Technical University of Crete
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DEVELOPMENT OF A COMPUTER CONTROLLED TUNABLE WAVELENGTH LIGHT SOURCE FROM ULTRAVIOLET TO INFRARED

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

ABSTRACT

In this thesis, the development of an innovative Tunable Wavelength Light Source from Ultraviolet to Infrared is presented, which is able to emulate spectral distribution of various light sources.

Various Tunable Light Sources (TLS) based on different technologies already exist such as Lasers (Distributed Bragg Reflector, Distributed Feedback, Ion and Dye) and Tunable Filters (Liquid Crystal, Optical Parametric Oscillator and Acousto-optic). However, they present major disadvantages such as low throughput, high cost, low emitted optical power, and they usually operate on a few (less than ten) simultaneous emitted wavelengths.

The TLS designed in this thesis is capable of simulating spectral distribution of various light sources in the UV-VIS and VIS-IR regions as well as any (single or multiple) monochromatic wavelength in this range. The TLS has excellent throughput, more than 85%, great stability, low cost and high tunability, up to 22 individual emitted wavelengths.

The TLS consists of miniature high power solid-state light sources and variable filters. Each solid-state light source is driven independently, allowing individual control of the emitted optical power. Also, a Graphical User Interface (GUI) application is developed enabling the TLS to be fully PC controlled.

Calibration of the TLS's wavelength and optical power was performed using a spectrometer and a photometer. A series of laboratory tests have been conducted to evaluate the performance of the designed TLS, i.e. emulation of a flat line response light source and random light sources. Performance evaluation showed about 85% flat transmittance in almost all the available wavelengths while the full-width at half maximum in each wavelength curve is less than 20nm.

The intended applications of the innovative TLS spans a wide range of disciplines including but not limited to microscopy, ophthalmology, endoscopy, quality control, calibration etc.

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INTRODUCTION

In this thesis, the development of an innovative Tunable Wavelength Light Source (TLS) from Ultraviolet to Infrared is presented, which is able to emulate spectral distribution of various light sources. The next chapters analyze the procedure of the development of the TLS.

In Chapter 1, we present the characteristics and physics of various Light sources, depending on the output spectrum. Specifically, we discuss about black body radiation sources, gas-discharge light sources, lasers and LEDs.

Furthermore, in Chapter 2, we will deal with light sources that can "tune" their output spectrum, i.e. Tunable Light Sources. Tunable light sources are used to illuminate objects with only a small specific range of wavelengths. The spectral bands of TLS can be from UV to IR. They are used to study wavelength dependent chemical, biological, and physical changes or properties. They can also be used in color analysis and reflectivity measurements of products for aesthetic purposes.

In Chapter 3, the aim of this project is presented, which is the construction of a multi-wavelength Tunable Light Source using white LEDs, Monochromatic LEDs and linear variable filters. LEDs are arranged on a board which is placed behind the variable filters. This tunable light source is able to illuminate in a wide range of bands (390 – 810nm) with high emitted optical intensity.

Also, in Chapter 4 the software development of the TLS is presented that enables the user of the TLS to control the output wavelength of the light source, the switching of enabling/disabling and dimming of the LEDs. The designing procedure was divided into several tasks that were necessary for the completion of the software.

The technical evaluation of the TLS is presented in Chapter 5.A series of laboratory tests have been conducted to evaluate the performance of the designed TLS, i.e. emulation of a flat line response light source and random light sources.

In the last Chapter (Chapter 6) conclusions and future work are discussed. Reference is made to applications for which the TLS is intended to. Also, some ideas for upgrading the device in the future are mentioned.

1 LIGHT SOURCES

The human eye can detect only a small portion of the electromagnetic spectrum, called “visible” light. Light in general is electromagnetic radiation and “visible” light is the electromagnetic radiation that the eye can detect. The human vision is mainly restricted to a wavelength in the range of about 380nm to about 740nm.

The most common natural light source for vision 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 to navigate our environment.

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.

But now the question arises of how we can see in the invisible region. The answer is computer vision. With the development of imaging detectors we are capable to probe objects in different wavelengths. Nowadays, imaging sensors cover almost the whole electromagnetic spectrum from gamma-rays to radio waves. For object identification and geometric measurements, illumination is taken as given and optimized to illuminate objects with high contrast. Also, a light source can be used to visualize quantitatively physical properties of objects by analyzing their interaction with the radiation produced by the source.

Combining light sources and imaging detectors we can probe an object in way that we would not have thought in the past. Taking images of an object in different wavelengths we can probe the internal structure of it, the radiation that is emitted, scattered, absorbed or refracted. Also, we are capable to take images from different depths of the object, illuminating with different radiation. For example, infrared radiation between 3 and 5 μm is absorbed by the human skin to a depth of <1 mm. Thus, the imaging sensor will record only the skin temperature. On the other side of the wavelength spectrum, x-rays penetrate human body without major attenuation. Thus, the imaging sensor will record the skeletal structure.

1.1 Physics [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 1). 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.[citation needed]

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.

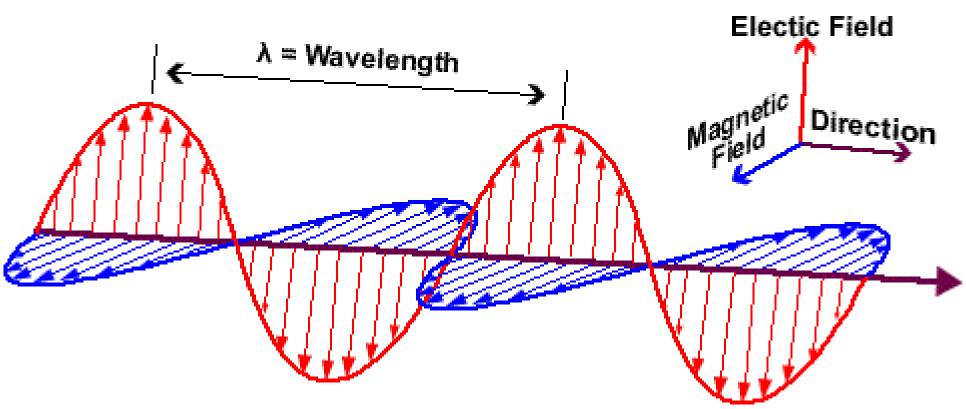


Figure 1 - Electromagnetic wave 1

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

$$E = hf = \frac{hc}{\lambda}$$

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 2 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.

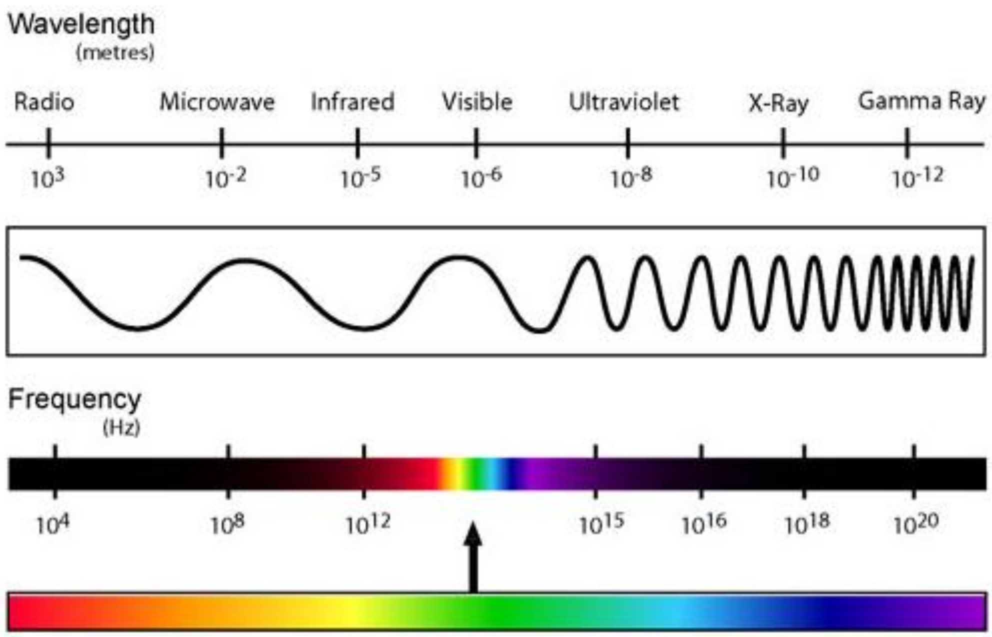


Figure 2 - Electromagnetic Spectrum

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 Continuous Spectrum Light Sources

In the previous section we discussed the basic principles of light. Thus, we are ready to focus on the main topic of this chapter, the Light Sources. Light sources are divided according to whether they have discrete or continuous spectrum. There are continuous spectrum light sources, linear spectrum light sources and continuous mid-range bandwidth spectrum light sources. In this section, we are going to discuss Continuous Spectrum Light Sources.

Light sources that emit in an **extensive or limited continuous wavelength range** are called **Continuous Spectrum Light Sources**.

We are going to present three characteristic continuous spectrum light sources.

1.2.1 Black Body Radiation Sources [2]

Black body radiation source has got as active element a red solid (conductive wire) whose temperature is controlled by the electric current flowing through it. The emitting radiation comes from free electrons of the solid which undergo statistical acceleration and deceleration due to impact with the ions of the solid. **The radiation has a specific spectrum and intensity that depends only on the temperature of the body.**

Luminance of a black body radiation source, measured in SI unit (lm m^{-2} sr^{-1}), is the amount of power which is emitted from a point on a surface in a given direction, in a frequency range dω. The dependence of these two sizes from the source temperature and the frequency of the emitting radiation is described by the Planck's law:

$$L_\omega(\omega,T)\,d\omega = \frac{\omega^2}{8\pi^3 c^2}\frac{h\omega d\omega}{e^{\left(\frac{h\omega}{kT}\right)}-1}$$

Where c is the speed of light in vacuum, k is the constant of Boltzmann and

h is the constant of Planck.

Also, from the above equation we can see that the increase in temperature, in addition to increasing the transmitted power, results in a shift of the spectrum to higher frequencies (shorter wavelengths)(figure 3). This is described by the Wien displacement law:

$$\lambda_m T = 2898\mu mK$$

Where λ_m is the wavelength of the spectrum's peak in temperature T.

For example, the Sun is an almost black body with surface temperature 6000K and λ_m~483nm which is slightly smaller

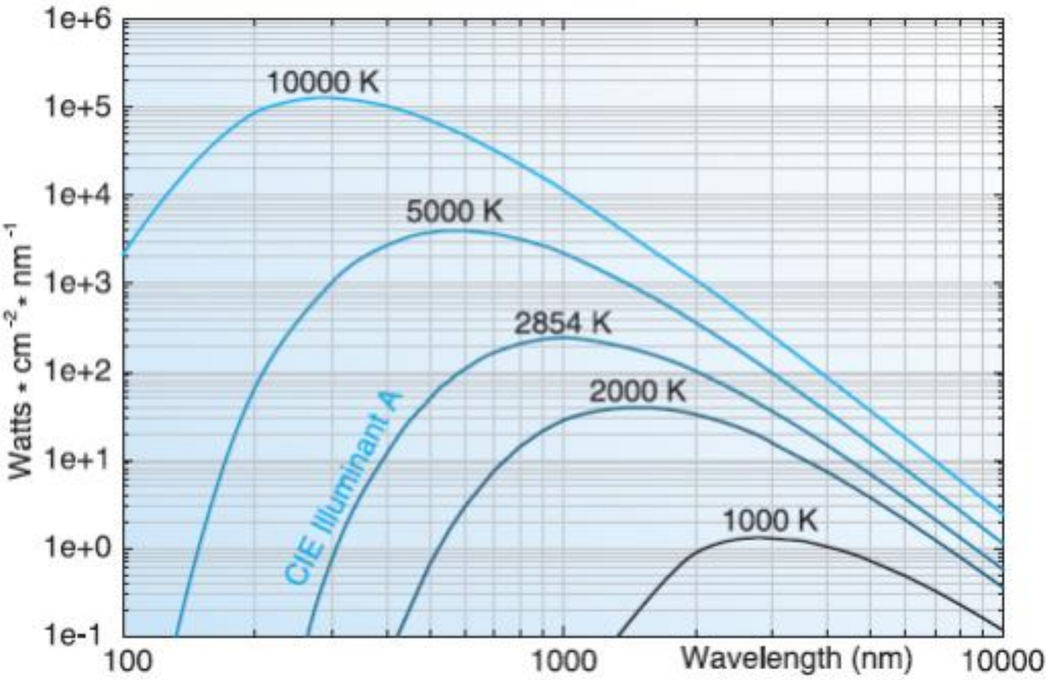


Figure 3 - Blackbody radiation at several color temperatures

There are several commercial sources of radiation, which reproduce faithfully the radiation of a black body:

- Black body simulators which are absorbent cavities of various shapes with small holes to control the emitted radiation.

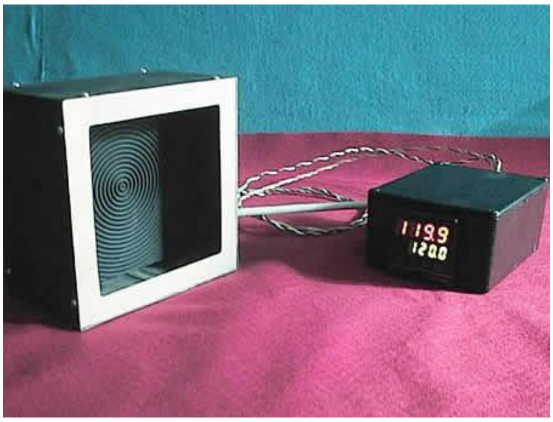


Figure 4 - Black body simulator

- Red-hot body sources consisting of a solid body, usually in cylinder form, which is heated by the flow of electric current. For example Nernst Glower (zirconium oxide (ZrO_2), yttrium oxide (Y_2O_3) and erbium oxide (Er_2O_3) cylinder), Globar (silicon carbide cylinder), Gas Matle (grid of thorium oxide).

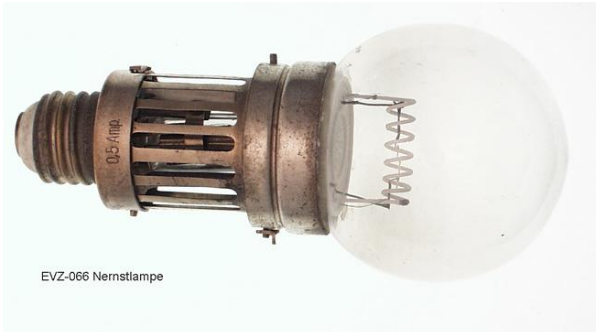


Figure 5 - Nerst Glower Lamp

- Tungsten lamps, in which usually added a small amount of halogen to increase the shelf life (Tungsten-halogen) with a black body temperature greater than 300K.

Figure 6 - Tungsten Lamp

1.2.2. Gas-Discharge Light Sources [2]

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. 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.** 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. **Each gas, depending on its atomic structure emits certain wavelengths which translate in different colors of the lamp(Figure 7).**

Compared with incandescent lamp, gas-discharge lamps offer longer life and higher efficiency, but are more complicated to manufacture, and require auxiliary electronic equipment such as ballasts to control current flow through the gas. Some gas-discharge lamps also have a perceivable start-up time to achieve their full light output. Still, due to their greater efficiency, gas-discharge lamps are replacing incandescent lights in many lighting applications.

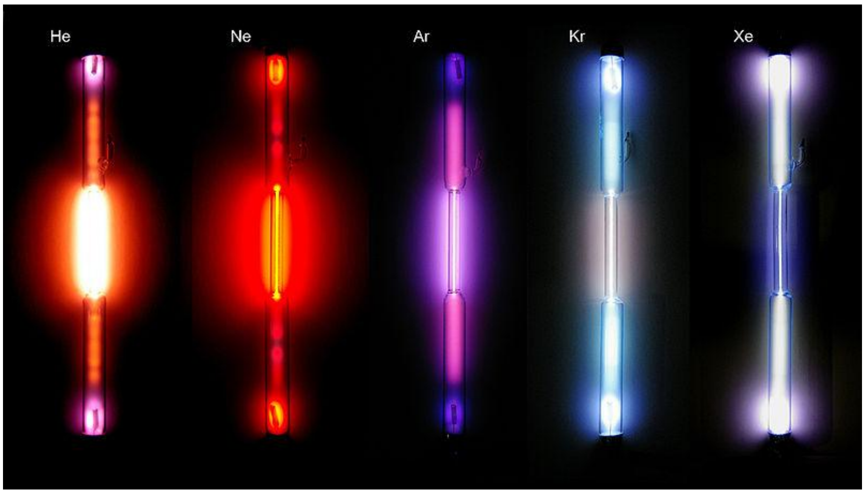


Figure 7 - Noble gas discharge tube

1.3 Linear Spectrum Light Sources

Linear Spectrum Light Sources have got active element a gas at low pressure and at room temperature. In these conditions, the broadening and overlapping of energy states of the electrons in the gas atoms are insignificant, so resurfacing the **quantum nature of the systems**, resulting in linear energy diagram and linear spectra. An example of a linear spectrum source is atomic hydrogen lamp at low pressure.

Depending on whether the radiation emitted from spontaneous or forced excitation, the linear spectrum light sources are distinguished into two categories: (a) Incoherent linear spectrum light sources and (b) coherent linear spectrum light sources (Laser).

1.3.1. Incoherent Linear Spectrum Light Sources [2]

Incoherent Linear Spectrum Light Sources are composed of a glass tube with two electrodes, in which gas in low pressure injected or in the case of metal elements, a small amount of metal (ex. Hg, Cd). High voltage is applied on electrodes resulting in electrical discharge that causes stimulation of individual electrons. The excitation of these electrons results in the 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.

In the case of hydrogen, depending on the combination of the transition of the unique electron from atomic layer n_2 to atomic layer n_1 we have the following spectral series of emission lines:

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

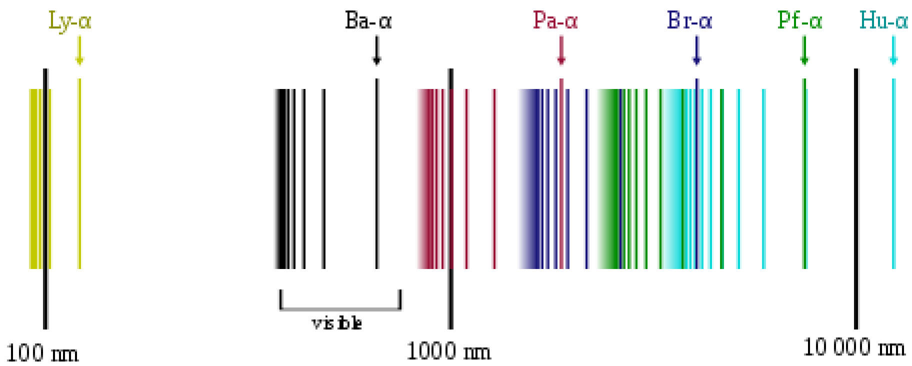


Figure 8: The spectral series of Hydrogen

The following table shows the wavelengths of the characteristic emission lines of various elements for individual regions of the visible spectrum.

Element	Color and wavelength (nm)					
	Red	Amber	Yellow	Green	Blue	Violet
H	656	-	-	-	486	410
Na	-	615	589	498	466	449
Hg	691	-	577	546	436	405
K	759	-	587	556	-	445
Kr	-	-	-	-	-	427
He	-	-	-	-	-	412
Ar	696	-	-	-	-	395
Ne	627	598	585	533	-	-

Table 2 - Colors and wavelengths of linear spectrum light sources

1.3.2. Coherent Linear Spectrum Light Sources (Laser)

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.

1.3.2.1 Physics [3]

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.

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.

