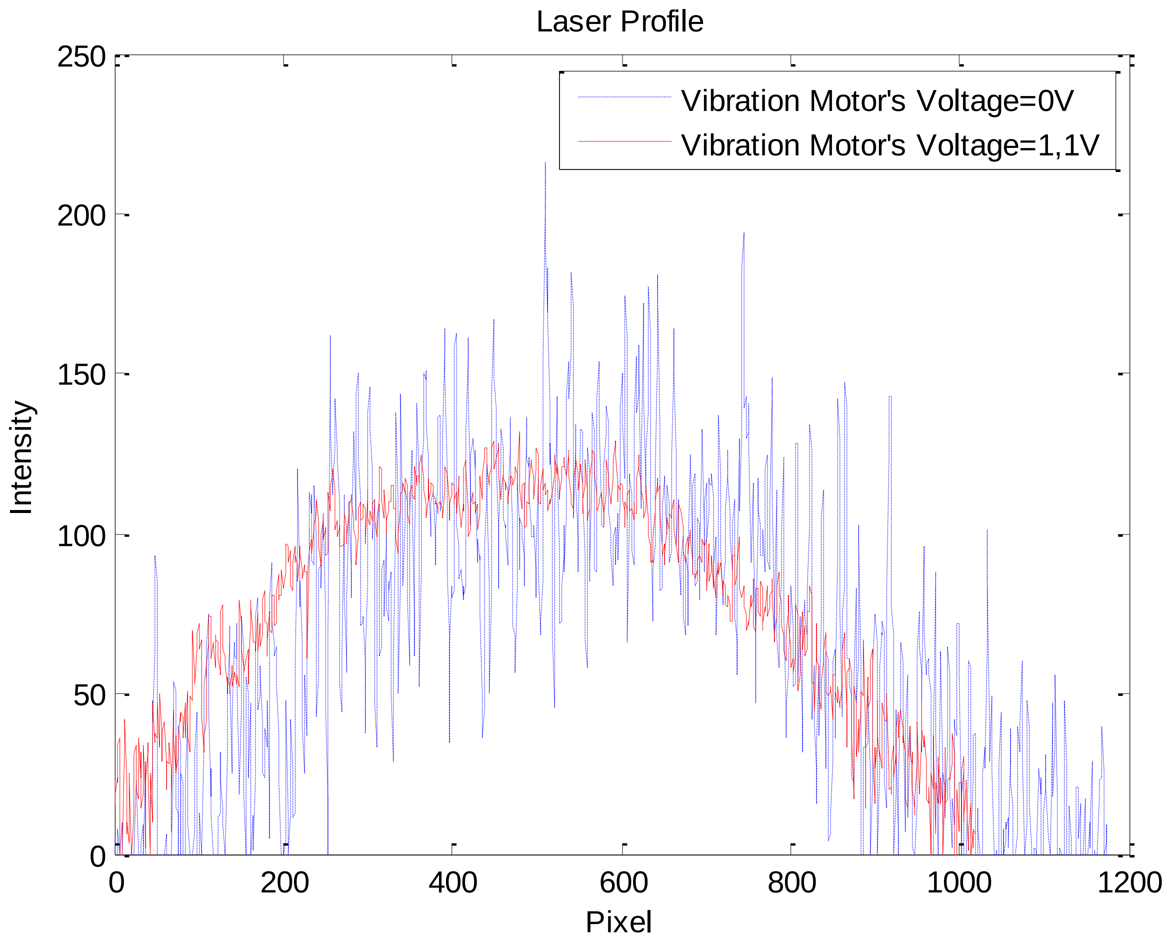


Figure 181 – Spot capture and Laser Profile at 1,1V compared with non-vibrated graph