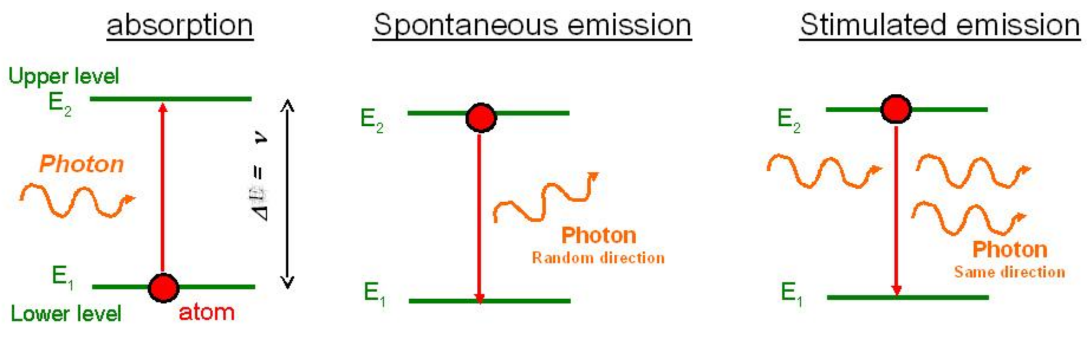


Figure 9 - Mechanism of the interaction between an atom and a photon

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.

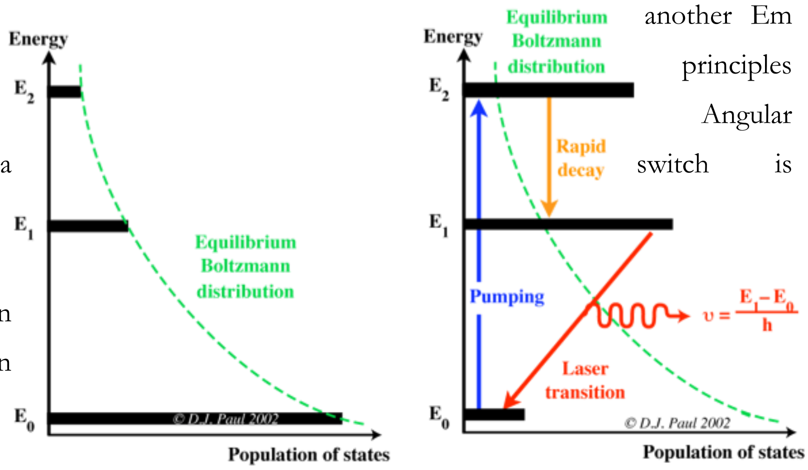


Figure 10 - Population Inversion

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.

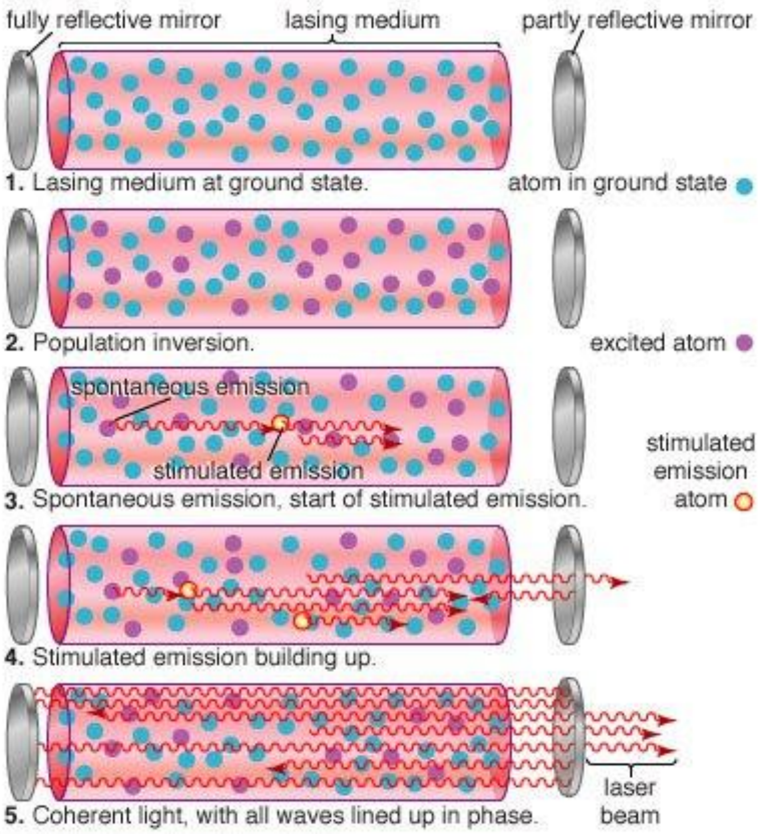


Figure 11 – Stimulated Emission in a mirrored laser cavity

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.

1.3.2.2 Gas Lasers [2]

The laser gas are 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

1.3.2.3 Solid-state Lasers[2]

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.

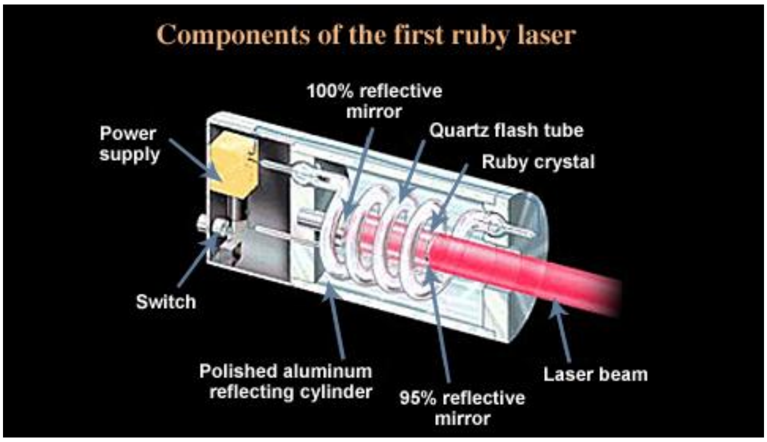


Figure 12 - Ruby Laser

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.

1.3.2.4 Semiconductor Lasers

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 13 - 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.

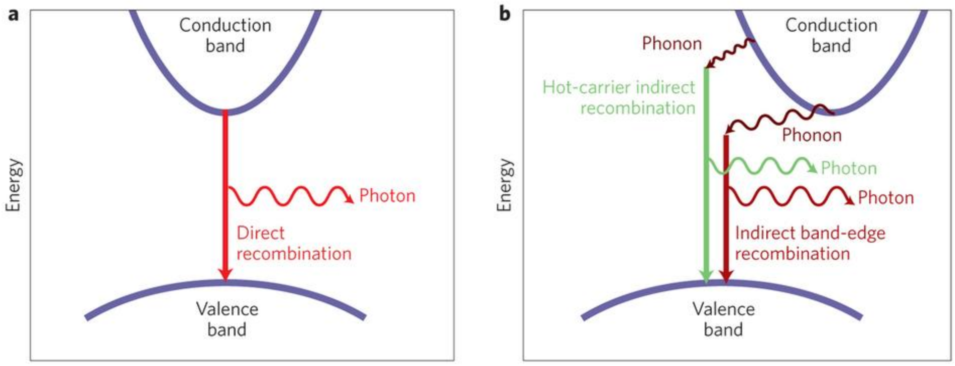


Figure 14 - Radiative recombination in direct and indirect bandgap semiconductor.

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.

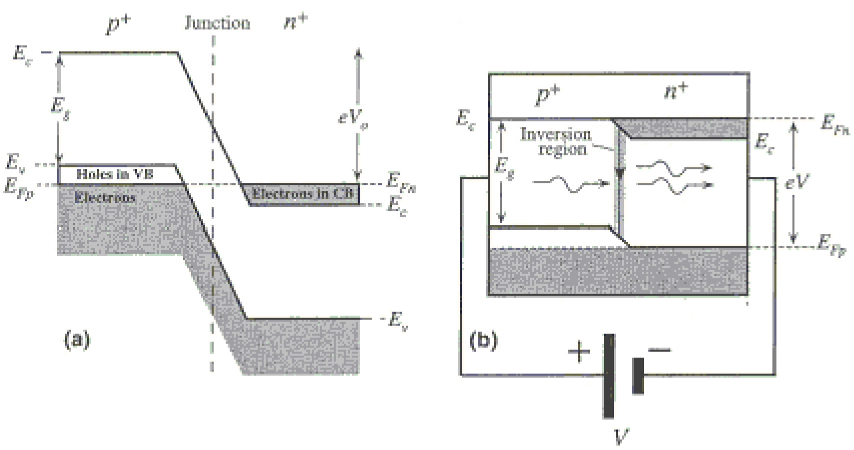


Figure 15 – (a) Diode is zero biased (b) Forward electrical bias across the laser diode causes the electrons to be excited in the conduction band and in a very small area population inversion takes place.

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.

1.3.2.4.1 Double Heterostructure Lasers[4]

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.

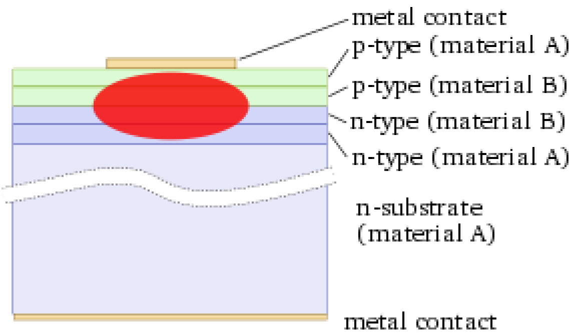


Figure 16 – Internal structure of the Double Heterostructure Laser

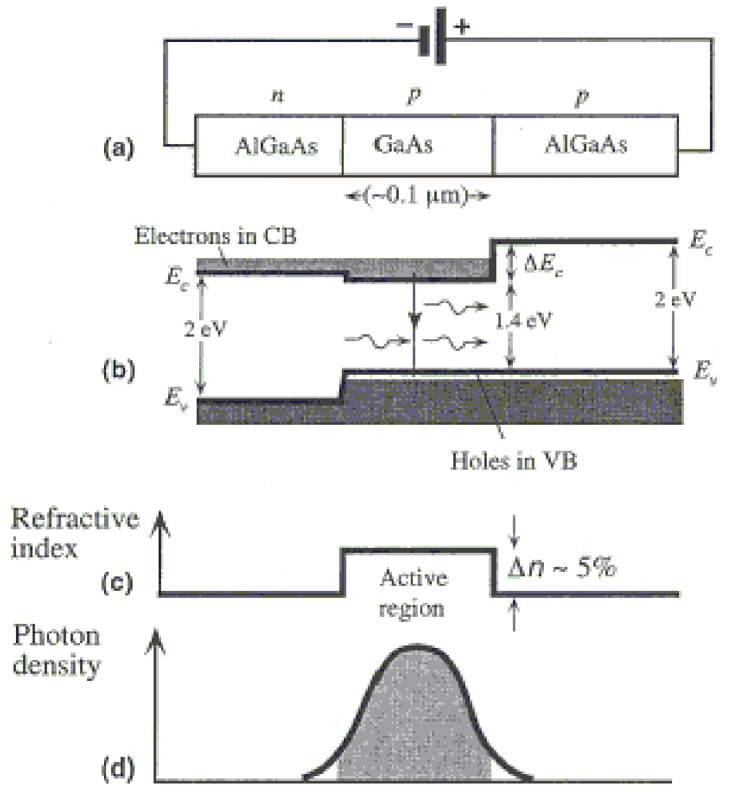


Figure 17 - Double Heterostructure Laser diode

1.3.2.4.2 Quantum Well Lasers[5][6]

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.

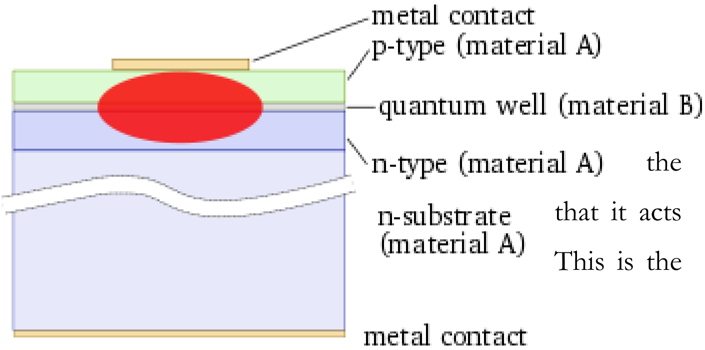


Figure 18 - Quantum Well Laser

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.

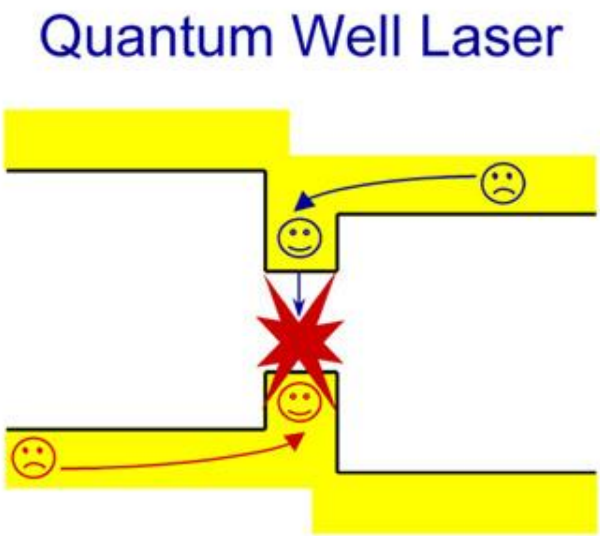


Figure 19 - Quantum Well

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.

1.3.2.4.3 Quantum Cascade Lasers [7][8]

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.

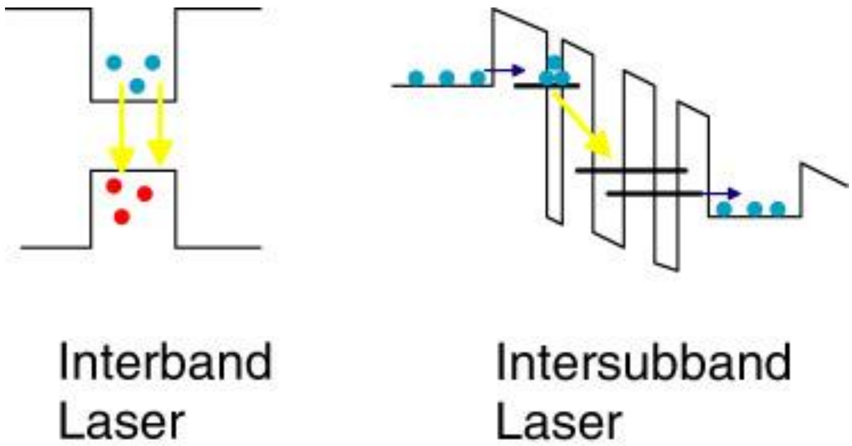


Figure 20 - In an intersubband laser, there is no electron-hole recombination.

1.4 Light Emitting Diode (LED)

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 light** sources including lower energy consumption, longer lifetime, improved physical robustness, smaller size, and faster switching.

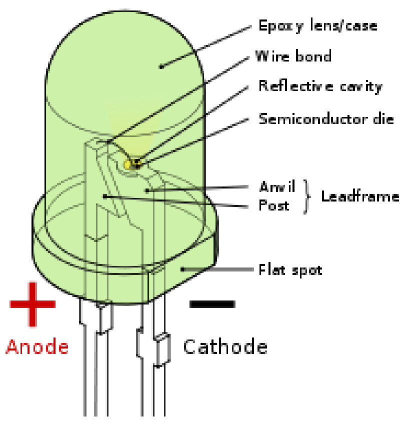


Figure 21 – Parts of a (through-hole) LED

1.4.1 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.

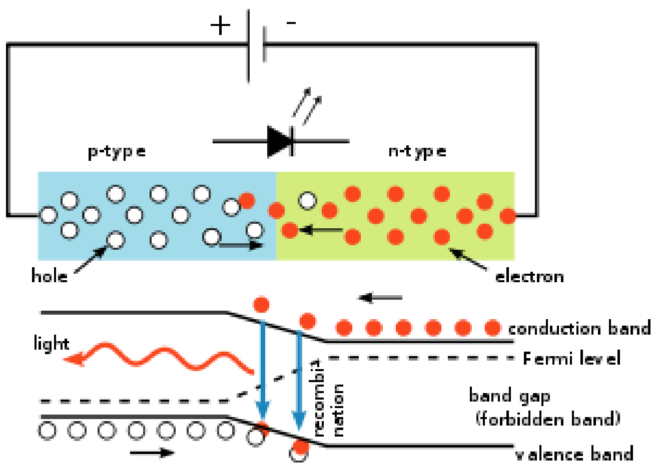


Figure 22 - Circuit and Band diagram

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 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.

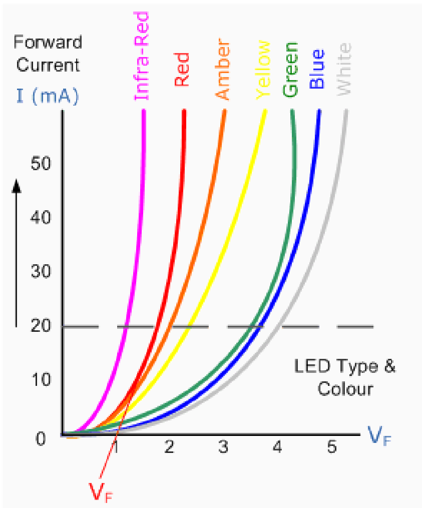


Figure 23 - I-V Characteristics Curves showing different LEDs.

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

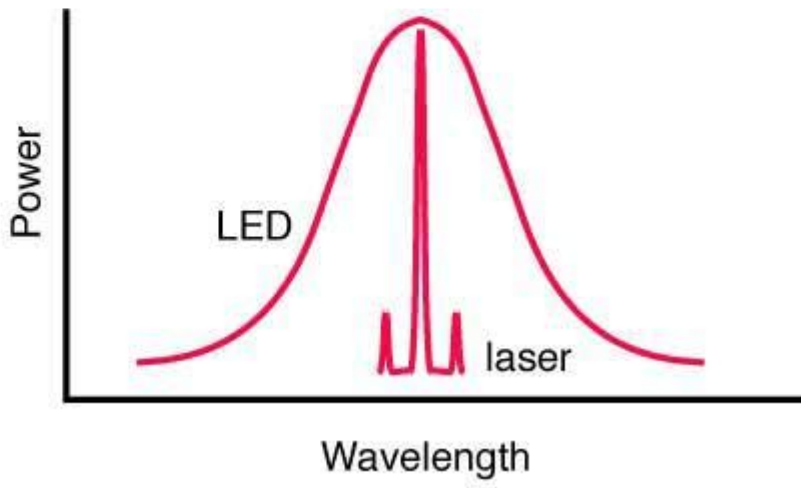


Figure 24 - Spectral width of Led and Laser

1.4.2 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 25 - 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.

1.4.3 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.

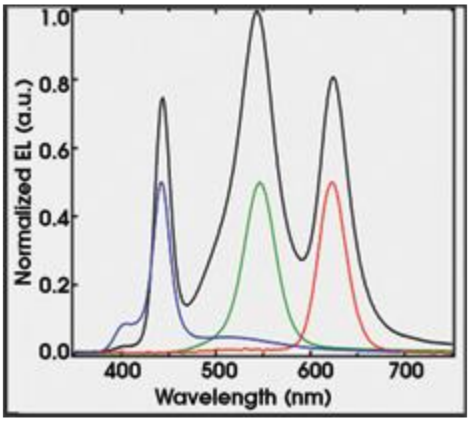


Figure 26 - White Led by mixing red, green and blue Leds

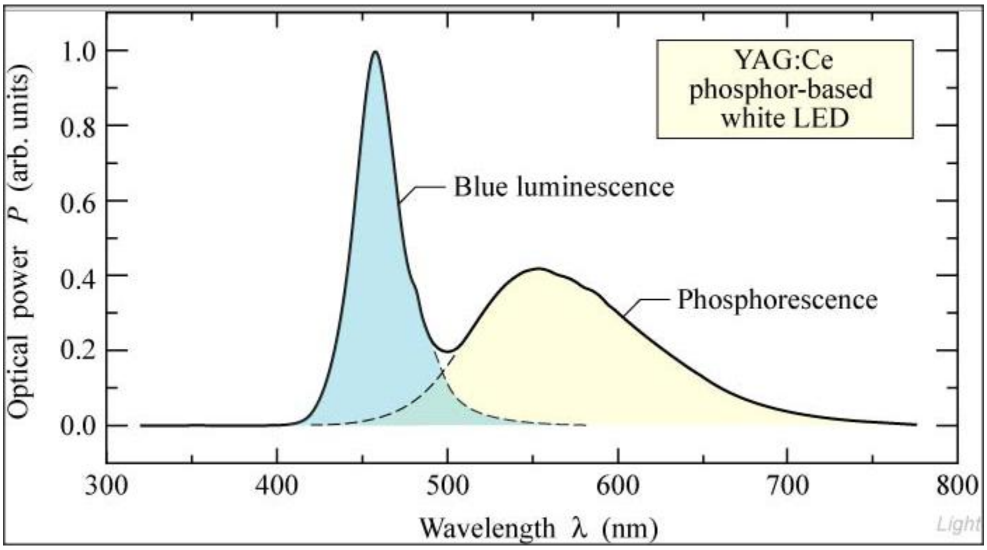


Figure 27 - Spectrum of a phosphor-based white LED

1.4.4 Organic LEDs (OLEDs) [11]

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.

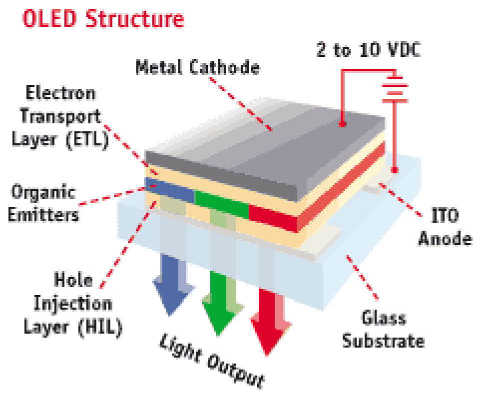


Figure 28 - OLED structure

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.

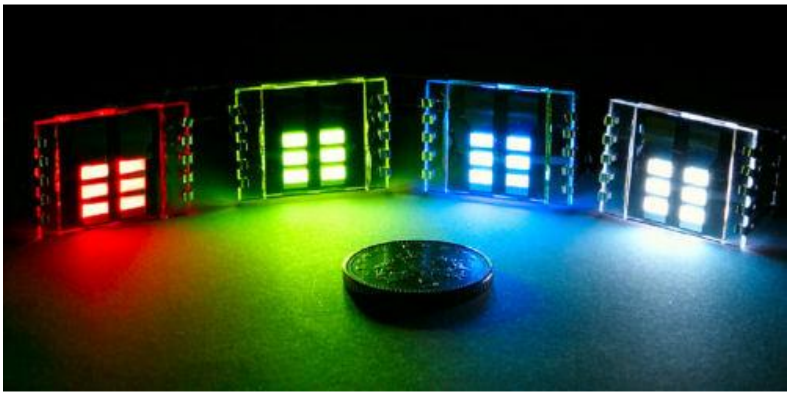


Figure 29 – OLEDs with different wavelengths

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.

1.4.5 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

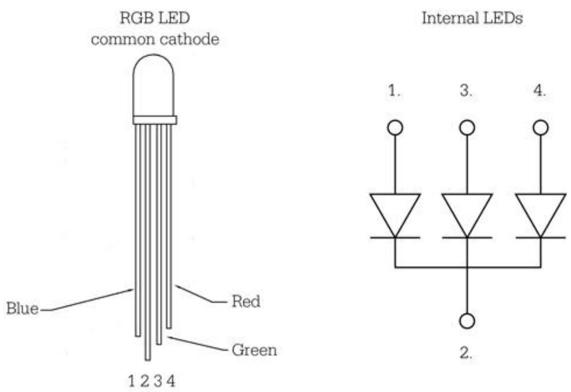


Figure 30 – Common Cathode RGB Led

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.

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.

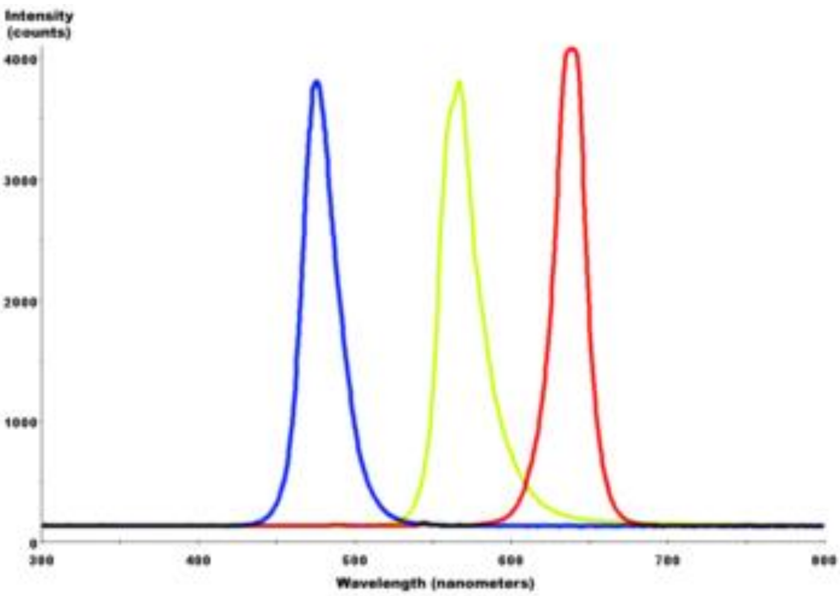


Figure 31 - Combined spectral curves for blue, yellow-green, and high-brightness red solid-state semiconductor LEDs.

1.4.6 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 32 – LED lamp using miniature white LEDs

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

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.

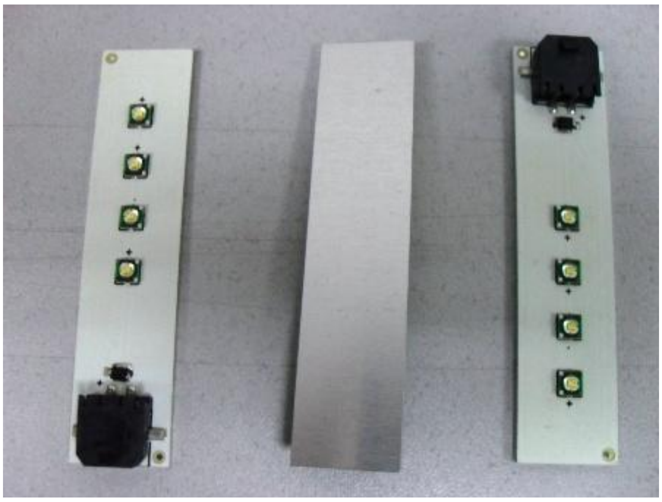


Figure 33 – High Power White LEDs on an Aluminium PCB

Mid-range LEDs

Figure 34 – 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.

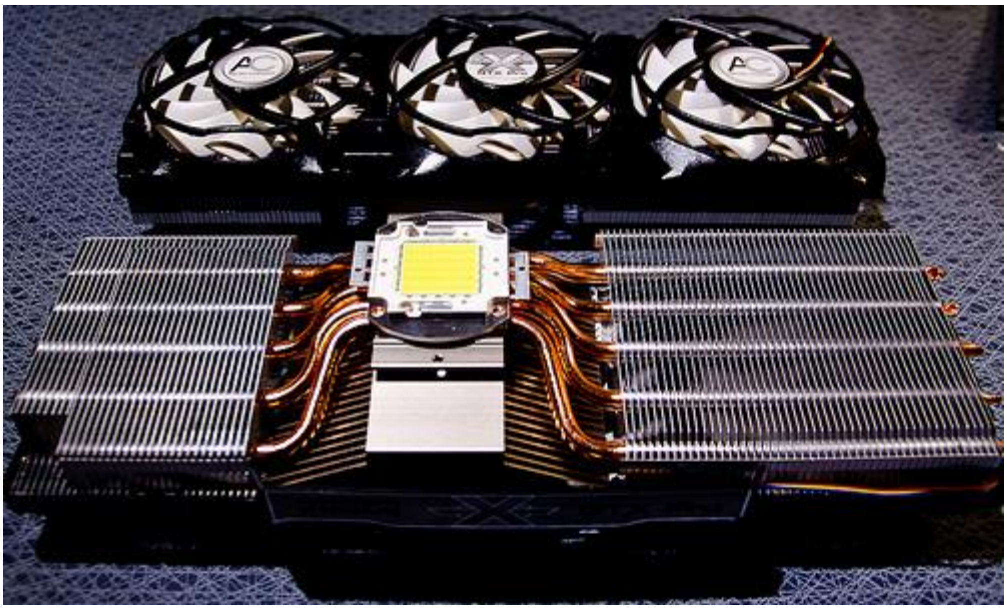


Figure 35 –High Power LED cooled with a big cooling assembly.

1.4.7 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 TUNABLE LIGHT SOURCES

In the previous chapter, there was an introduction to the concept of light from the physical side and we introduced some basic light sources. We described light sources depending on whether their spectrum was continuous or linear. So we talked about black body sources, gas discharge sources, lasers and LEDs. Of course, the drawback of these sources is that they don't give us the possibility to "tune" their spectrum. That is, there is no concept of tunability.

In this chapter, we will deal with light sources that we can "tune" their output spectrum, i.e. Tunable Light Sources (TLS). Tunable light sources are used to illuminate objects with only a small specific range of wavelengths. The spectral bands of TLS can be from UV to IR. They are used to study wavelength dependent chemical, biological, and physical changes or properties. They can also be used in color analysis and reflectivity measurements of products for aesthetic purposes.

The most common Tunable Light Source assembly is a white light source (halogen, Xe) and a monochromator. A monochromator is an optical device that transmits a mechanically selectable narrow band of wavelengths of light or other radiation chosen from a wider range of wavelengths available at the input light source. The selection of wavelengths is usually done using a diffraction grating. However, the available wavelengths depend on the spectrum of the input light source.

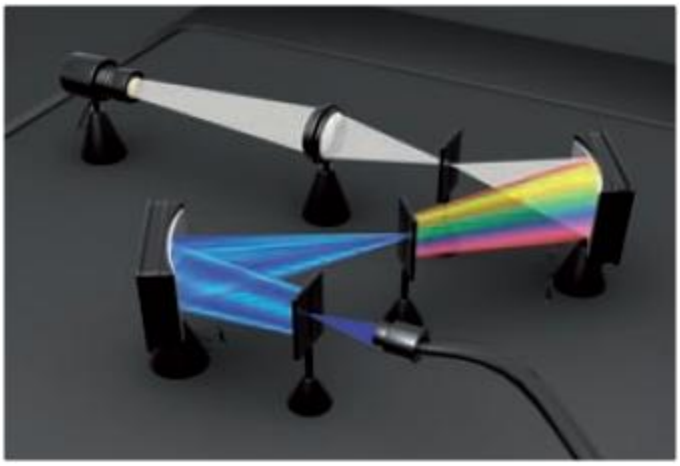


Figure 36 –The way monochromator works

The overarching goals of a TLS are excellent tunability, low cost and high power. Regarding tunability, the selection of narrow band of wavelength, such as monochromator does, is not sufficient for us. We need such a tunability so we can create a "custom" spectral curve, with the wavelengths we choose and the intensities of each wavelength we choose. Secondly, the cost is very important to be as low as possible. Third and last, the light power of the source must be as high as possible with great efficiency.

2.1 Tunable Lasers

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

2.1.1 Distributed Bragg Reflector (DBR) Laser [12]

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.**

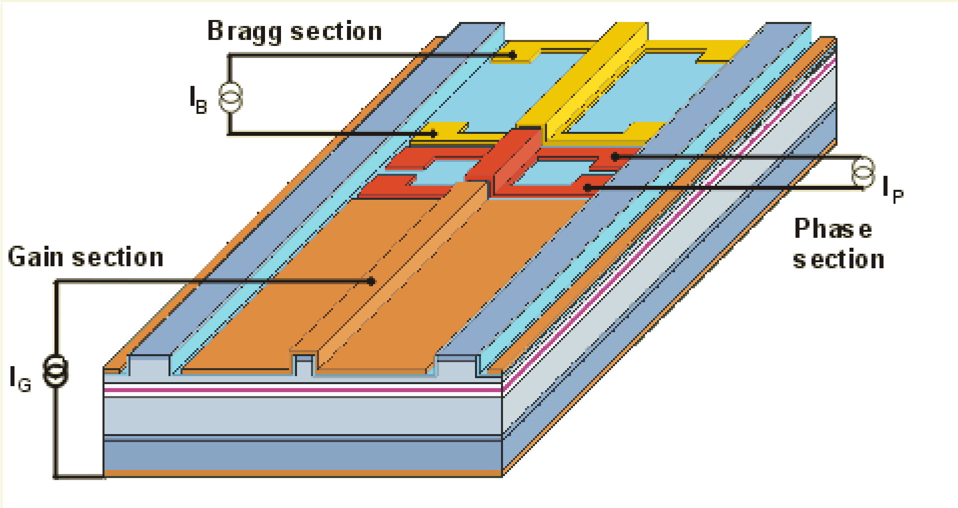


Figure 37 – Schematic of a DBR Laser

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.

2.1.2 Distributed Feedback (DFB) Laser [13]

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.

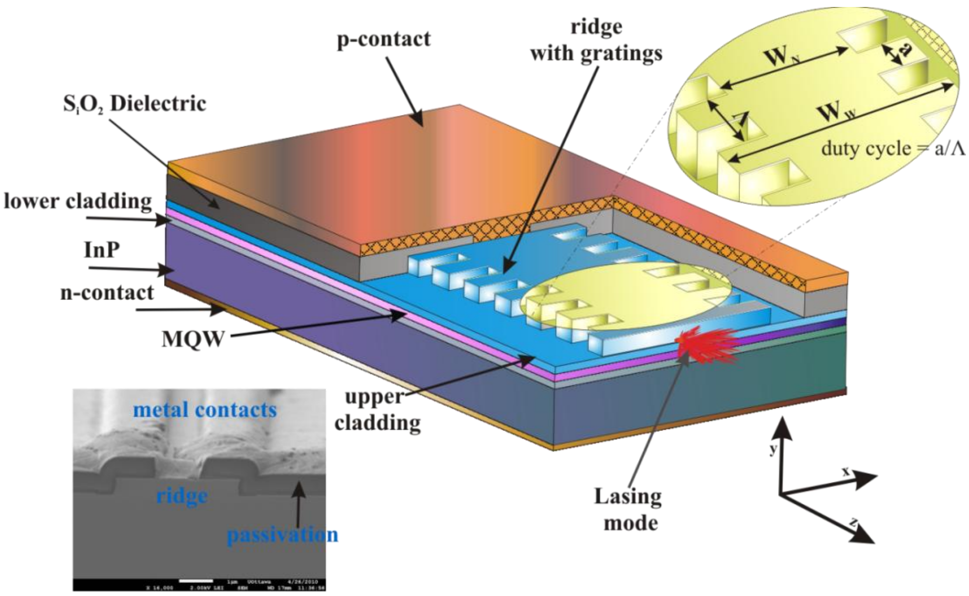


Figure 38 – Schematic of a DFB Laser

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.

2.1.3 Tunable External Cavity Lasers [14]

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.

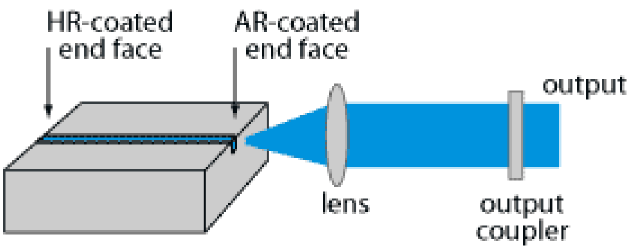


Figure 39 – Schematic of a DFB Laser

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.

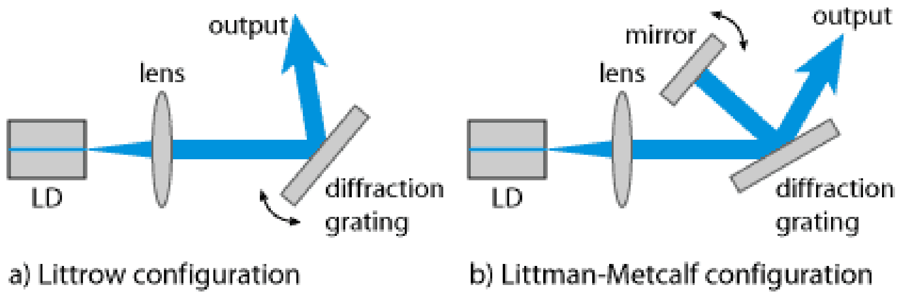


Figure 40 – Tunable external-cavity diode lasers in Littrow and Littman–Metcalf configuration.

2.1.4 MEMs Tunable Vertical-cavity surface-emitting laser[15]

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.

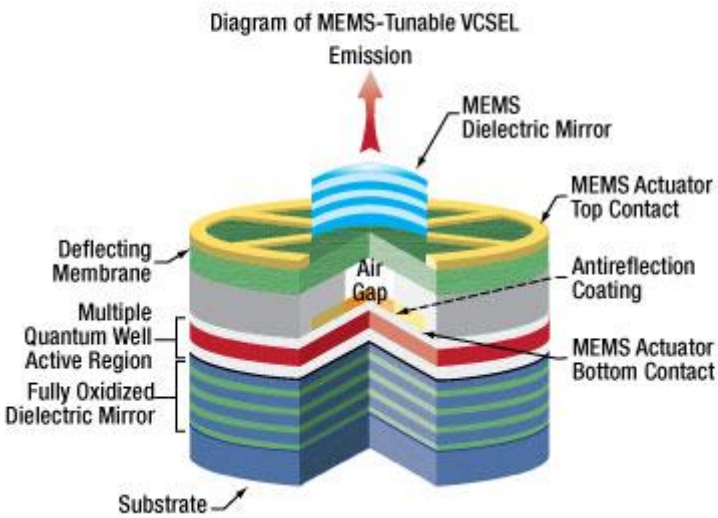


Figure 41 – MEMs Tunable Vertical Cavity Surface Emitting Diode

2.1.5 Ion Laser

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.