Vibration Motor's Voltage → 1,2 V / $C_{Speckle}$=0.44

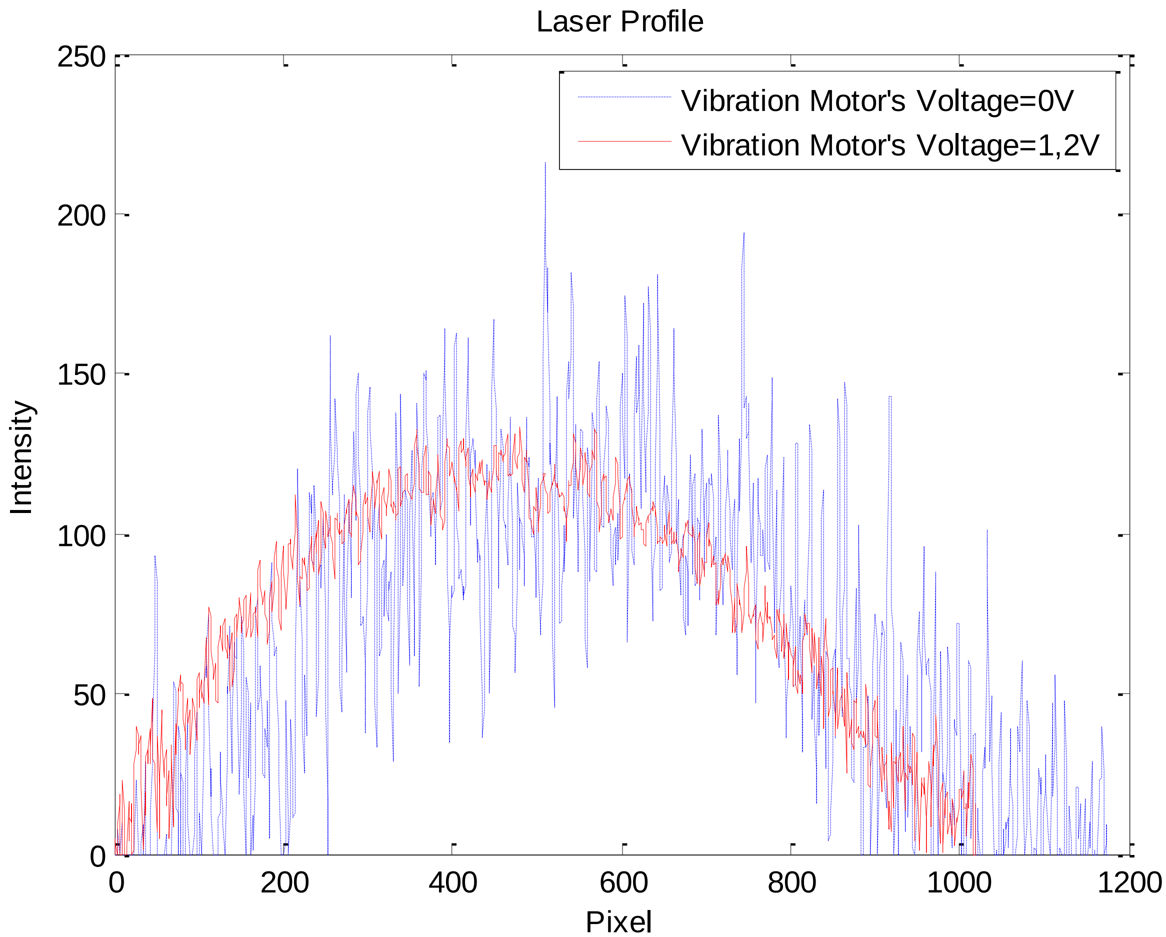


Figure 182 – Spot capture and Laser Profile at 1,2V compared with non-vibrated graph

Vibration Motor's Voltage → 1,3 V / $C_{Speckle}$=0.43

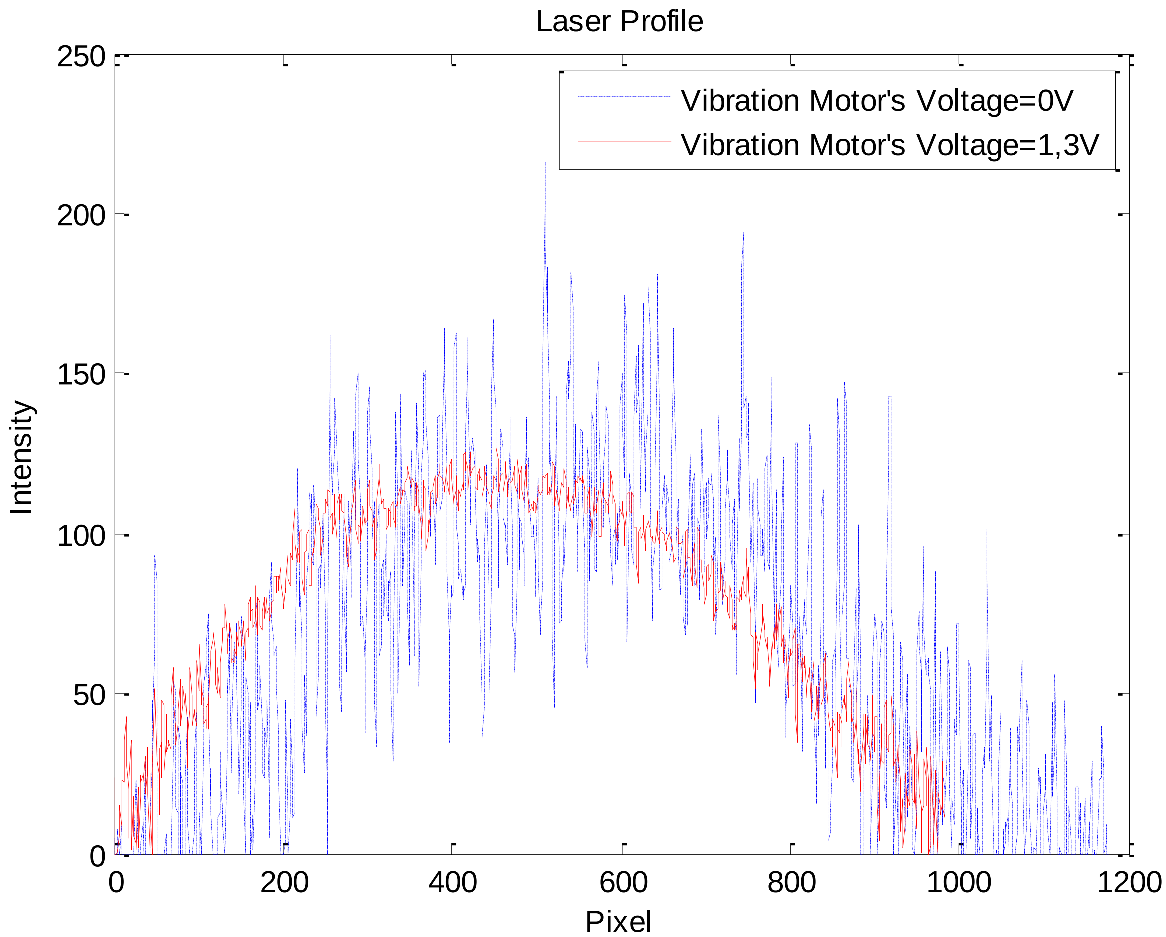
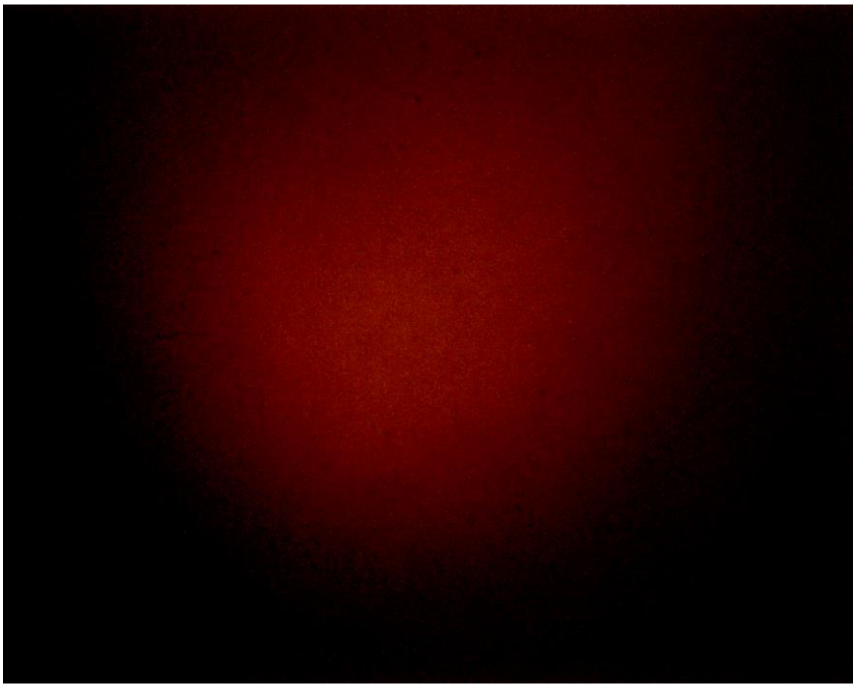


Figure 183 – Spot capture and Laser Profile at 1,3V compared with non-vibrated graph

Vibration Motor's Voltage → 1,4 V / $C_{Speckle}$=0.41



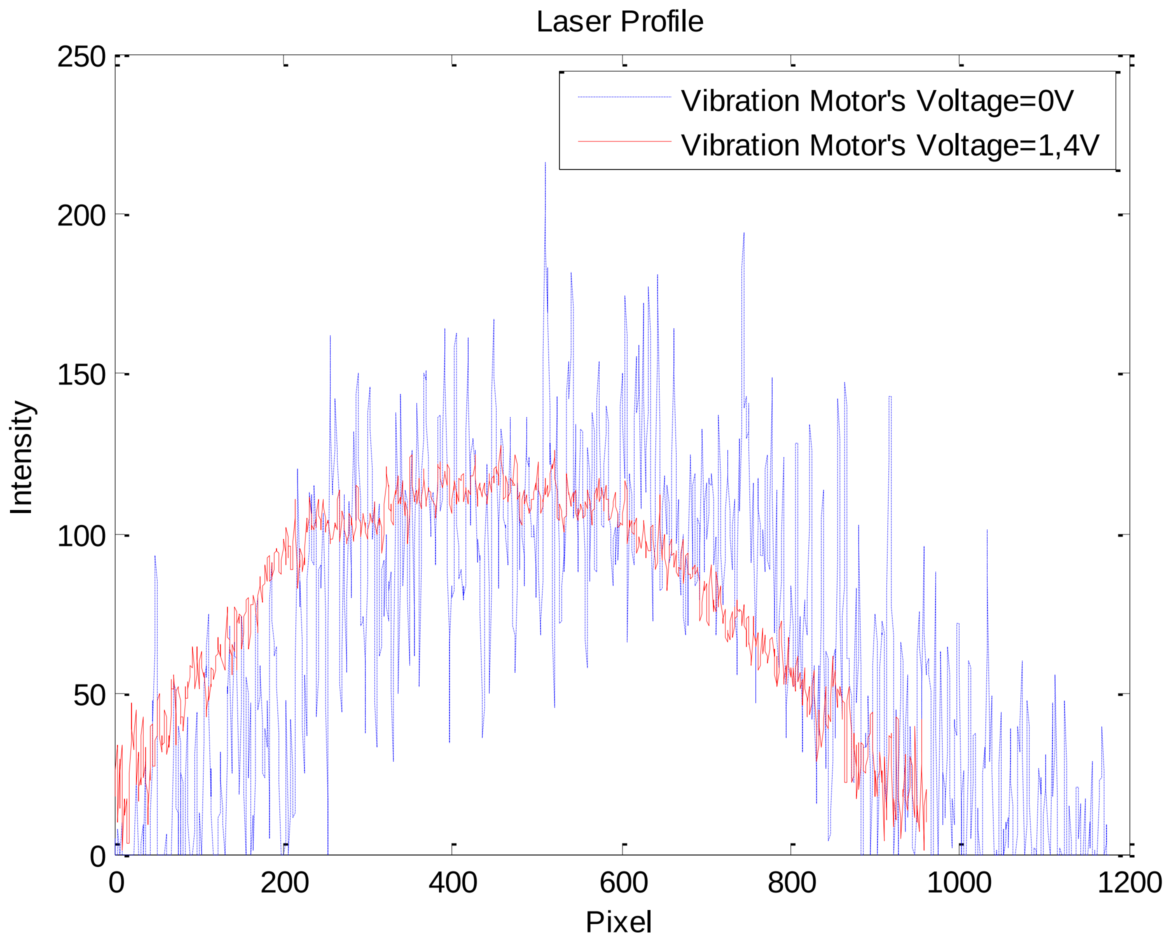


Figure 184 – Spot capture and Laser Profile at 1,4V compared with non-vibrated graph