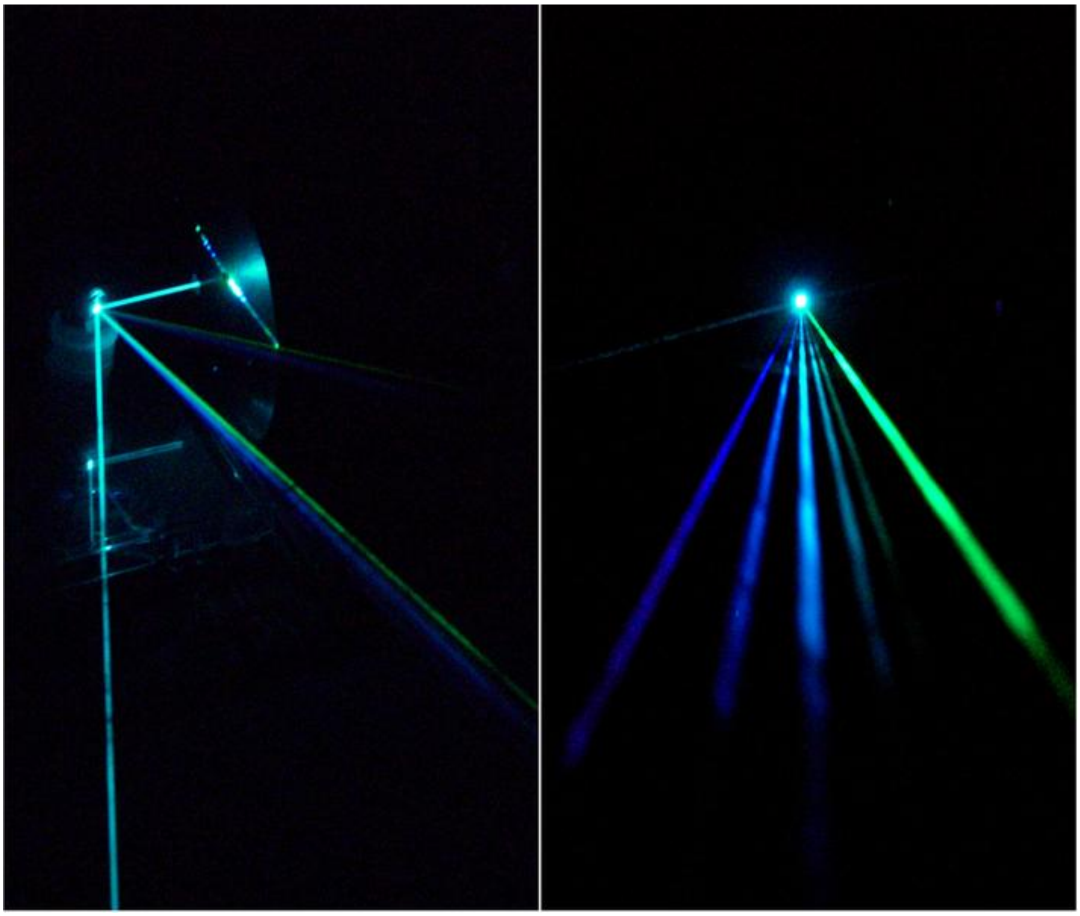


Figure 42 - An argon laser beam consisting of multiple wavelengths strikes a silicon diffraction mirror grating and is separated into several beams, one for each wavelength.

2.1.6 Dye Laser [17]

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.

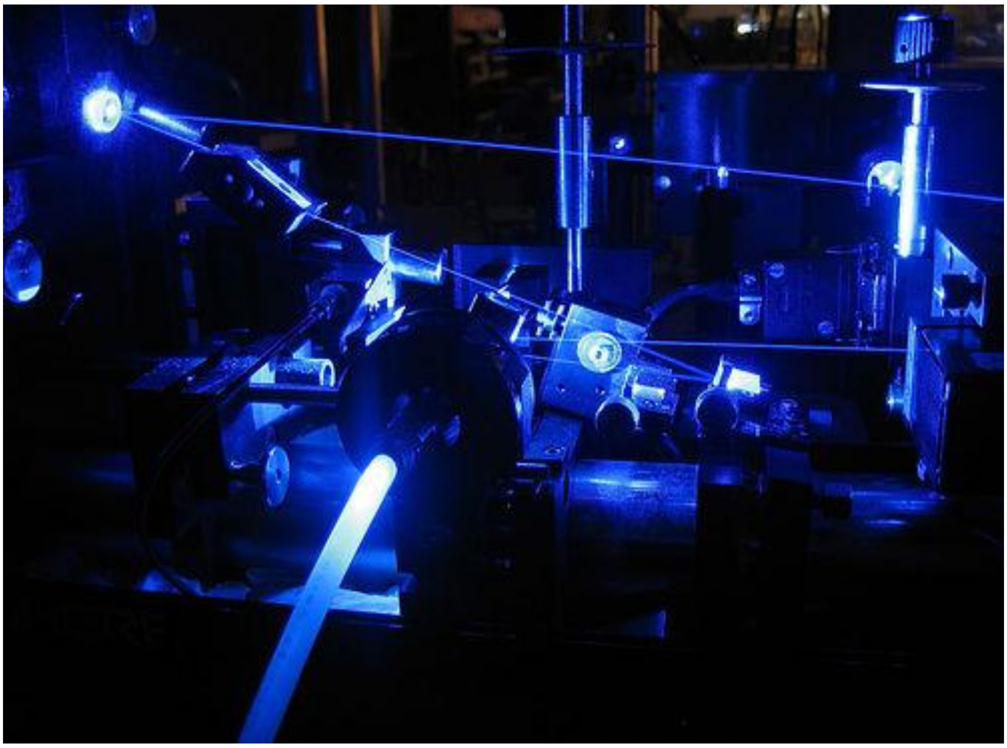


Figure 43 - Blue Dye Laser

2.2 Tunable Configurations [16]

2.2.1 Liquid Crystal Tunable Filter (LCTF)

A liquid crystal tunable filter (LCTF) is based on a Lyot filter, invented by Bernard Lyot in 1920. The Lyot filter employs polarizing interferometry to yield a narrow-band filter suitable for recording monochromatic images. It consists of N birefringent plates (retarders) each positioned between parallel polarizers oriented such that the polarizer axis forms an angle of 45 degrees to the optic axis. As it is known, a birefringent crystal, such as calcite or boron nitride, exhibits two different indices of refraction. Because of that, linearly polarized light propagating through the crystal is resolved into orthogonally polarized components, called "ordinary" and "extraordinary" rays, traveling at different speeds. This introduces a mutual optical path difference ($d\Delta n$) between these two components, where $\Delta n = n_o - n_e$ is the birefringence, no and ne are the ordinary and extraordinary refractive indices and d the thickness of the crystal. The associated mutual phase retardation is then $\Gamma = 2\pi d\Delta n/\lambda$, where λ is the wavelength. The 45o angle between the polarizer and optic axes indicates that equal ordinary and extraordinary components are transmitted. At the crystal's exit these two components are superimposed and their combined polarization depends on their mutual phase retardation. Phase retardation can turn the polarization plan of the light transmitted through the crystal so that it can in general form a non-zero angle with the axis of the output polarizer (analyzer). The projected to the analyzer's axis light intensity component will be finally transmitted from the polarizer-retarder-analyzer stage. The transmitted intensity or the transfer function of the stage is given by the formula:

$$T = \cos^2(\frac{\Gamma}{2}) = \cos^2(\pi d \Delta n / \lambda)$$

As in can be seen in equation (1), the light transmittance of the stage is a function of d, Δπ, and λ. Assuming a birefringent crystal with a given d and Δπ, and broad band light entering the stage, a certain set of wavelengths will be transmitted, while the remaining wavelengths will be rejected as not fulfilling the transmission criteria. In order to reduce the bandwidth and the number of the transmitted spectral bands, several cascaded polarizer-retarder-analyzer stages are assembled in series, with the output of one being the input of the other (Figure 44).

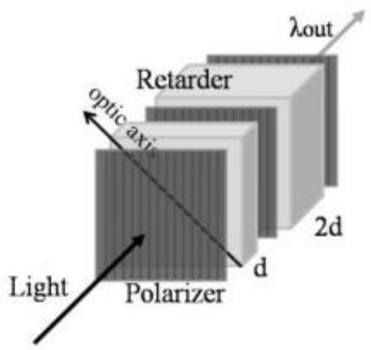


Figure 44 – A two stage Lyot filter assembly

The thickness of the retarder varies from stage to stage and more specifically, the ratio between the thicknesses of consecutive retarders (waveplates) is a factor of two. Particularly, if the thickness of the thinnest plate is d then the thickness of the jth plate is 2j-1d. The spectral transmission function of an N-waveplate Lyot filter is the product of the transmission functions of all constituent waveplate/polariser assembly and is given by

$$\mathrm{T} = \prod_{j=1}^{N} \cos^2\left(2^{j-2}\Gamma\right)$$

Apart from the optimum number of stages determining the spectral discrimination performance of the Lyot filter, it can be proved that the thickness of the first stage determines the free spectral range and the thickness of the final stage determines the spectral resolving power (Brady 2009). What it has been described so far is a multistage Lyot filter, which with a given set of alternating birefringent retarders and analyzers it behaves as a bandpass filter, transmitting certain spectral band(s). Tunability of the transmitted bands is achieved by modifying the Lyot filter for enabling the external control of the birefringence and hence the control of phase retardation (eq. 2). The Lyot filter becomes a liquid crystal tunable filter (LCTF) when thin liquid crystal layers, acting as electronically controlled phase retarders, are added to each stage side-by-side with the fixed retarders.

Two transparent electrodes are placed on either side of the liquid crystal waveplate. The liquid crystal cell contains nematic crystals that are aligned with their long axis nearly perpendicular to the light path. The inner surfaces of the liquid crystal cell are prepared in such a way that the molecules have a preferred orientation parallel to the surface. However, when a voltage is applied across the electrodes an electric field parallel to the light path generates a torque that twists the liquid crystals into the direction of electric field. The molecules are then aligning with the applied electric field, thus degreasing the retardance through the liquid crystal waveplate (Slawson 1999). The electronically adjustable retardance enables the tuning of the transmitted wavelength. The LCTF's spectral transmittance dependents on the phase shift, which inherently depends on the total retardance by both the fixed and the liquid crystal waveplate adjustable retarders. LCTF is a wonderful device offering versatile and relatively fast wavelength selection, without much image distortion or shift. Switching speed is limited by relaxation time of the liquid crystals, being of the order of ~50 msec. Special devices can be designed for fast switching (~5 msec) through a short sequence of wavelengths. LCTFs can cover both visible and infrared spectral bands but with different module assemblies, each spanning approximately one octave of wavelength (e.g. 400-750nm). The minimum output bandwidth is 5nm increasing with the wavelength up to 30nm or more. The major problem of LCTFs is their poor light throughput since half of the light corresponding to one polarization state is rejected by the input polarizer, and peak transmission of the other half probably is less than 40%. Poor filter transmittance will require long sample and sensor exposure times especially in low-light applications. Long light exposure of the sample would results in unwanted effects such as fluorophore photobleaching. Long camera integration times would in practice cancel the fast switching ability of a spectral imager integrating an LCTF. Insufficient out-of-band rejection is a second problem of LCTFs requiring extra optics for blocking light leaks. Finally, due to the thermal instability of the liquid crystals maximum operating temperature of LCTFs is low, ranging between 10o-40o, which should be taken into account when the filter is indented to be used for filtering light sources.

LCTF's science and technology evolves very rapidly because of its proven applicability in a variety of biomedical imaging applications. Recently, a number of more efficient, compact and less expensive liquid crystal based tunable filter configurations have been developed, departing from the Lyot's filter concept. Amongst the most interesting implementations, are the Holographic polymer-dispersed liquid crystals (H-PDLC) (Woltman 2007, Bowley 2001, Qi 2004, Fox 2007) and the vertically aligned deformed helix ferroelectric liquid-crystals (VA-DHFLC) (Woltman 2007, McMurdy 2006). H-PDLCs and VA-DHFLCs form photonic crystals with a tunable photonic band gap determining a range of wavelengths, which are reflected by the crystal, according to the coupled mode theory. In each case, the optical anisotropy and the responsivity of liquid crystals to electric field or heating is exploited for altering or deactivating the wavelength selectivity of the photonic crystal. The spectral resolution of both the H-PDLC and the VA-DHFLC is in the range of 15-20nm. Another very exciting progress in liquid crystal tunable filter science and technology is the liquid crystal tunable Fabry-Perot filters (LCFP). Fabry-Perot cavities are optical resonators consisted of two planar, partially transparent, reflective surfaces, separated by an intermediate medium which can be air or some kind of dielectric material. A Fabry-Perot filter is penetrable by wavelengths for which a standing wave condition is satisfied inside the cavity. In a LCFP, a liquid crystal is used as the medium. By applying potential to the crystal, the refractive index of the medium changes and therefore the transmission modes supported by the cavity are affected. This enables the control of the transmitted wavelength. Using this configuration, switching times of the order of few milliseconds can be achieved. The minimum bandwidth in each tuning step is very narrow (0.05nm) but the tuning range is not larger than 100nm. A succession of cavities may be used for broadening the range of frequencies but such a configuration is inefficient in terms of throughput, being at the same time more expensive.

LCTFs have been proved as an indispensable tool in biomedical optical imaging in wide range of in vivo and in vitro applications. Attached to an endoscope, LCTFs were proved efficient in detecting small differences in fluorescent properties of malignant versus non-malignant mice tissues (Martin 2006). Integrated with a colposcope, the LCTF was used to identify the optimum spectral bands for monitoring the uptake kinetics of biomarkers for improving diagnostic accuracy of cervical neoplasia (Balas 2001). LCTFs have also been used in hemodynamic imaging studies, in mapping of oxygen transfer and oxygen saturation levels in tumors (Sorg 2005, Scala 2009). In this study, the variation of the oxy- and deoxy-hemoglobin optical signatures in the red/NIR range of wavelengths is investigated and the information obtained is used for understanding of tumor growth and proliferation. LCTFs have been used for studying retinal oxygen saturation in retina (Hirohara 2007). Moreover, combination of LCTFs with photostable, bright, narrow bandwidth, Quantum Dots-based fluorescent probes has been used for in vivo fluorescence imaging of small animals (Gao 2004) and in human tissues (Tholouli 2006). Last, LCTFs have been used in two-photon fluorescence microscopy (Lansford 2001), for discriminating mixtures of florescent proteins.

2.2.2 Acousto-optic Tunable Filter (AOTF)

An Acousto-optic Tunable Filter (AOTF) (Tran 2003, Stratis 2001, Bei 2004) consists of an acousto-optic crystal, a birefringent material whose optical properties can be altered by applying acoustic frequencies to the crystal. Crystals that are commonly used in the construction of AOTFs are Tellurium Dioxide (TeO2), Lithium Niobate (LiNbO3) and Calcium Molybdate (CaMoO4), among others. Operation of the AOTF relies on the interaction of light and acoustic waves traveling through a birefringent crystal. The density of the atoms making up the crystal is modulated by the acoustic or pressure wave. This results in modulation of the refractive index, which is directly affected by the structure of the atoms. Therefore, a volume grating is formed and moves with the speed of sound inside the crystal.

An AOTF works in so-called non-collinear configuration when the acoustic and optical waves propagate at quite different angles through the crystal. A piezoelectric transducer, bonded to the one side of the crystal, emits acoustic waves, usually at radio frequencies (50 to 200MHz). As these acoustic waves propagate through the crystal, they cause the crystal lattice to be alternately compressed and relaxed. The resultant density changes produce periodic refractive index variations via the elasto-optic effect. This periodic perturbation acts like a transmission diffraction grating, diffracting a narrow band of spectral frequencies at a time. The undiffracted wavelengths exit the crystal at the same angle as the incident light beam (zero-order beam). The diffracted wavelength is determined by the momentum matching condition for a transmission diffraction grating, described as

$$\mathrm{K}_d = K_i \pm K_g$$

Where Kd, Ki and Kg are the wave vectors of the diffracted beam, the incident beam and the acoustic wave respectively. The corresponding magnitudes of the vectors are I^=2π^/λ0, Ki=2mi/X,0 and I^=2π^ν, where f is the acoustic frequency, V is the acoustic speed in the crystal, λü is the centre wavelength and ni, nd the indices of the refracted and diffracted beams respectively. Equation 3 describes a phonon-photon interaction in which photons of appropriate wavelength interact with phonons- the "packets of energy" transferred through the acoustic waves.

Figure 45 illustrates the principle of operation of a non-collinear AOTF. When unpolarized white light is incident on an AOTF, light of specific wavelength will be diffracted in two directions with orthogonal polarizations. One has Doppler up-shifted (+ diffracted beam) and the other has Doppler downshifted (-diffracted beam) optical frequency for the applied radio frequency. When the zero-order beam is used as output, the AOTF functions as a notch filter; if the ±1-order beam is used, the AOTF functions as a bandpass filter. The unwanted beams are rejected with a beam stop. Changing the frequency of the acoustic wave has the effect of changing the grating spacing, thus adjusting the wavelength of the diffracted beam. The wavelength of the diffracted beam is selectable at a bandwidth less than 2 nm by electronically varying the radio frequency. **When multiple radio frequency signals are applied, multiple wavelengths are simultaneously diffracted in the same direction. This is an advantage over LCTFs, which generate only a single bandpass at a time.** One should however keep in mind that AOTF devices require the incident light to be collimated.

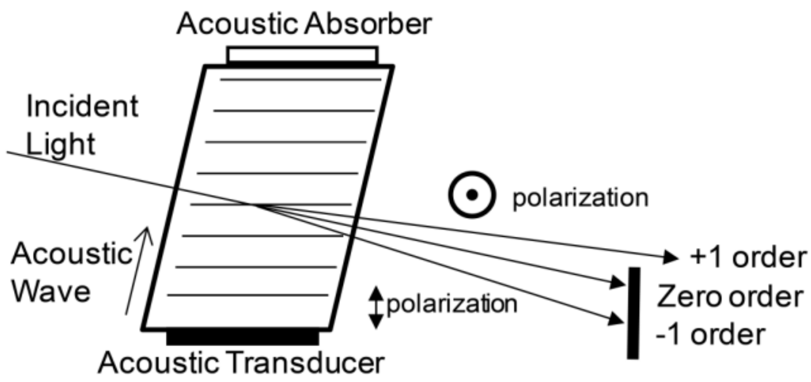


Figure 45 – Schematic representation of an AOTF

The spectral operation range of an AOTF is quite extended and depends on the material used for the fabrication of the filter. For example, for TeO_2 the operation range is 350-4500nm while for quartz crystal the range is extended to the UV range (120-6500nm). The bandwidth of the transmitted wavelength ranges from about 1nm in the UV range (using quartz crystal) to 15-25nm in the 1.5-2^m IR range (using the TeO_2 crystal). Transmission efficiency is high, reaching the value of 98% when the incoming beam is polarized. Tuning speeds are often less than 50 μsec, determined by the transit time of the acoustic wave inside the crystal.

The fact that the diffracted rays do not exit the acousto-optic crystal at a unique direction, as determined by eq.4.3, but over range of diffraction angles, causes the unwanted effects of image distortion and blurring. These affects restricted the maximum resolution to less than 1 μm and this was for a period of time the main reason that the AOTFs were not widely used for imaging applications. The first attempt to correct this deficiency is dated back to 1996 when Wachman et al. (Wachman 1996) investigated the origins of AOTF image blurring. By employing image processing techniques the resolution increased at 0.35μm. Since then, several other methods have been applied for improving image quality involving optical correction (Wachman 1997, Suhre 2005) or digital image postprocessing (Suhre 1998, Frances 2006).

AOTF-based spectral imagers have been used in several biomedical optical imaging applications (Rawja 2005, Treado 1992). Martin et al. (Martin 2006) demonstrated a dual-modality hyperspectral imager based on an AOTF, which was used for distinguishing normal from malignant mouse tissues. Wachman et al. (Wachman 1997) presented an AOTF-SI adapted to a microscope and recorded spectral images of oxyhemoglobin and deoxyhemoblobin in the brain of a living mouse. A dispersive prism was added in the experimental set-up to compensate for blurring effects. AOTFs have also been used in conjunction with fluorescence microscopes for multispectral image cytometry applications (Rajwa 2005), with confocal microscopes (Song 2008) and with endoscopes (Vo-Dinh 2004).

2.2.3 Optical Parametric Oscillator (OPO)

The last device that will be presented in this section is the optical parametric oscillator (OPO). Optically parametric oscillators are powerful solid state sources of broadly tunable coherent radiation covering the entire spectral range from the near UV to the mid IR and can operate down to the femtosecond time domain. As a result of recent advances in nonlinear optical materials research, these oscillators are now practical devices with broad potential applications in research and industry. Ever since the invention of the laser, there has always been a great deal of interest in the development of continuously tunable coherent light sources. Such sources would have broad applications in research and industry. The development of tunable oscillators has been difficult because conventional lasers tend to be discrete-wavelength devices involving stimulated emission between quantized energy levels in the laser media. Only when these quantized energy levels are tunable or there are neighboring energy levels that are sufficiently broadened to merge into each other to form a continuous band can a continuously tunable laser be built. Even then, the tuning range tends to be limited.

The optical parametric process is a nonlinear optical process in which a pump photon, propagating in a nonlinear optical crystal breaks down into two lower-energy photons with different frequencies. The crystal is placed inside an optical cavity (resonant Figure 46) and thus optical gain for parametric amplification is produced. So the difference between OPOs and lasers is that the optical gain of the output light is not based on stimulated emission. The main principle of the OPO operation is that the frequencies of the two photons produced (signal and idler) can be tuned in a wide wavelength range depending on the phase matching condition.