Vibration Motor's Voltage → 1,5V / $C_{Speckle}$=0.40

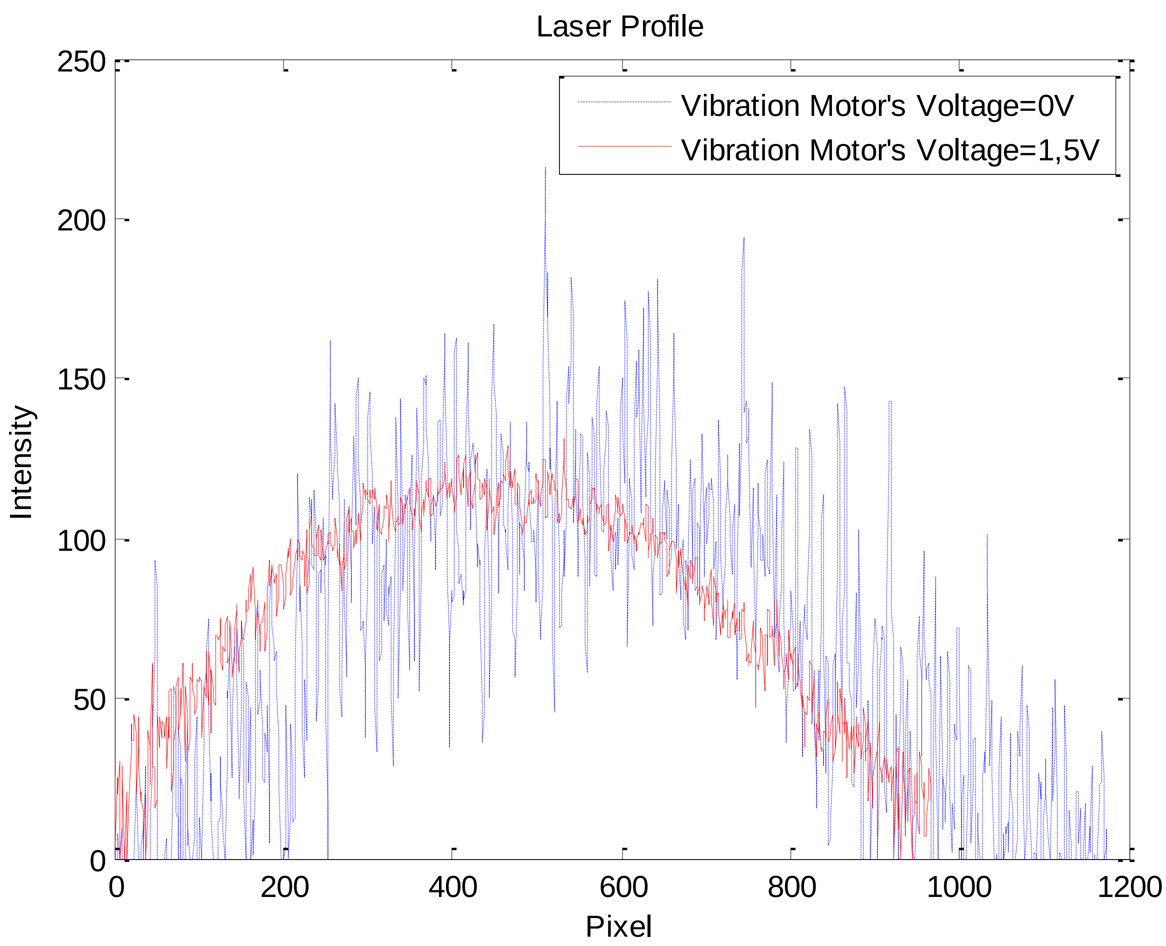


Figure 185 – Spot capture and Laser Profile at 1,5V compared with non-vibrated graph

Vibration Motor's Voltage → 1,6 V / $C_{Speckle}$=0.39

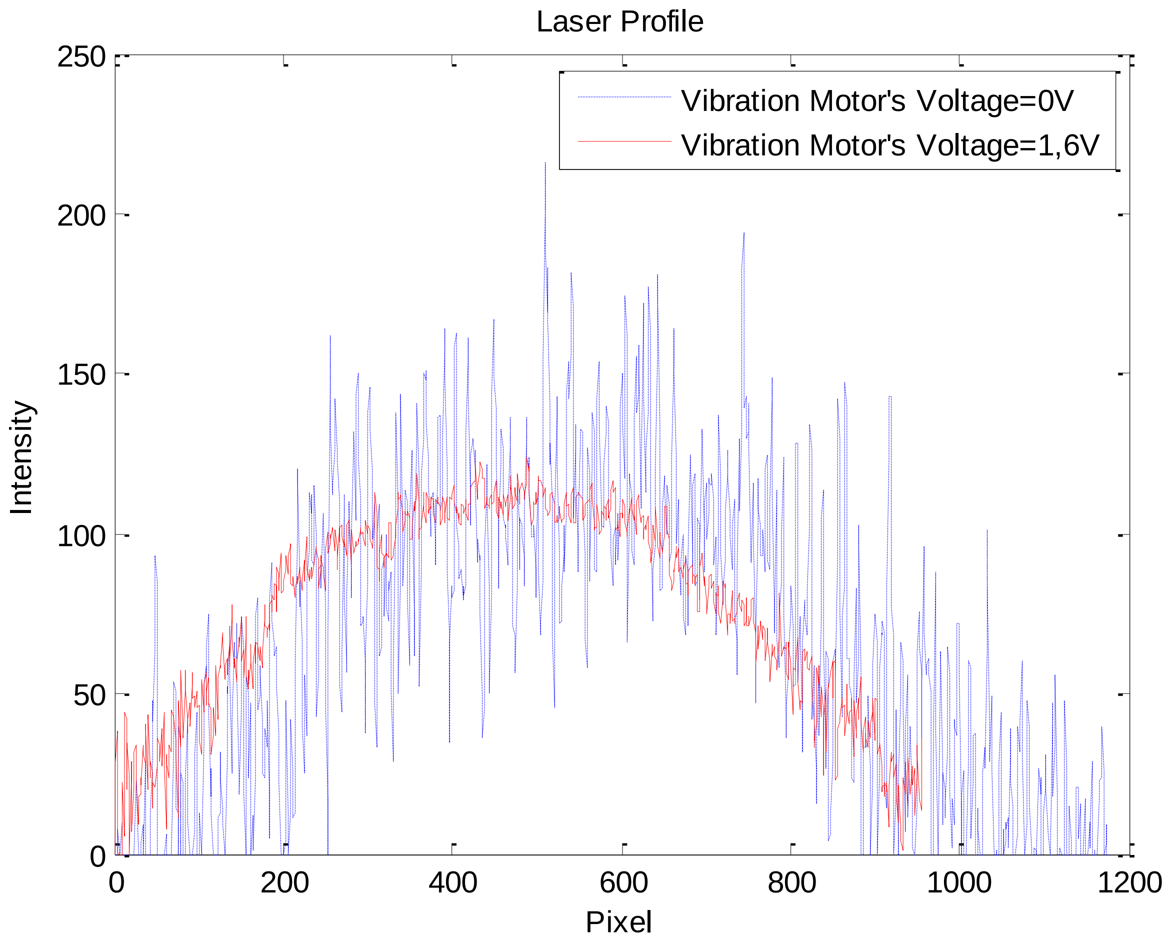


Figure 186 – Spot capture and Laser Profile at 1,6V compared with non-vibrated graph

Vibration Motor's Voltage → 1,7 V / $C_{Speckle}$=0.37

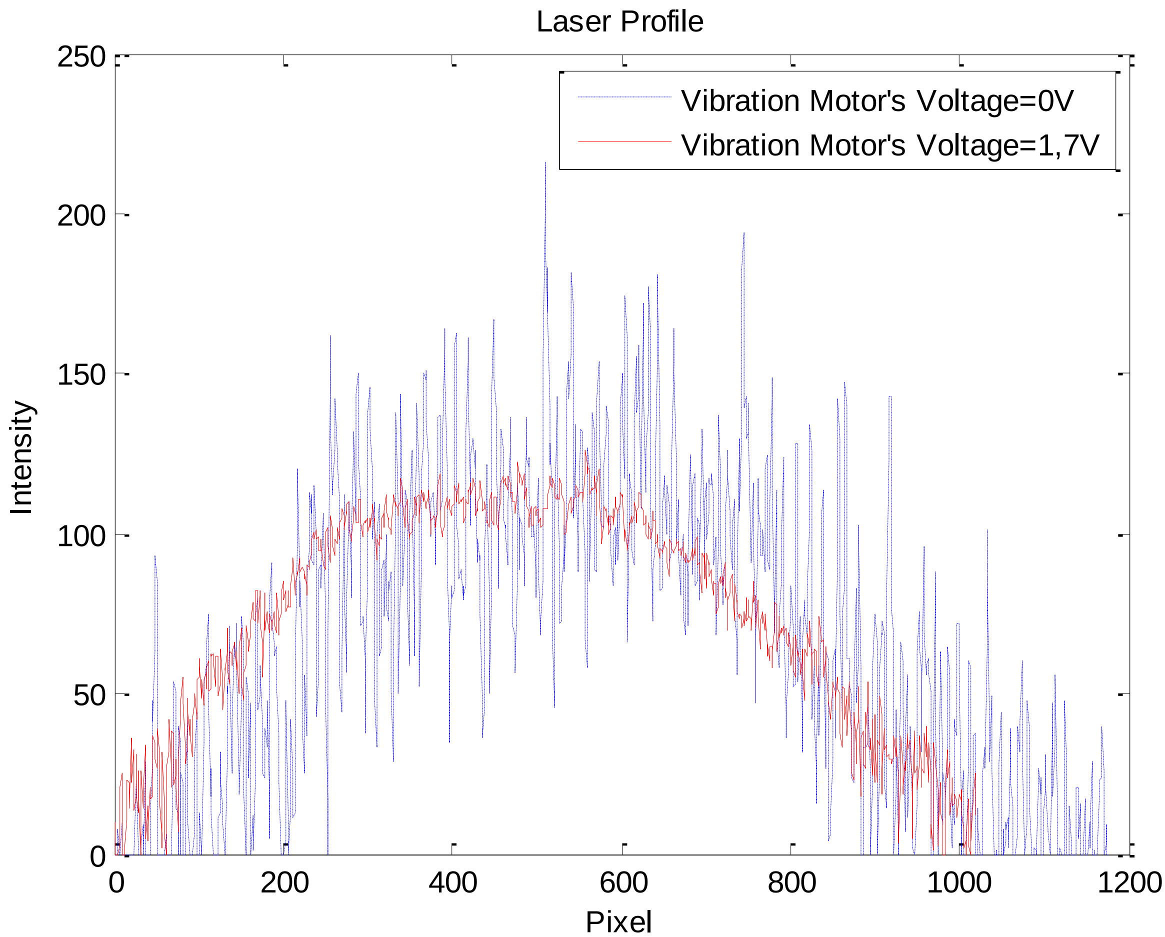


Figure 187 – Spot capture and Laser Profile at 1,7V compared with non-vibrated graph