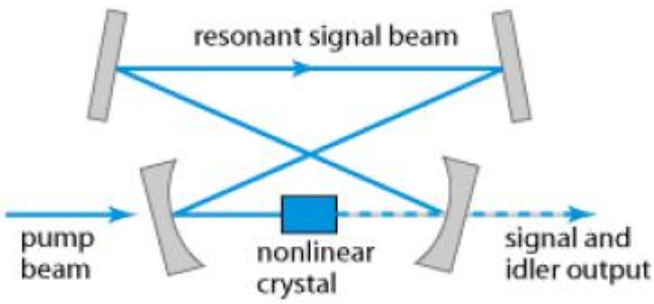


Figure 46 – Typical OPO configuration

Phase matching is defined as a group of techniques for achieving efficient nonlinear interactions in a medium. Typically the phase matching in OPOs is ensured by the use of birefringent materials. The table below presents the tuning range of some OPOs according to the nonlinear optical crystal used.

Crystal	OPO tuning range (nm)
LBO	415-2500 (λ_p=355)
BBO	415-2500 (λ_p=355)
KTP	577-4400 (λ_p=532)

Table 4 – Tuning tange of some OPOs

2.3 Central purposes: high tunability, high power and low cost

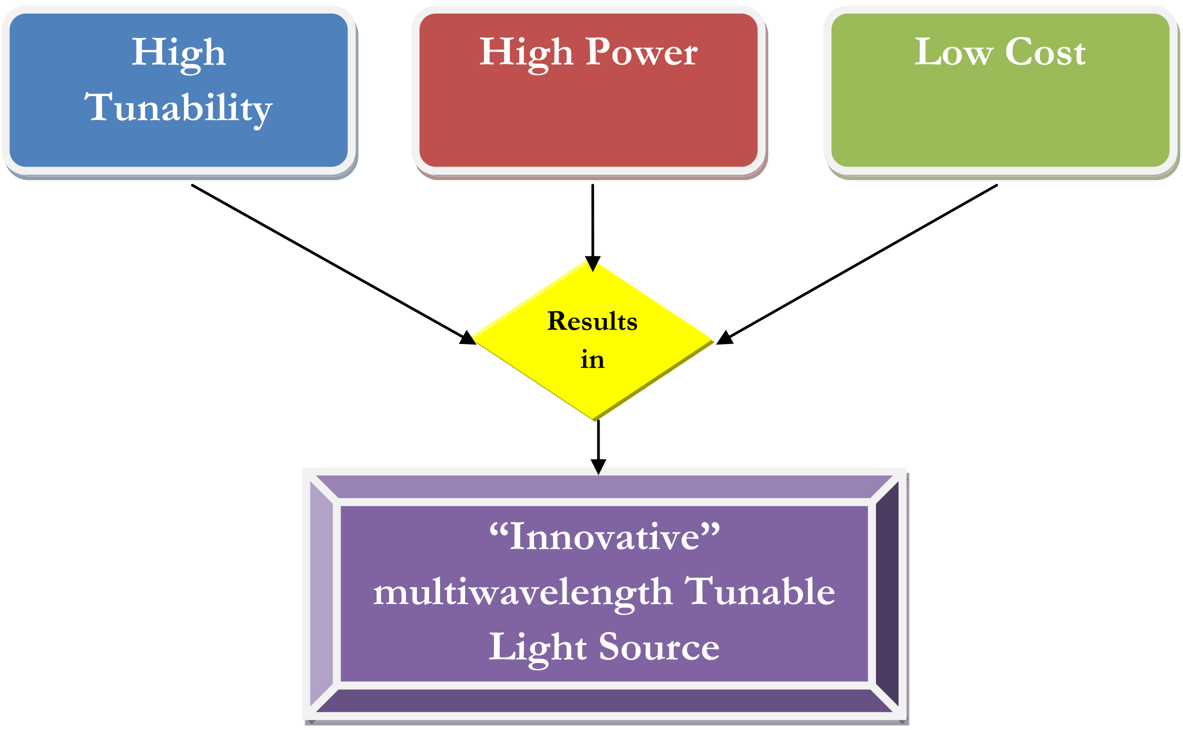
The ideal tunable light source is one that has high wavelength tunability, high power and low cost.

Regarding the **tunability**, some of the tunable light sources and configurations which described in previous sections emit on a single bandpass wavelength and others emit multiple wavelengths simultaneously in the same direction. For example, DBR and DBF lasers work in single mode and the tuning range is about 4nm. MEMs Tunable Vertical-cavity surface-emitting lasers work in single mode and are capable of tuning over 100nm. Also, Liquid Crystal Tunable Filter work in single mode and the tuning range is below 100nm. In contrast to Liquid Crystal Tunable Filter, Optical Parametric Oscillator has a tuning range which can reach about 4000nm. On the other hand, emittance of multiple wavelengths simultaneously in the same direction is achieved in External Cavity Lasers using multiple-prism grating and in Acousto-optic Tunable Filter configuration. In Acousto-optic Tunable Filter configuration, multiple radio frequency signals are applied which results in multiple wavelengths simultaneously diffracted in the same direction. However, the above sources could not achieve emittance of multiple wavelengths simultaneously with narrow spectral linewidth without complex and expensive assemblies. **Our goal is to construct a computer controlled Tunable Light Source which emits multiple (over 20) wavelengths simultaneously with very narrow spectral linewidth (FWHM) from Ultraviolet to Infrared. The selection of the wavelengths is achieved without complex and expensive assemblies.**

What about **power**? Tunable Light Sources should produce as much light power is possible. Also, efficiency is an important factor for Light Source construction. For that reason LEDs is the best choice for our lighting project. LEDs as the years pass become more efficient and powerful. Lasers require more energy to operate than LEDs but increasing the demands for optical power the cost is increasing as well. However, some lasers are very powerful but this fact conflicts with energy reduction due to the many filter stages, such as multiple prism gratings.

For the end we left the **cost**. Our goal is to construct a Tunable Light Source with low cost which means that the light source consists of a few low-cost parts. The tunable light sources that described in the previous sections have quite large cost. For example, white laser has a cost about EUR 20000. As the power increases so does the price with exponential rate. The high cost is justified by the complex structure of these sources, which most of them require machining at the nanometer scale. Furthermore, some light sources require additional optical elements to achieve tunability which increases the cost of the assembly.

Our multi-wavelength Tunable Light Source combines high tunability, high power and low cost. This combination is not found in some source of those mentioned.


High Tunability
High Power
Low Cost
Results in
"Innovative" multiwavelength Tunable Light Source

3 HARDWARE CONFIGURATION

The goal of this thesis is to construct and drive a hardware assembly that works as an excitation/emission device. Our main concern in the project is to construct a multi-wavelength Tunable Light Source using white LEDs, Monochromatic LEDs and a linear filter. LEDs are arranged on a board which is placed behind the variable filter. This tunable light source is able to illuminate in a wide range of bands (390 – 810nm) and high output intensity. Also, the device can emit up to 22 individual wavelengths with a spectral linewidth of about 20nm. So we have the ability to select any LED, thus there are 22 different wavelengths. The intensity of each emitted wavelength can be adjusted by PWM pulses with a resolution up to 1024 steps.

The following figure illustrates a general overview of the device. The components which are used in the system are depicted in Figure 47. Their description and analysis will be the subject of this chapter and the following paragraphs.

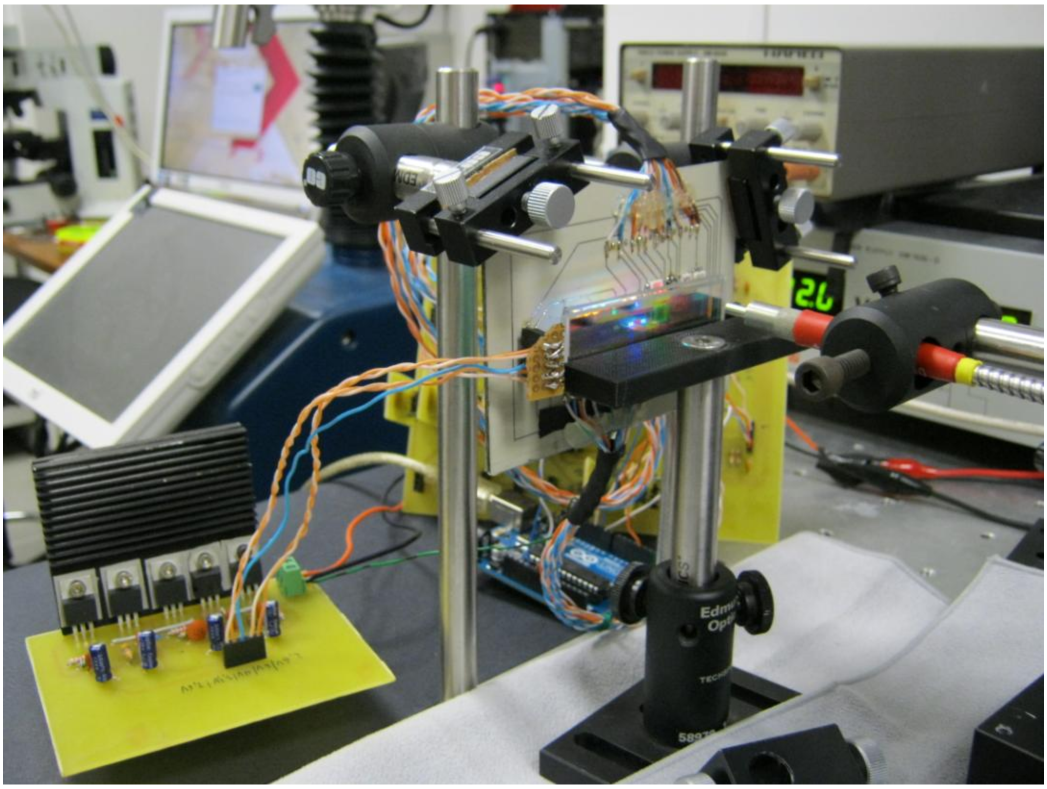


Figure 47 – System Overview

3.1 Linear Variable Filters

The tunability of our light source depends on two components; the linear variable filters used to produce (ideally) monochromatic light and the LEDs which are arranged in specific positions behind the filters. In this manner, each LED illuminates a particular area behind the filters and gives a different wavelength each time. In this paragraph we will present the main characteristics of the linear filters we used in this project.

A Liner Variable Filter (LVF) is a wedged filter, whose spectral properties vary linearly. A single LVF for example can replace a number of dedicated filters in an instrument. It is possible to adjust the position of the edge by sliding the filter.

In this thesis we used two linear variable filters from DELTA, a Linear Variable Long Wave Pass filter and a Linear Variable Short Wave Pass filter. The long-wave pass filter attenuates shorter wavelengths and transmits (passes) longer wavelengths over the active range of the target spectrum. In contrast, short-wave pass filter attenuates longer wavelengths and transmits (passes) shorter wavelength over the active range of the spectrum.

Figure 48 – Delta filter

The long-wave pass filter we used is the 1GLVLWP. This filter has cut-on wavelength from 300nm to 850nm. The average transmission in the 300-420nm band is greater than 85%. Moreover, the average transmission in the 420-850nm band is greater than 92%.

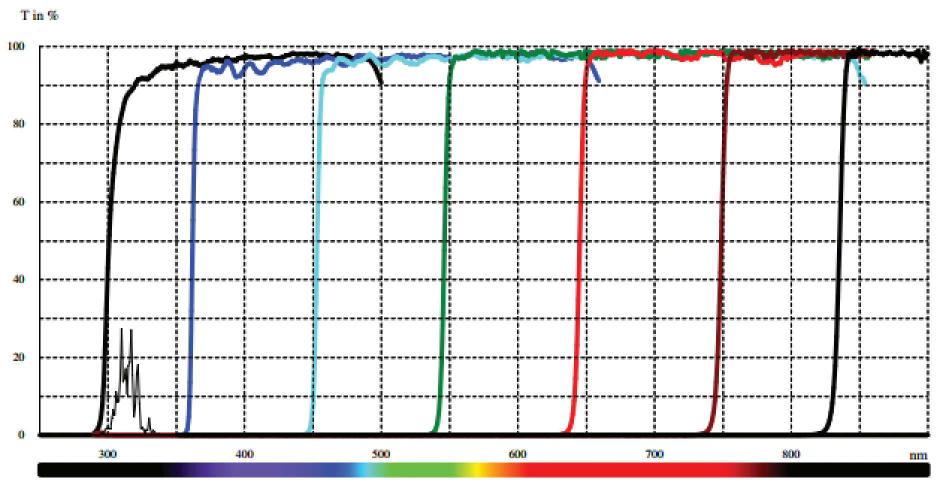


Figure 49 – Long-wavelength pass

The short-wave pass filter we used is the 2GLVSWP. This filter has cut-off wavelength from 340nm to 850nm. The average transmission in the 340-420nm band is greater than 70%. Furthermore, the average transmission in the 420-500nm band is greater than 85% and in the 500-850nm band is greater than 92%.

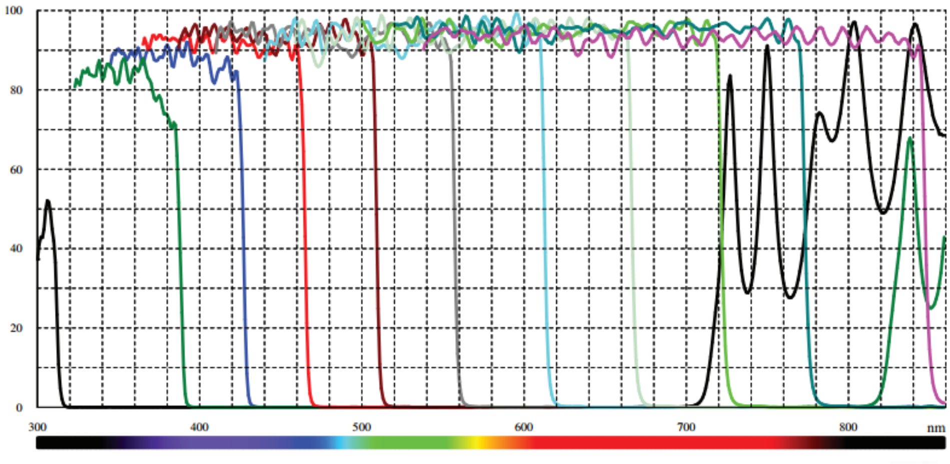


Figure 50 – Short-wavelength pass

In our design, we combined the two linear filters and this resulted in a custom bandpass filter with excellent performance compared to a regular bandpass filter. This is based on the fact that by sliding one filter to the other and vice-versa it is possible to have a tunable full width half max.

3.2 LEDs

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.

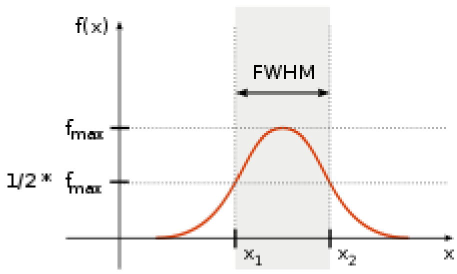


Figure 51- FWHM

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.

3.2.1 White LED

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 48 illustrates the specific white LED used in this project, Nichia NF2L757ART. This LED emits warm white light.

Figure 52 – Nichia NF2W757ART

Nichia 757 LED series is a medium power SMD LEDs from Nichia. Of course, considering its small size (3mm x 3mm) we can characterize it as high power LED for its category. At 1.3 Watt this LED can reach an amazing 189 lumen for warm white. The efficiency is excellent having 145 lumen per watt. Durability, extreme brightness and performance are among the major strengths of this LED. Also, the viewing angle of the LED is 120°.

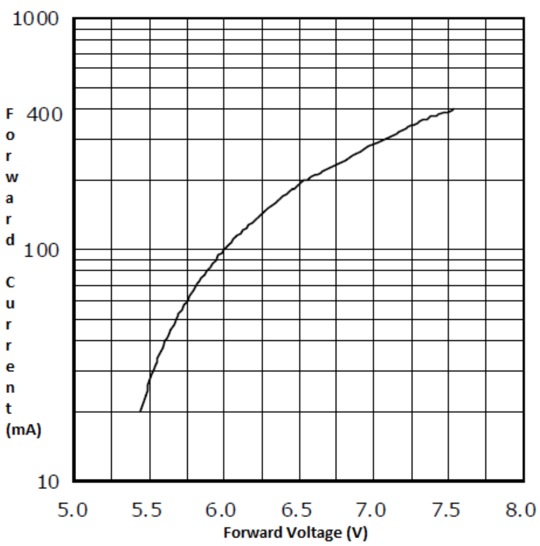


Figure 53 – Forward Voltage vs Forward Current

The color of the LED is warm white and color temperature is 2700k. The spectrum of the LED is illustrated below in Figure 54.

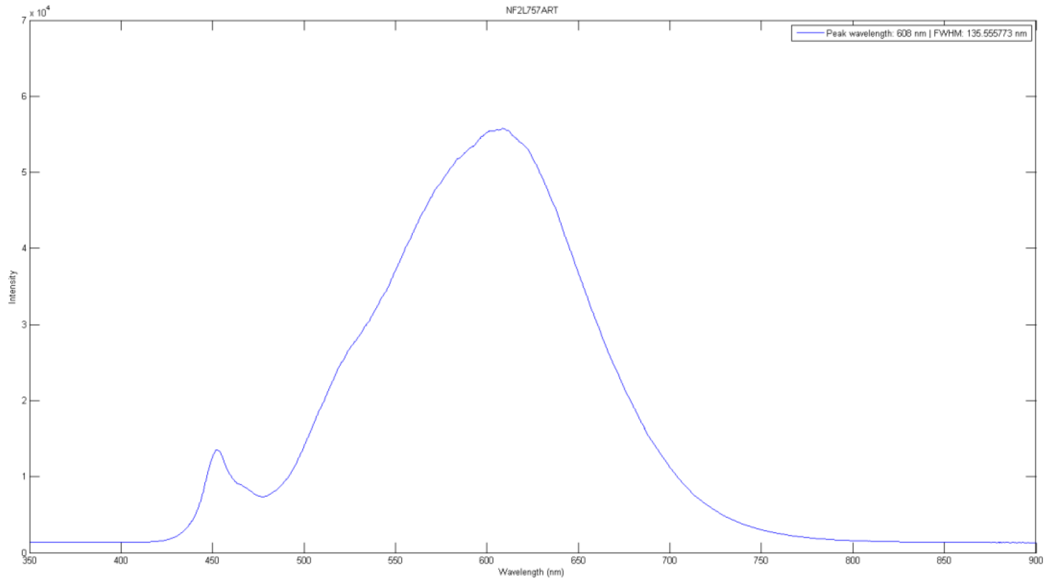


Figure 54 – Spectrum of the Nichia LED

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.

Furthermore, the 470-520 nm region forms low relative emission intensity well below 40%. So monochromatic LEDs must be used in order to have high emission intensity.

About heat dissipation, Nichia 757 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.

3.2.2 Monochromatic LEDs

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°C. The output optical power of this LED is up to 260mW. The spectrum of the LED is illustrated bellow.

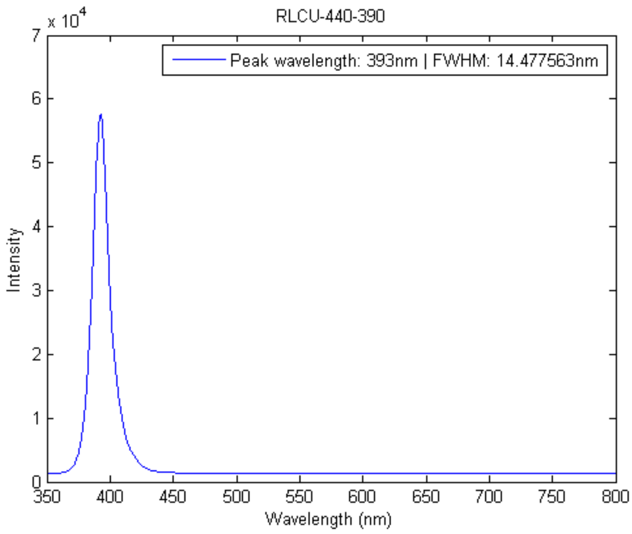


Figure 54 – LED390 response

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.