Vibration Motor's Voltage → 1,8 V / $C_{Speckle}$=0.36

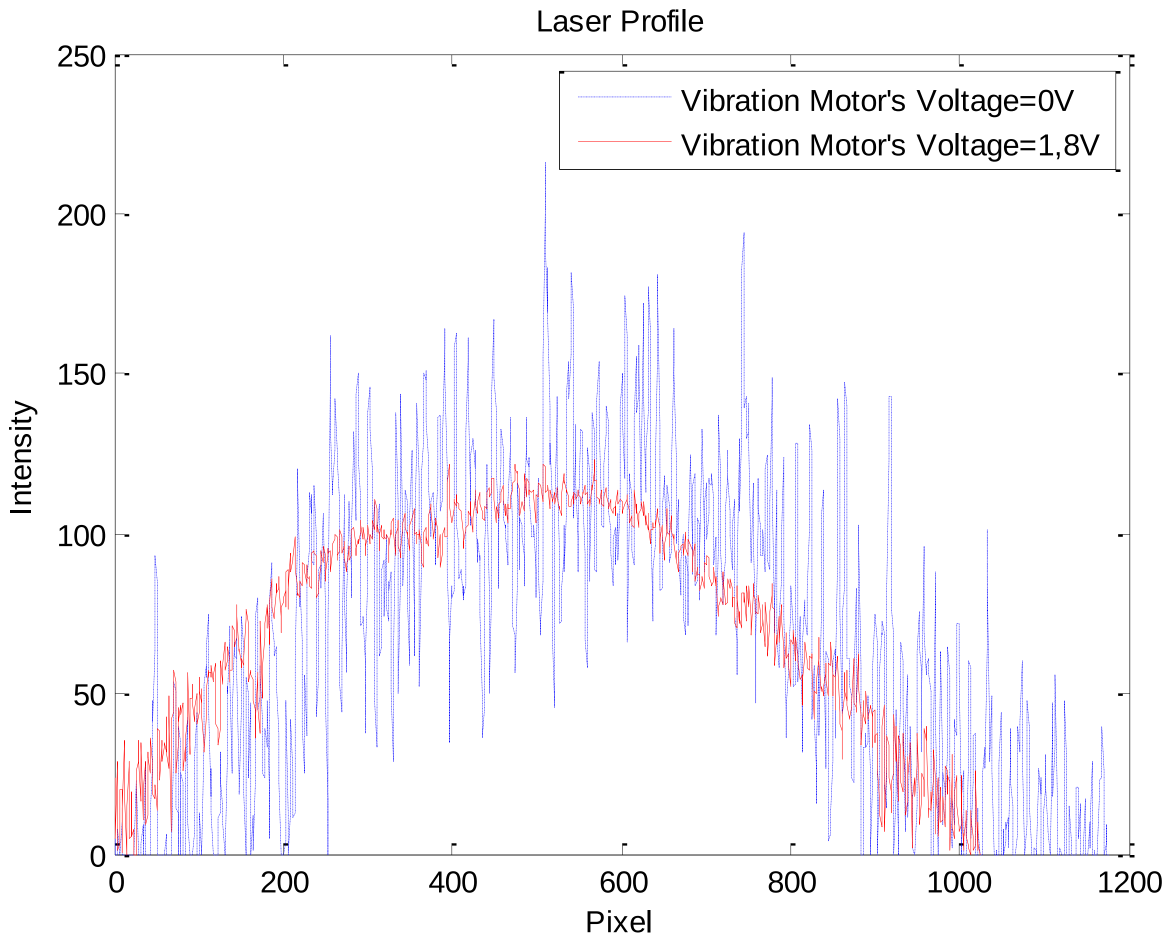


Figure 188 – Spot capture and Laser Profile at 1,8V compared with non-vibrated graph

Vibration Motor's Voltage → 1,9 V / $C_{Speckle}$=0.35

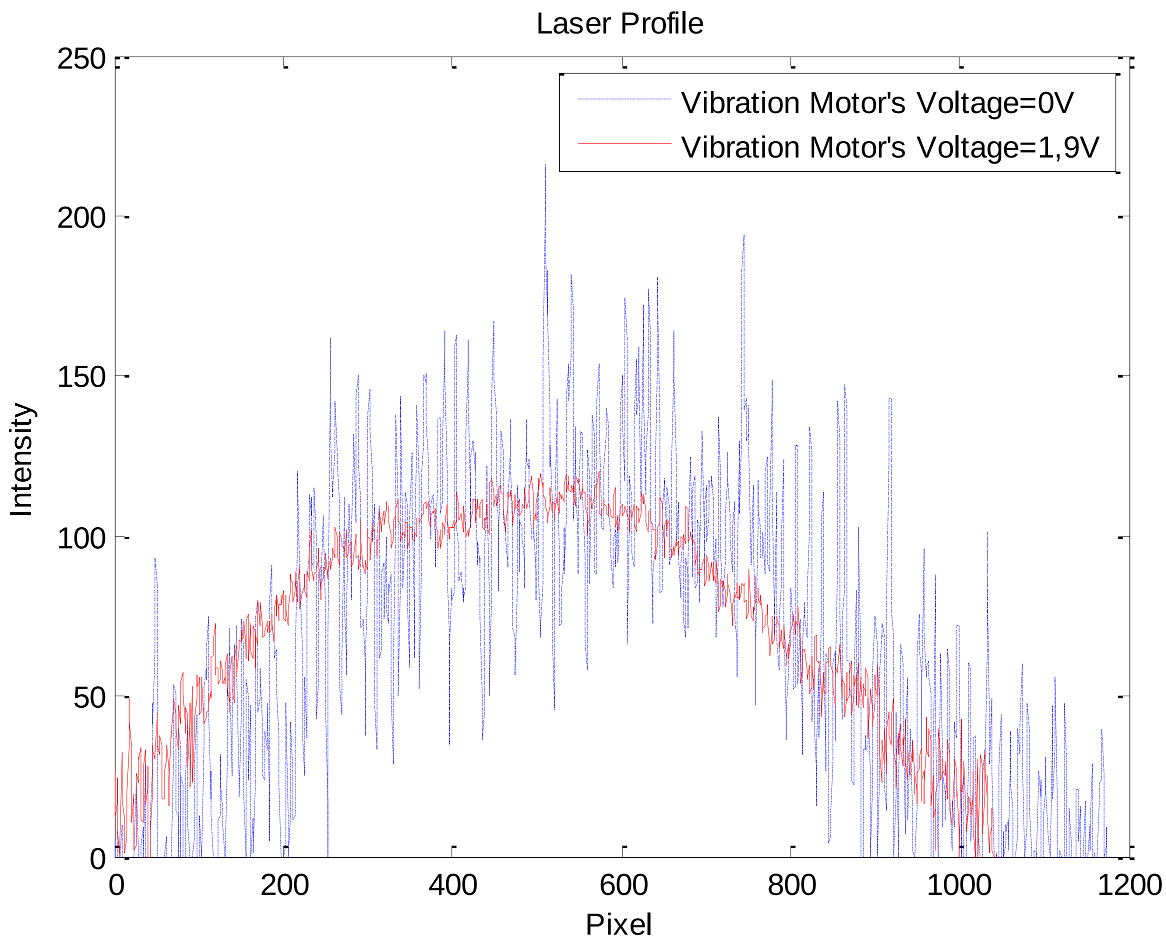


Figure 189 – Spot capture and Laser Profile at 1,9V compared with non-vibrated graph