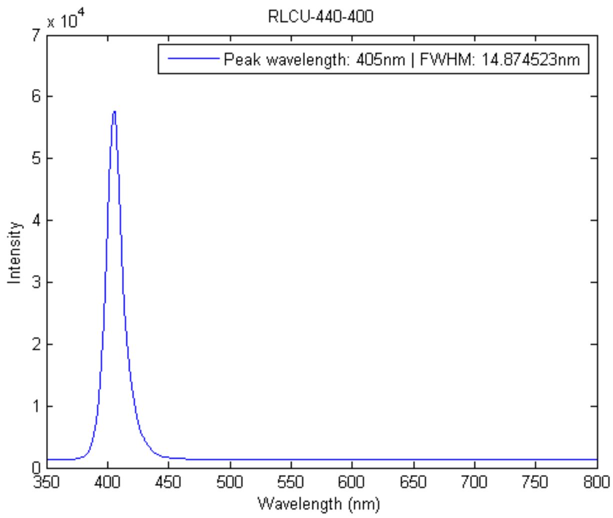


Figure 55 – LED400 response

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.

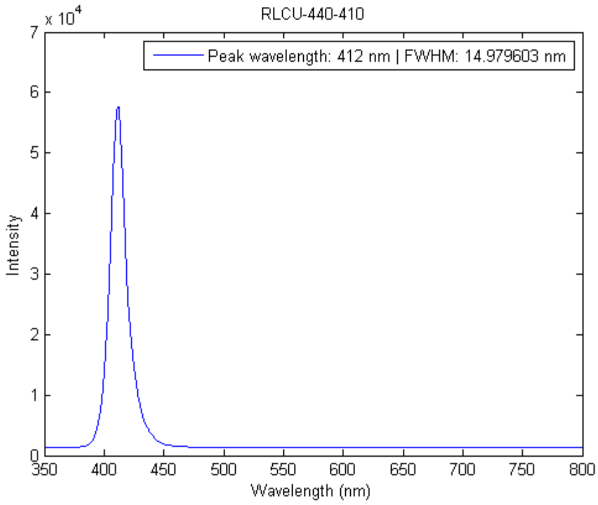


Figure 56 – LED410 response

415nm 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.

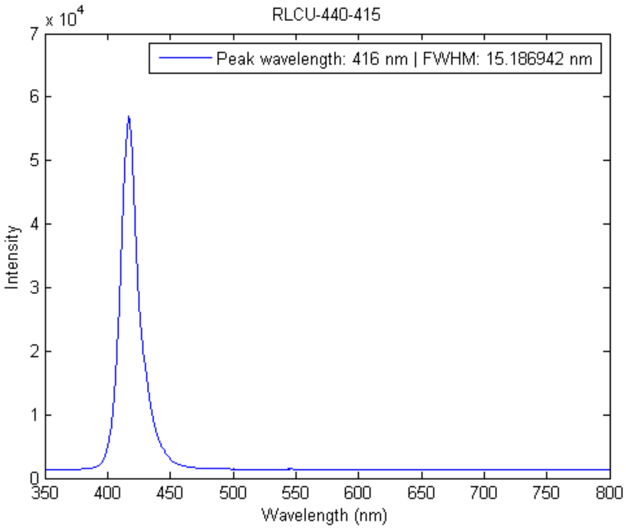


Figure 57 – LED415 response

470nm peak

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.5.0x1.8 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.

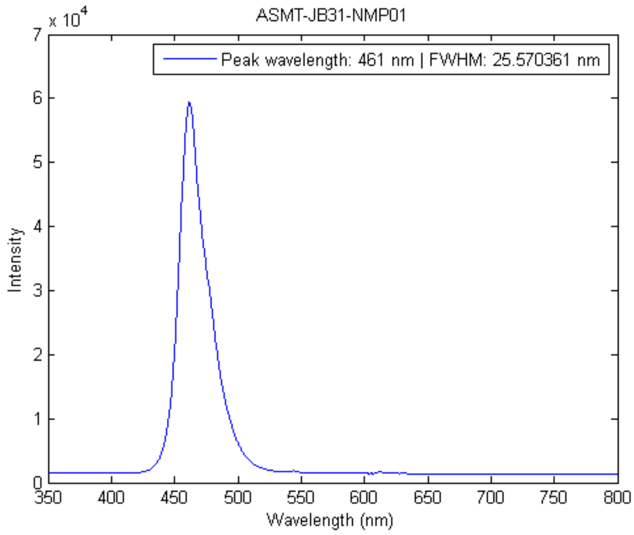
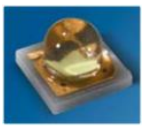


Figure 58 – LED470 response

505nm peak



This LED is a green single chip Emitter LED by Osram Opto Semiconductos, 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.

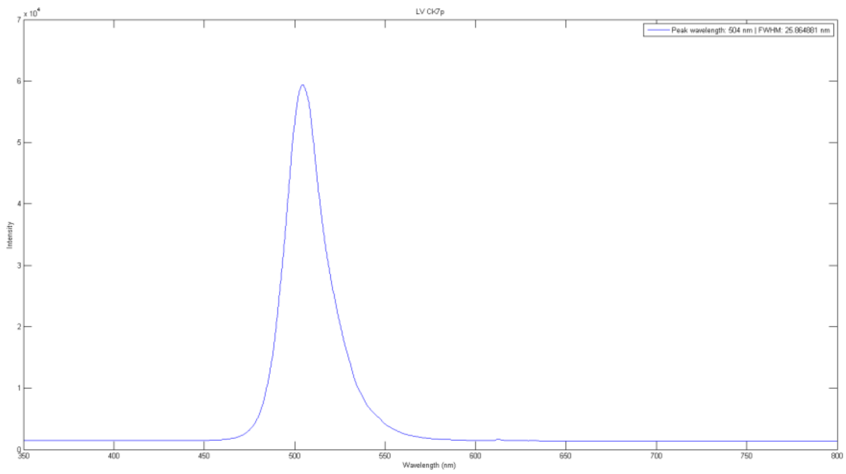


Figure 59 – LED505 response

520nm peak

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….120° C. The typical luminous flux of this LED is 130lm. Also, the viewing angle is 140°. The spectrum of the LED is illustrated bellow.

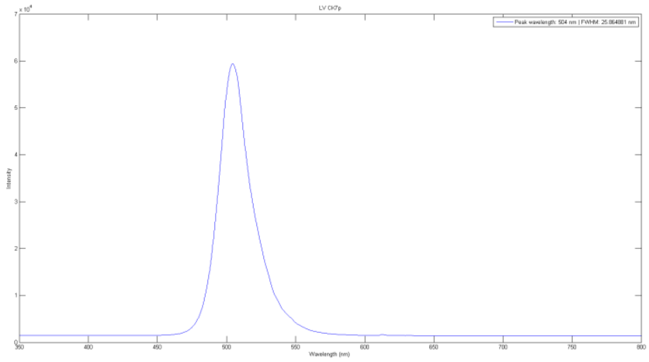
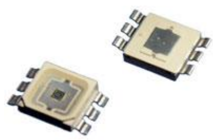


Figure 60 – LED520 response

670nm peak



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. It is high power SMD LED with chip size 1x1mm^2 mounted on copper heat sink into a hermetic ceramic SMD package. 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 124°. The spectrum of the LED, as measured with spectrometer, is illustrated bellow.

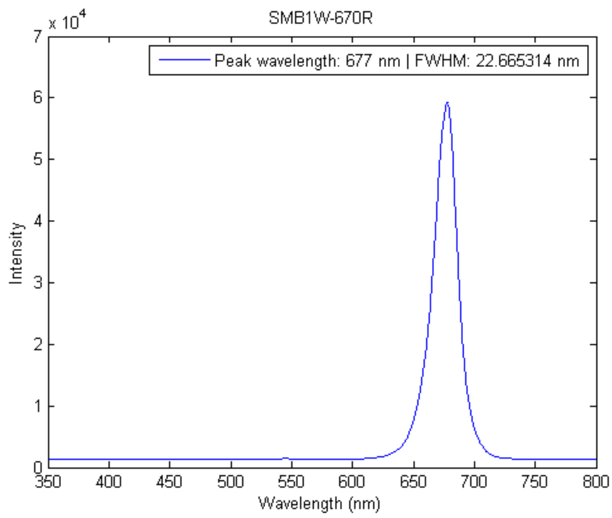


Figure 61 – LED670 response

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.

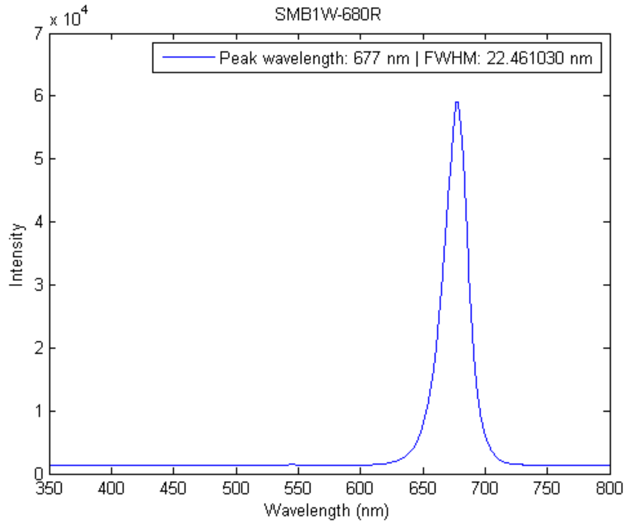


Figure 62 – LED680 response

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.

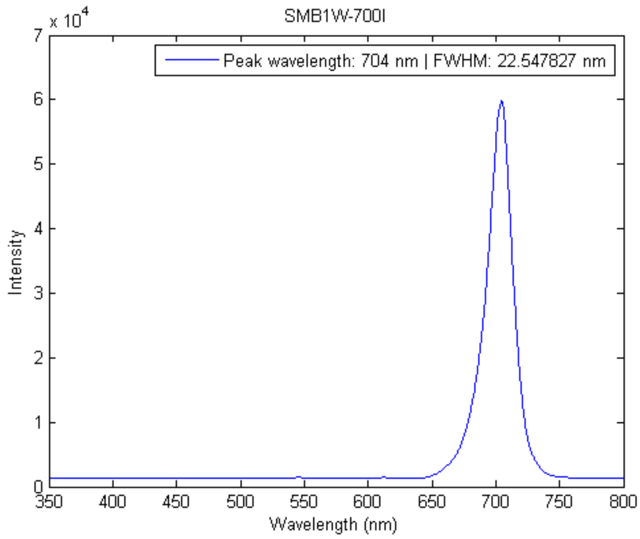
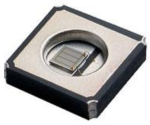


Figure 63 – LED700 response

720nm peak



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°C. The output optical power of this LED is up to 50mW/sr. Also, the viewing angle is 120°. The spectrum of the LED, as measured with spectrometer, is illustrated bellow.

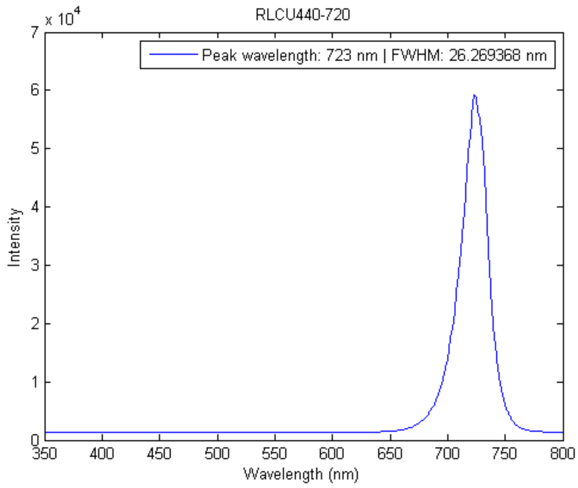


Figure 64 – LED720 response

730nm peak

This LED is an Infrared single chip Emitter LED by Everlight, Shuen series. The peak wavelength of this LED is λ_{peak}=730nm. It is a high power SMD LED. The dimensions of the LED are 3.05x4.5x2.0mm and the operation temperature is -40….100°C. The output optical power of this LED is up to 125mW. Also, the viewing angle is 120°..

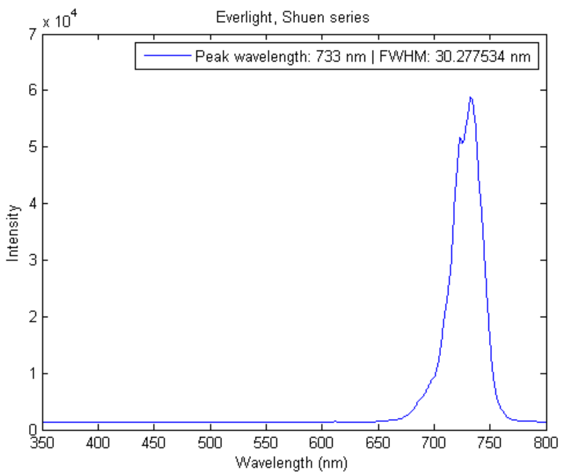


Figure 65 – LED730 response

740nm peak

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.

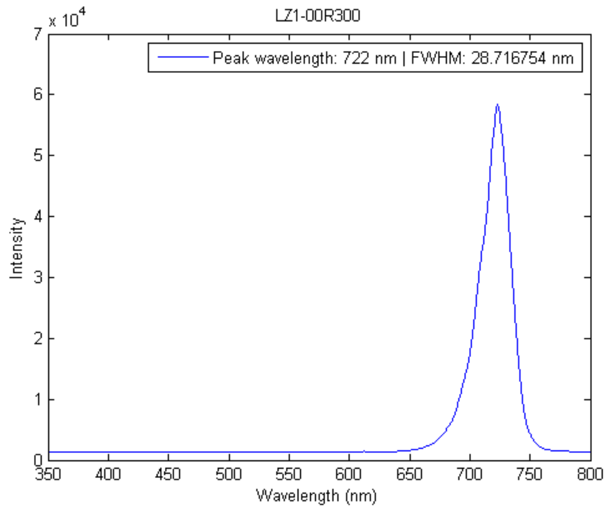


Figure 66 – LED740 response

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.

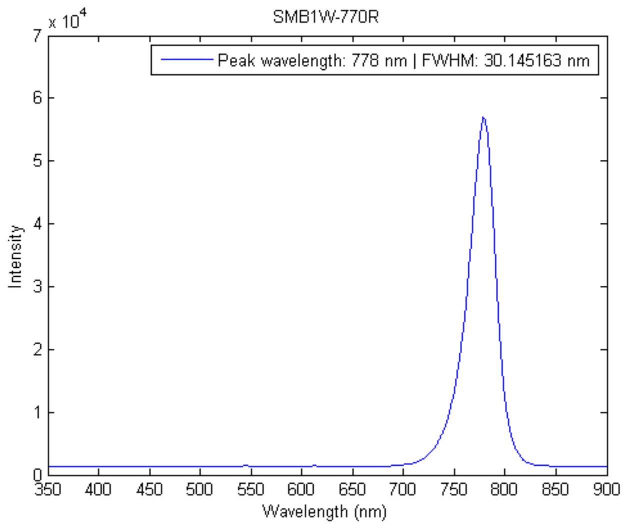


Figure 67 – LED770 response

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.

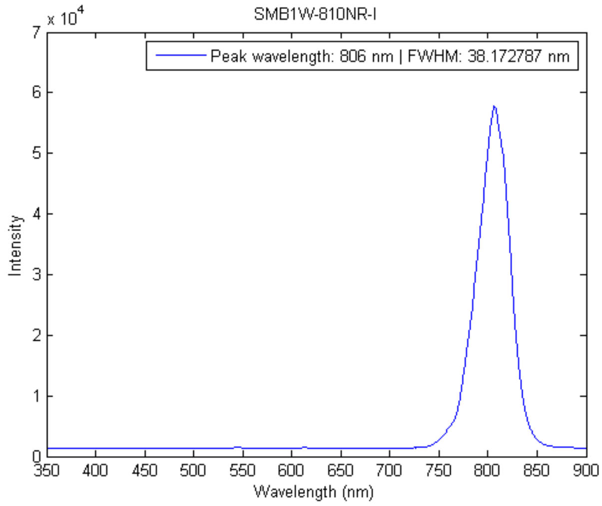


Figure 68 – LED810 response

3.2.3 LED Board

As we mentioned before, LEDs are placed behind the Variable Filters in specific positions. Also, as we mentioned in the presentation of the LVFs, the two LVFs combined into a bandpass wavelength filter. So, the center wavelength of the filter shifts linearly across the length of the filter. Thus, placing a LED behind a specific point of the filter, the output light spectrum will be a narrow curve (FWHM<20nm) with one center wavelength.

So, the main concern is the correct spatial arrangement of LEDs behind the linear filter and how many LEDs fit on the 'custom' bandpass filter surface. Regarding these issues, we have restrictions derived from the size of the LEDs and the size of the filters. The spatial arrangement of LEDs can be along and across the 'custom' bandpass filter, depending on the LED's wavelength and the filter's wavelength transmission on the specific point. . We consider that the center of the core of the LED is exactly behind the specific point of the center wavelength of the filter.

To make this possible, LEDs, since the LEDs are SMD (surface mount device), are placed in a Printed Circuit Board (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.

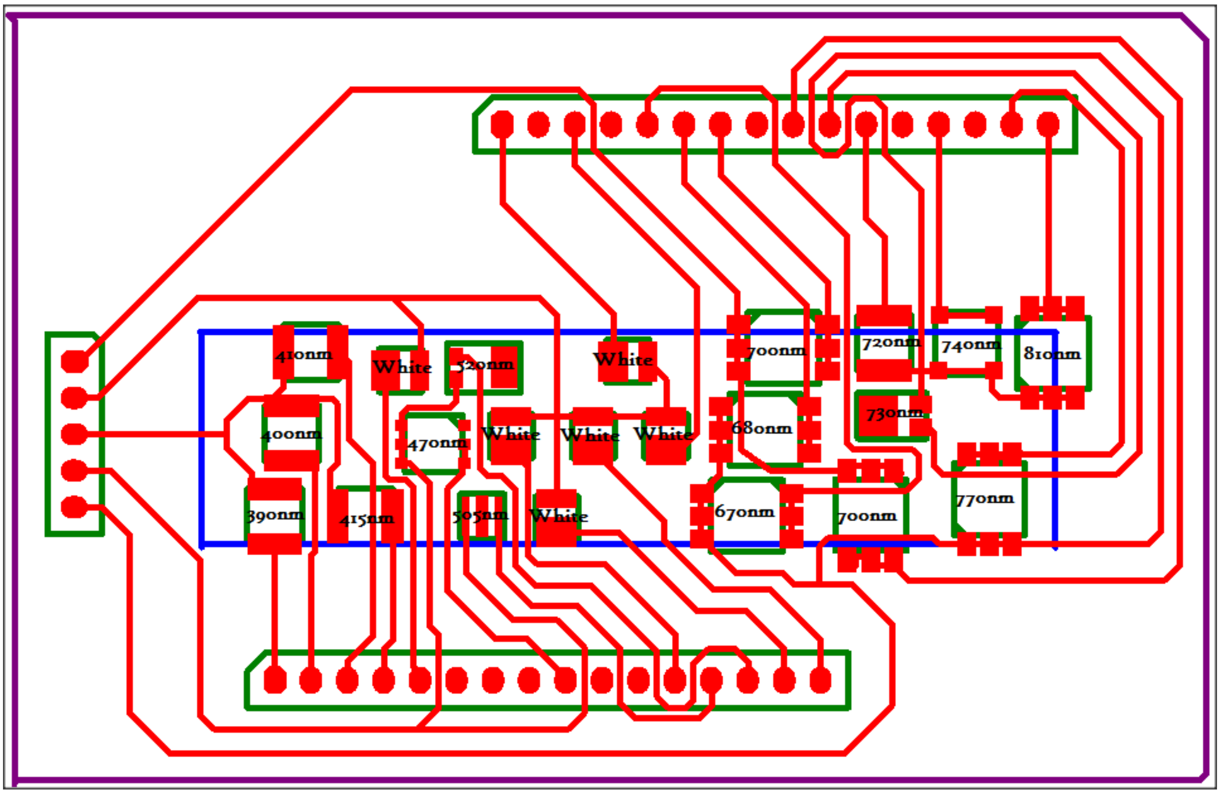


Figure 69 – LED PCB design

The first task is the designing of the PCB on an Electronic Design Automation software package. The program we used for this design is Protel. 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. Figure illustrated the PCB design on Protel.

We used 17 monochromatic and 5 white LEDs. Each LED, depending on its wavelength, is positioned at a specific point in the PCB so that when the filter is placed at the front of the board the LED will emit on the appropriate point of the filter.

Regarding the power supply of the LEDs, they divided into 5 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 will be presented later. 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 Driver board, which will be presented later.

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.

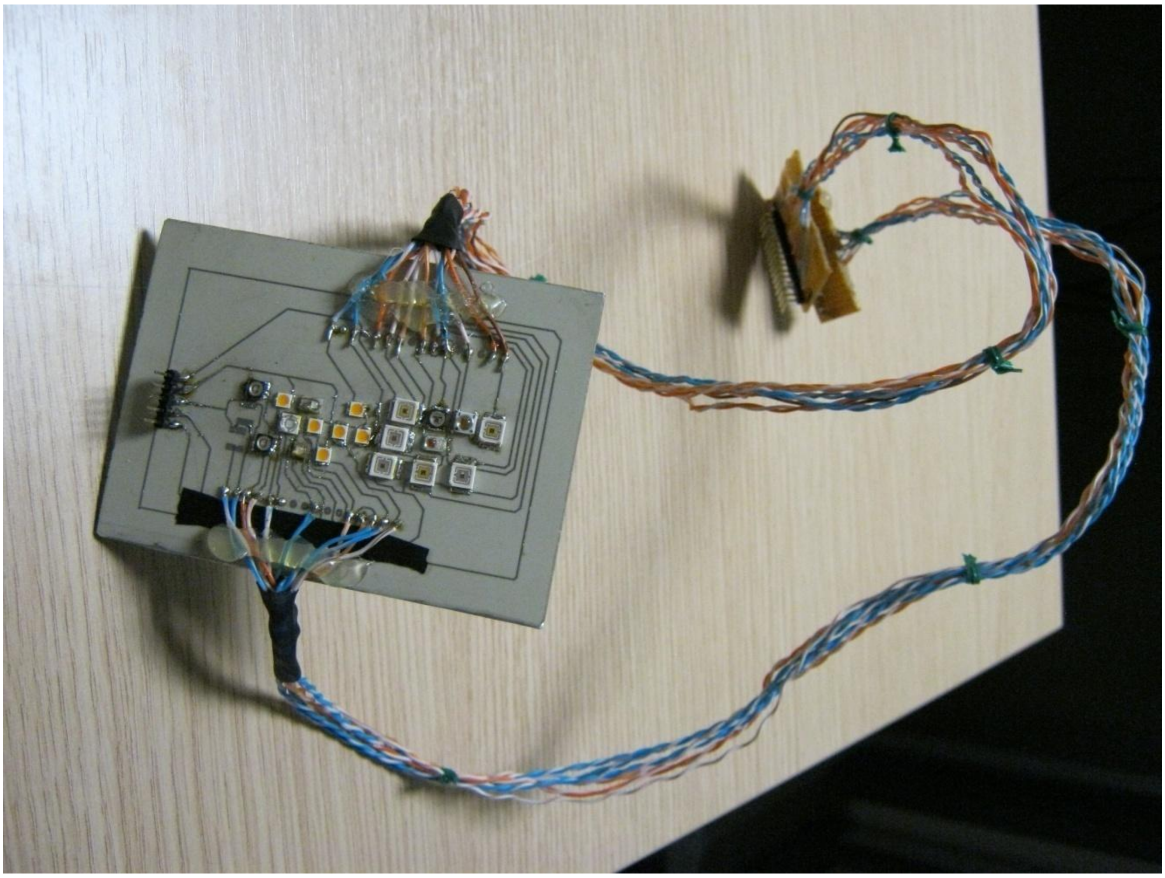


Figure 70– LED Board

3.3 LEDs 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 5 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:

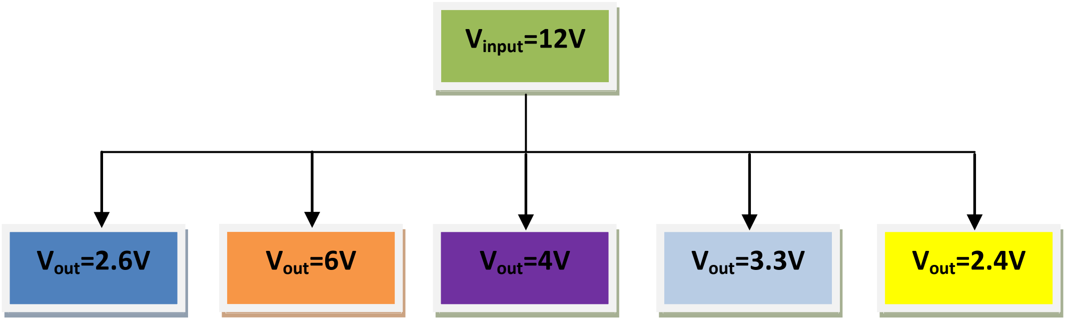


Figure 71– Voltage outputs

So as to create the 5 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.

In our assembly, we used the LM317 series of adjustable 3-terminal positive voltage regulators by Texas Instruments and the L7806 series of fixed three-terminal positive regulators by STMicroelectronics.

LM317 – TO220 package

The LM317 series of adjustable 3-terminal positive voltage regulators is capable of supplying in excess of 1.5A over a 1.2V to 37V output range. They are exceptionally easy to use and require only two external resistors to set the output voltage. Included on the chip are current limit, thermal overload protection and safe area protection. All overload protection circuitry remains fully functional even if the adjustment terminal is disconnected. The package we used is the TO-220.

LM7806 – TO220 package

The 7806 three-terminal positive regulator is fixed in the output voltage of 6V. They don't require external resistors like the LM317, so the connectivity is much simpler than the LM317's. The package we chose is the TO-220. These regulators can provide local on-card regulation, eliminating the distribution problems associated with single point regulation. Each type employs internal current limiting, thermal shut-down and safe area protection, making it essentially indestructible.

Specifically, we used LM317 regulators for generating the 4 of the 5 output voltages. The remaining output voltage, which is the 6V, is generated using the L7806 regulator. Power supply circuit's components are placed in a PCB which designed with the procedure mentioned in the previous chapter. In this design we noticed the conductive pads to be wide enough because the board will be flowed by large currents.

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 72– Voltage outputs

After various stress tests on the power supply we noticed that the voltage regulators reach high temperatures. So, a cooling assembly must support the voltage regulators, as shown above. To do this, we used an aluminium heatsink in which all voltage regulators are adjusted. Also, the heatsink is cooled with a low-noise fan.

3.4 Microcontroller

Figure 73 – 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.

3.5 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

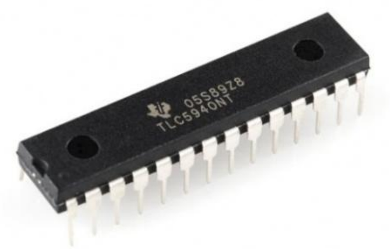


Figure 74 - TLC5940 in 28-pin PDIP package (TLC5940NT)

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.

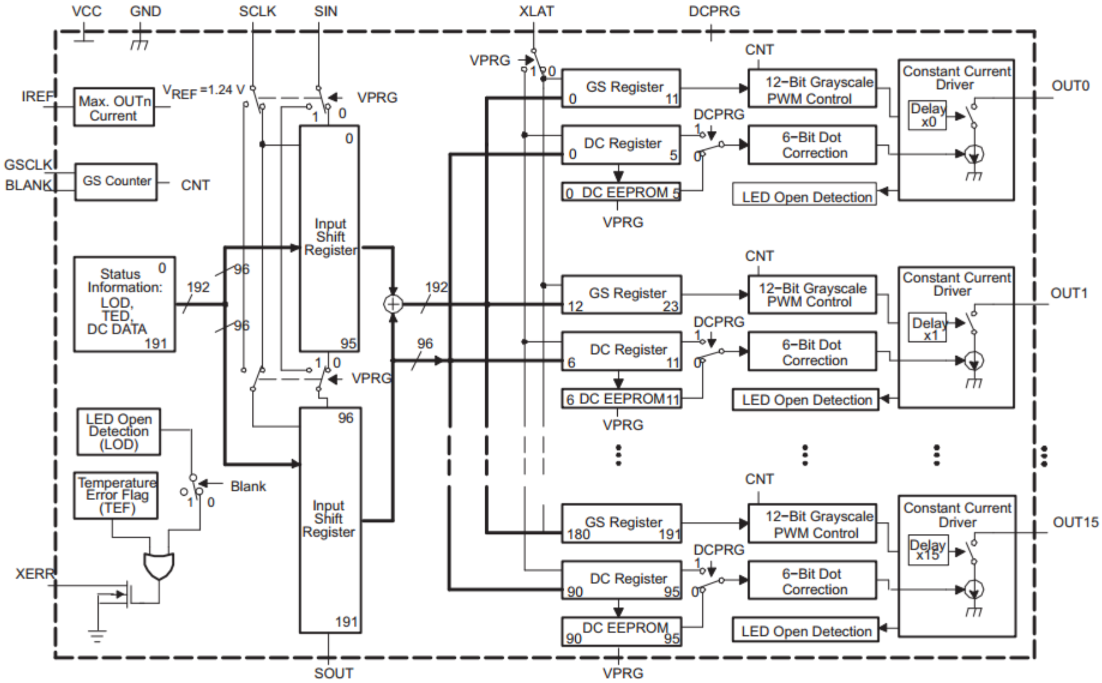


Figure 75 – TLC5940 Circuit diagram

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.

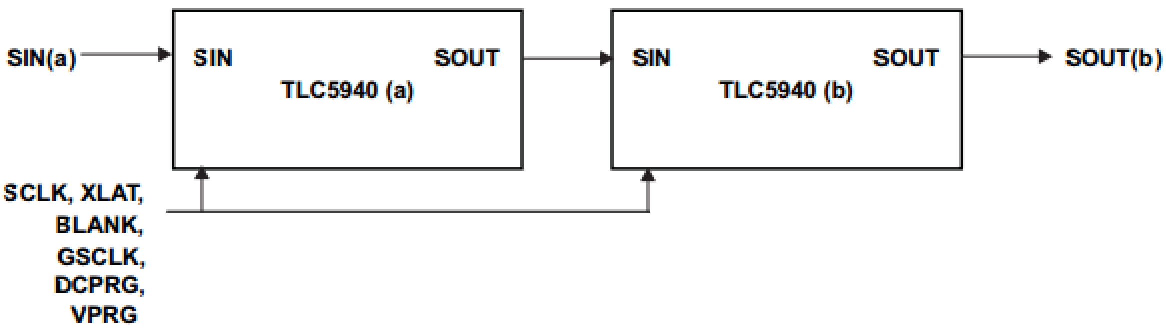


Figure 76 - Cascading two TLC5940 devices

CAT4101 constant-current LED driver

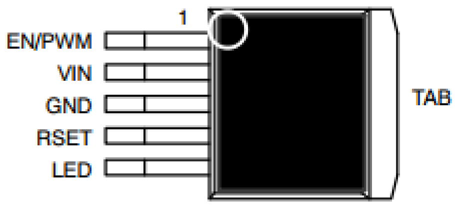


Figure 77 - CAT4101 pin connections

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.

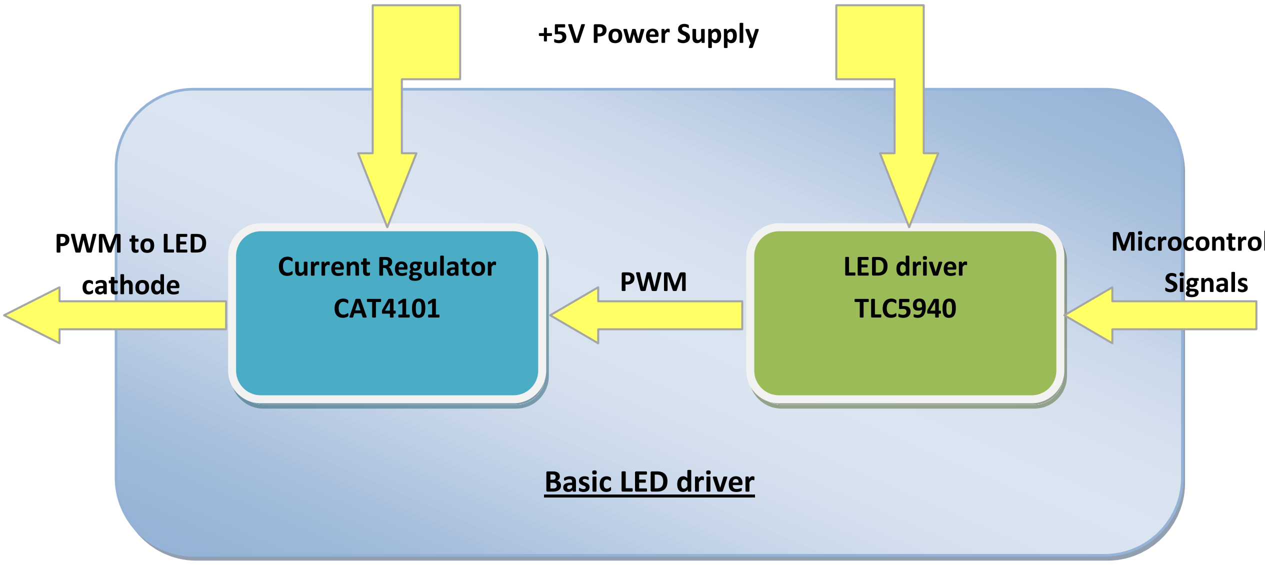


Figure 78 – Basic structure of LED driver

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.

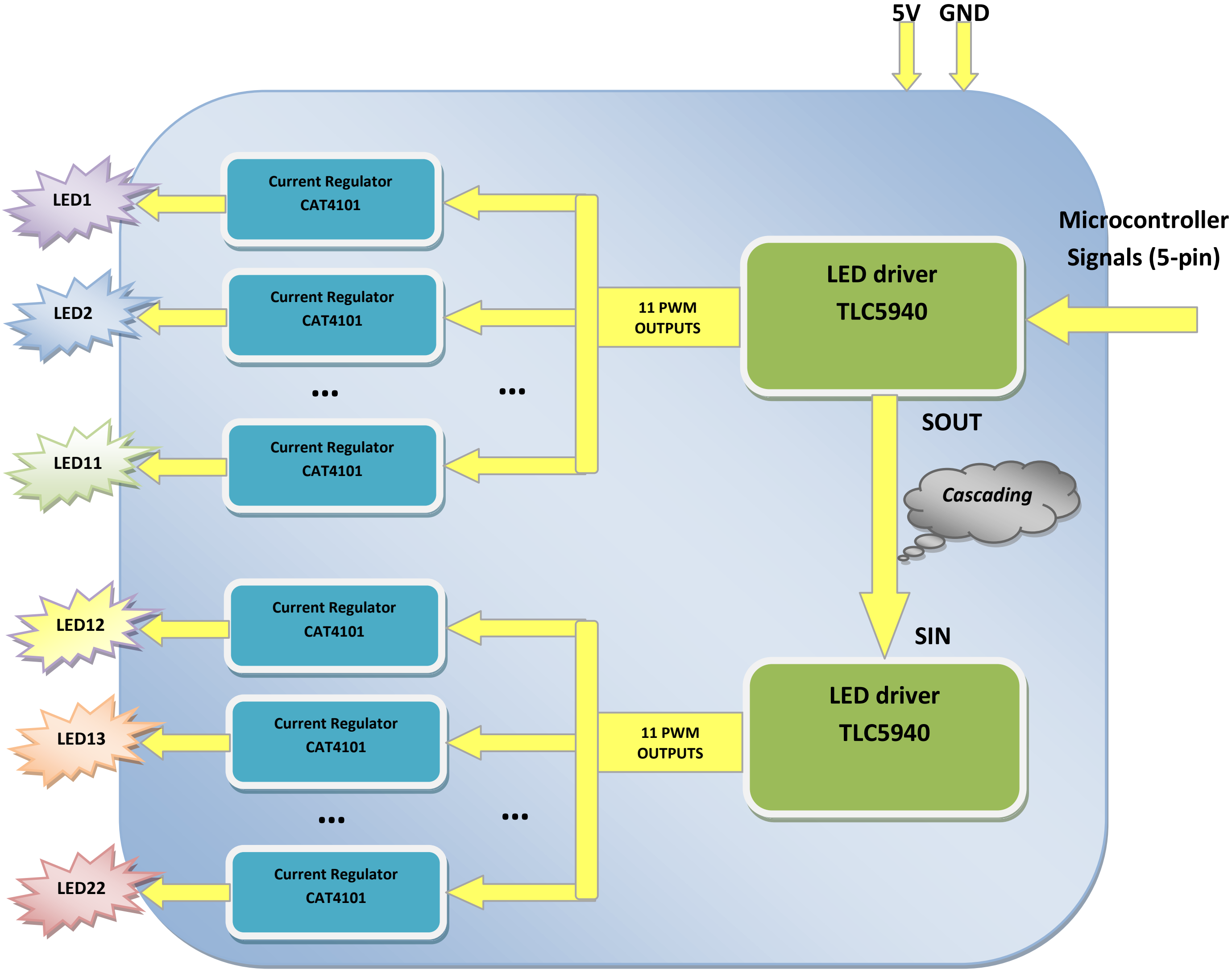


Figure 79 – LED driving board Block diagram

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:

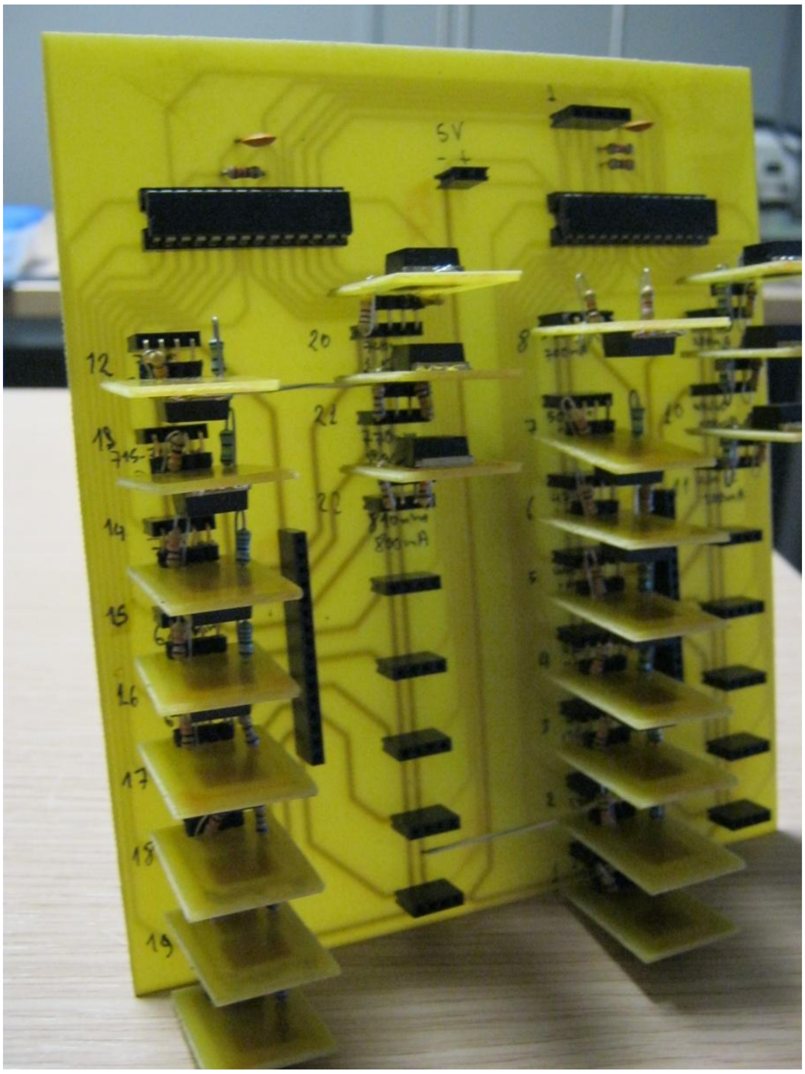


Figure 80 – LED driving board Block diagram

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.