Vibration Motor's Voltage → 2 V / $C_{Speckle}$=0.34

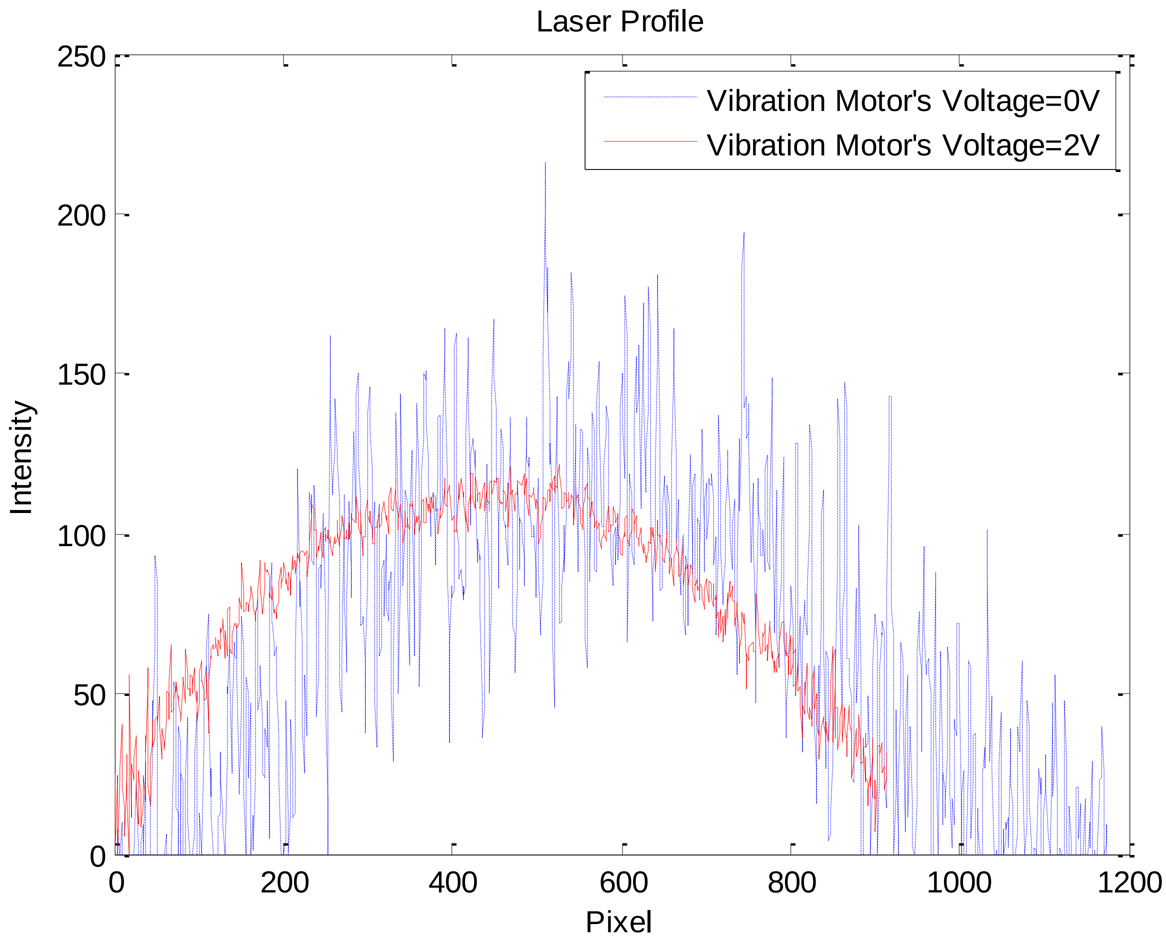


Figure 190 – Spot capture and Laser Profile at 2V compared with non-vibrated graph

Our idea using a vibration motor for reducing speckle phenomenon gives wonderful results. The speckle is significantly reduced as shown by the measurements. The speckle contrast radio is reduced down to 0.35 from 0.73. Let's gather the data above and create a graph where the x axis is measured in vibration motor's voltage and y axis in speckle contrast ratio.

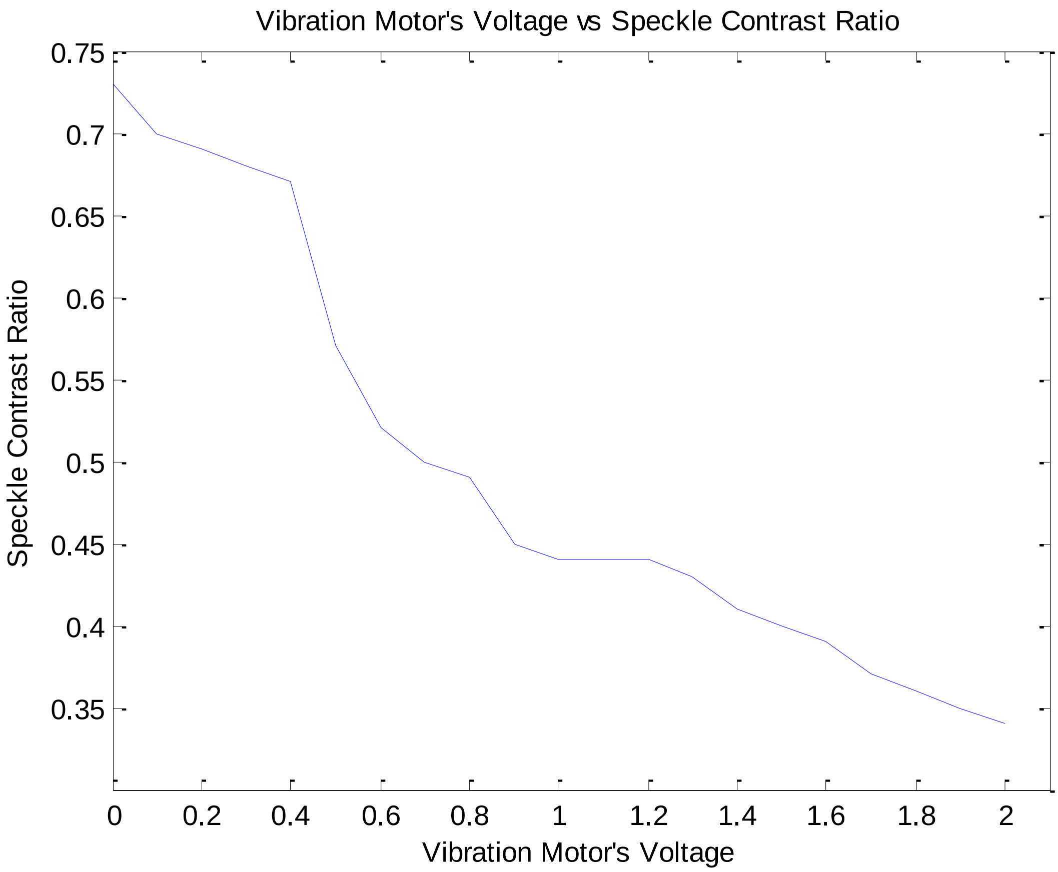


Figure 191 – Vibration Motor's Voltage vs Speckle Contrast Ratio

5.4 Potential Applications

Our coherent light source has got many applications including:

- Spectroscopy
- Confocal laser scanning microscopy
- Multiphoton excitation microscopy
- Fluorescence microscopy
- Fluorescence imaging
- Endoscopy
- Photodynamic therapy of various dermatological diseases

6 CONCLUSIONS AND FUTURE WORK

In this master thesis, the development and evaluation of two light sources is presented. One incoherent light source and one coherent light source.

Our goal is to fill the technological gap in incoherent and coherent light source for various scientific and medical applications. Conventional black-body or gas discharge light sources are still very popular, they suffer however from a long list of shortcomings including but not limited to: ramp-like spectral emission, heating, uncontrolled sparks (short-peaks) in their emission spectra, limited ability to control their intensity distribution along their emission wavelength range etc.

The Incoherent light source has been built on the key idea of several monochromatic and white LEDs which act as individual light sources. LED's are arranged in a PCB board and coupled with a fiber optic bundle that does the multiplexing of the several emitted wavelengths. The device can be tuned in wide spectral range (380-810nm) and is able to of emitting up to 22-wavelengths simultaneously, unlike other configurations in the market which are able to emit up to 8 wavelengths simultaneously. Furthermore, the device does not require a considerable period after ignition to reach thermal equilibrium and become stable like Xenon or Halogen light sources. This is because we use LEDs as individual light sources. Moreover, the changes in switching on and off of the LEDs are done very fast in contrast to other sources which use mechanical components. Also, the user of the device is able to manipulate the intensity of each one of the 22 available LEDs via a Graphical User Interface (GUI). This means that the device can simulate light sources with characteristics defined by the user. For example, our device is capable of simulating a continuous flat response light source, where all LED intensities are equal, or simulating a random light source.

We ended up in a compact device that has the ability of a computer controlled intensity distribution over its emission spectrum. It has a stable and high power optical power without power shifting and sparks. Also a new way of using a fiber optic bundle with multiple tails for multiplexing numerous LED light outputs has been developed and gave wonderful results.

The intended applications of the Incoherent Light Source span a wide range of disciplines including but not limited to microscopy, ophthalmology, endoscopy, quality control, calibration etc.

Concerning future work, there are a lot of improvements that could be implemented in hardware and in software. The available wavelengths can be increased by adding more LEDs to the system especially in the band of UV and

IR. This way, the tunability of the Incoherent Light Source will also improve as the available wavelengths would be more and the range of the intended applications will expand. Also, an improvement on the optical power output would be the replacement of some LEDs with more powerful and efficient LEDs. Nevertheless, a new ways of multiplexing emitted light wavelengths could be implemented that will be more flexible, more portable and with less optical components. Also an external touch screen that will allow the system to be used without a USB connection would be a great improvement. Finally, one more challenge will be the redesigning of all electronic component as a way to reduce the dimensions of the device. In terms of software, several features could be developed as a way to highlight the utility and functionality of the Incoherent Light Source. One improvement could be the possibility for the user to draw the spectrum of a source in a specific area of the GUI application and the Source will be able to simulate the user-defined source automatically, without the use of a spectrometer.

The Coherent Light Source has been built mainly for Fluorescence. It fills the technology gap of the existence of a coherent light source that excites several fluorophores that used in microscopy, biology chemistry and in other medical applications, without moving parts and without the need of additional optical filters. The Coherent Light Source's individual coherent light sources are four diode lasers. The laser diodes emit coherent light at 405nm, 450nm, 532nm and 635nm. These wavelengths have not been selected randomly but due to the fact that could excite many fluorophores included the most famous. The laser beams are multiplexed in a liquid light guide offering the ability to the user to have all laser beams in the tip of a 10mm flexible liquid light guide. The source can be controller with two ways. One way is via PC using a Source's Graphical User Interface (GUI) or via push button which are located in the front panel of the device.

The compact device developed is a coherent light source with high power and stable optical output. The laser beams have been multiplexed using a liquid light guide with 2-3% loss of optical power with a very effective and innovational way as a way to keep the dimensions of the light source in a compact level. Also a technique including a vibrating diffuser effectively reduced speckle pattern caused by the local interference of the laser coherent waves.

The intended applications of the Coherent Light Source span wide range of disciplines including but not limited to spectroscopy, confocal laser scanning microscopy, multiphoton excitation microscopy, fluorescence microscopy, endoscopy, photodynamic therapy of various dermatological diseased etc.

Concerning future work, there are a lot of improvements that could be implemented both in hardware and in software. The available laser wavelengths could be increased by adding more laser components to the system especially in UV and IR bands. Thus, the range of the fluorophores excitation and of other various intended applications will expand. Moreover, replacing the existing laser components with more powerful and efficient laser components, the output optical power will be increased. Nevertheless, a new ways of multiplexing emitted light wavelengths could be implemented that will be more flexible, more portable, with less optical components and with a higher optical power output. Finally, one more challenge will be the redesigning of all electronic and mechanical components as a way to reduce the dimensions of the device. Concerning the software, several features could be developed as a way to highlight the utility and functionality of the Coherent Light Source. For example, monitoring the temperatures of the laser diodes as a way to avoid overheat.

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