3.6 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:

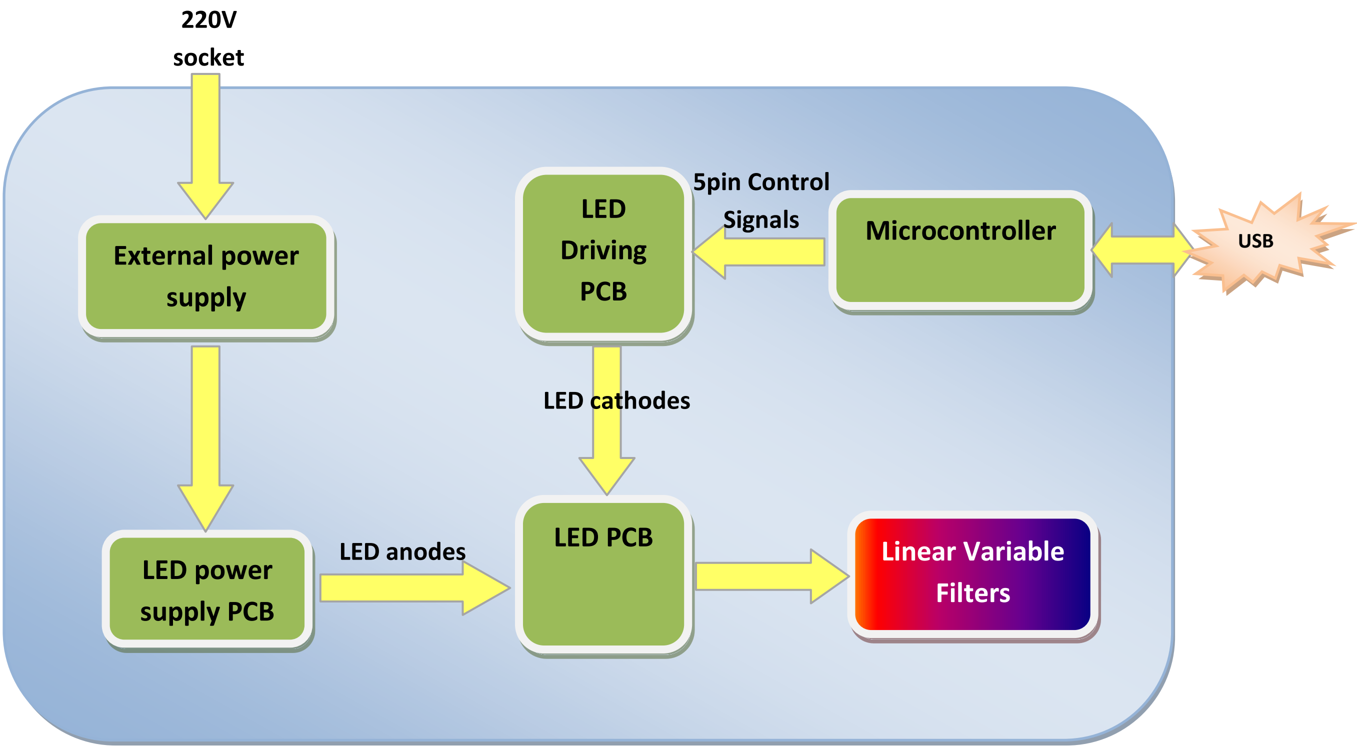


Figure 81 – Connectivity

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. The final device, after the connectivity setup is illustrated below:

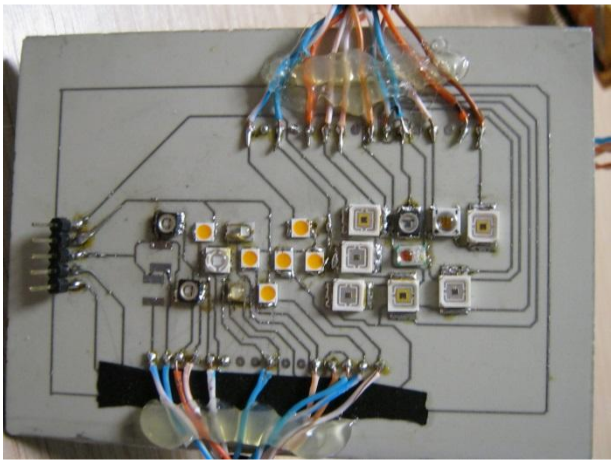


Figure 82 – LEDs

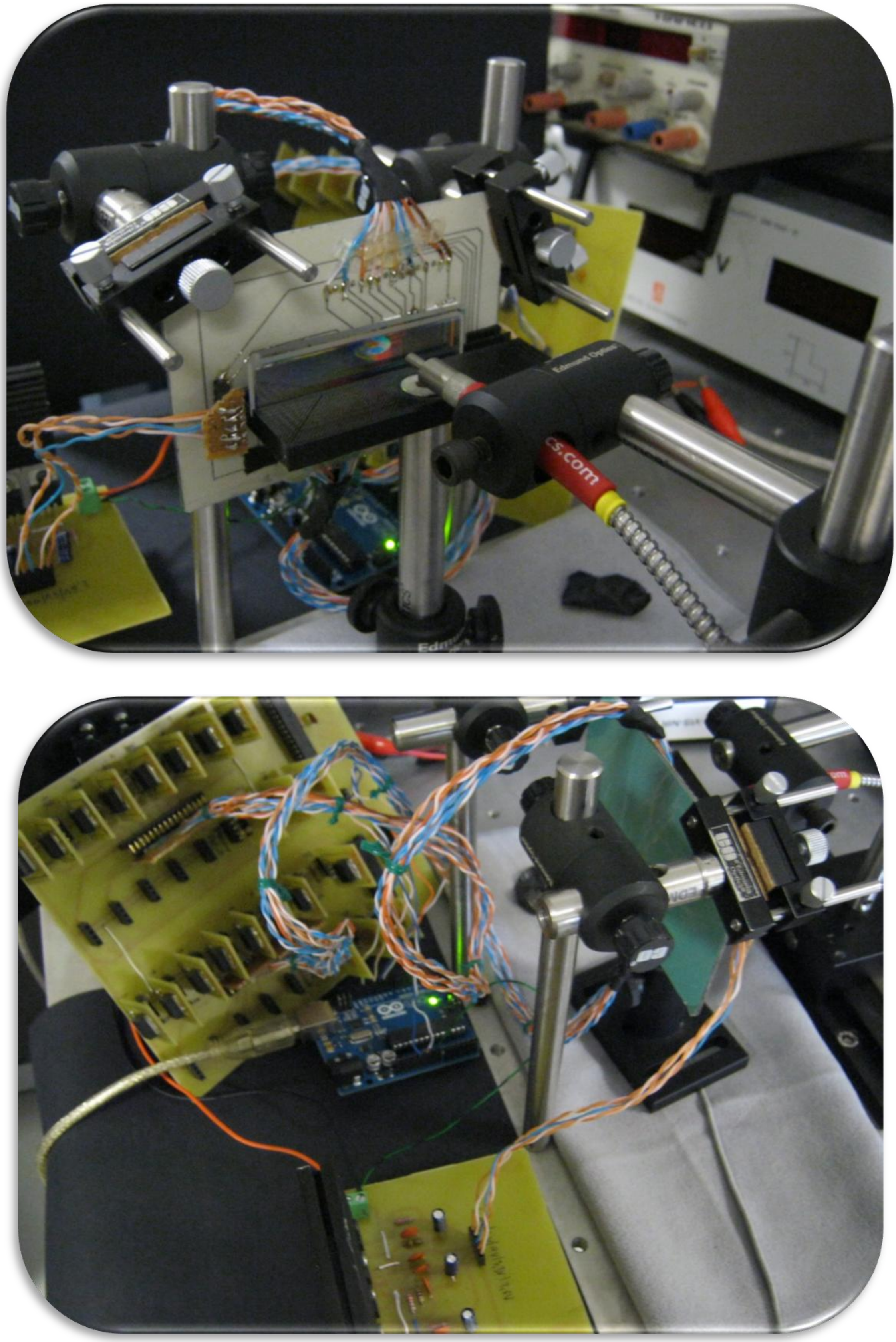


Figure 83 –Whole System Connected

4 SOFTWARE DEVELOPMENT

In this project we develop software that enables the user of our Tunable Light Source to control both the output wavelength of the light source and also the settings of enabling/disabling and dimming of the LEDs. The designing procedure was divided into several tasks that were necessary for the completion of the software. These tasks are analyzed in the following paragraphs.

Task 1: Programming the microcontroller

Task 2: Serial Communication with the microcontroller

Task 3: Creation of a GUI application for controlling LEDs

The division of the work to the previous tasks was in the spirit of bottom-up design. The most low-level task of the software design is the programming of the microcontroller. Then we establish a connection via serial port between the microcontroller and the GUI application (Tasks 2 and 3).

4.1 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)".

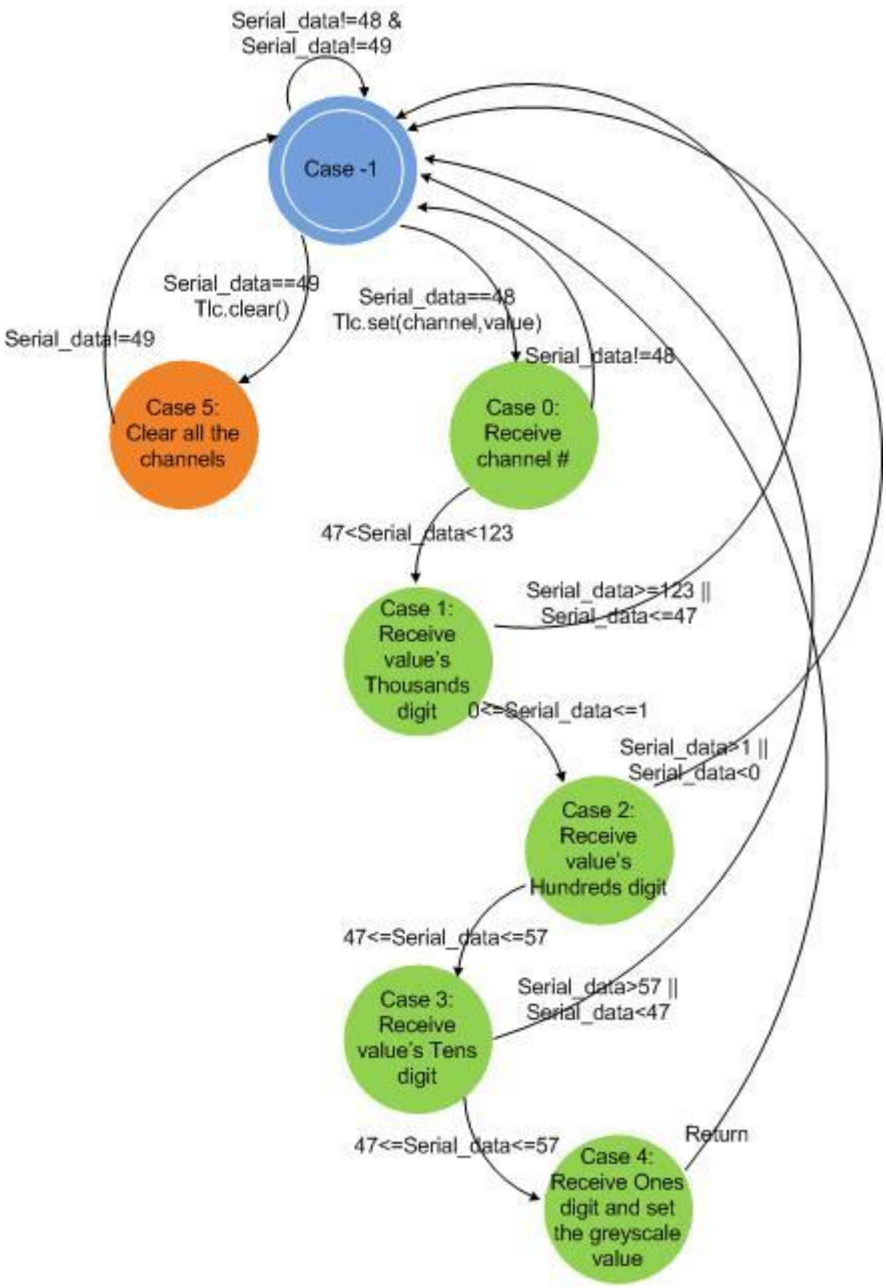


Figure 84 - Switch statement

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 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.

4.3 Creation of a GUI application for controlling LEDs

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.

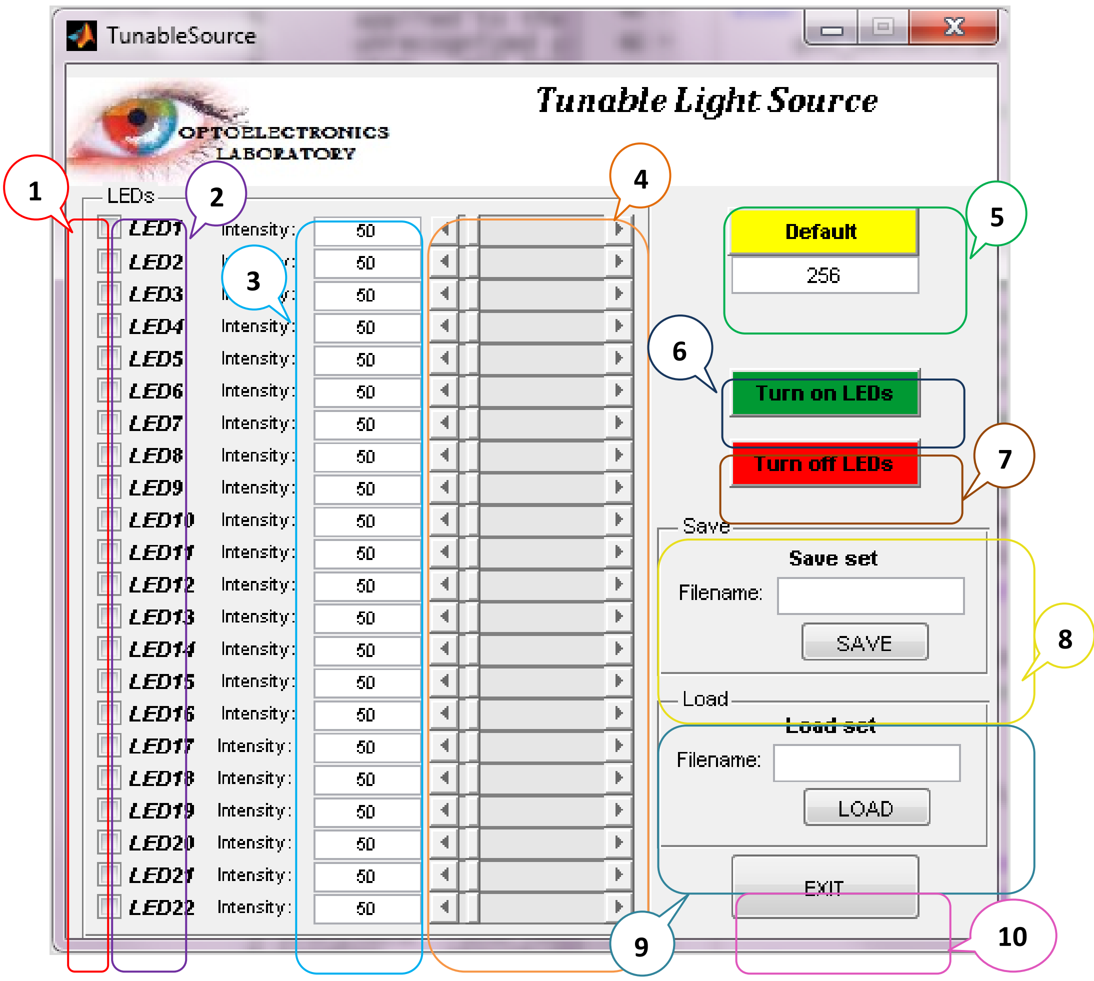


Figure 85 – GUI breakdown

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.

5 TECHNICAL EVALUATION

In this Chapter we will elaborate on the technical evaluation of the system we built. The aspects of evaluation will be the switching speed of the LEDs, the output light power and the stability during an experiment. All the aforementioned parameters are important to define the stability and quality of operation of our Tunable Light Source.

5.1 Switching speed of the 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.

5.2 Stability of the 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 Chapter 4, 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:

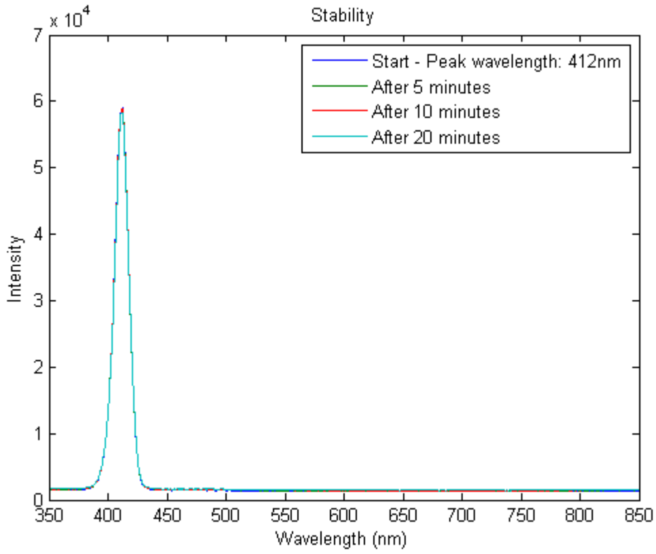


Figure 86 – Stability test, LED_peak=412nm

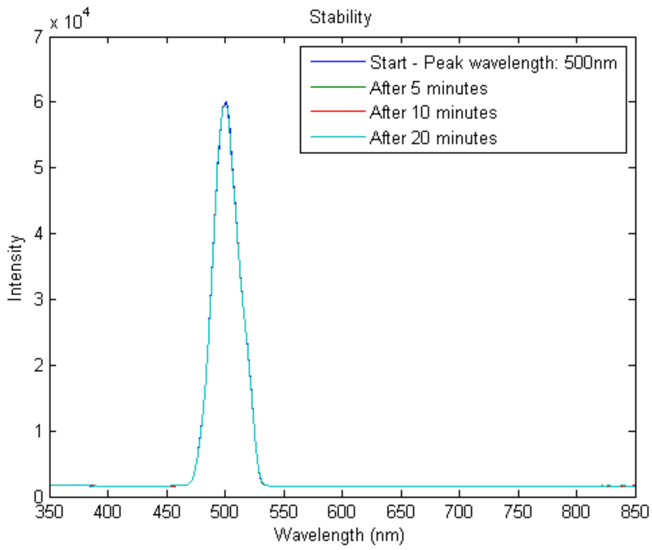


Figure 87 – Stability test, LED_peak=500nm

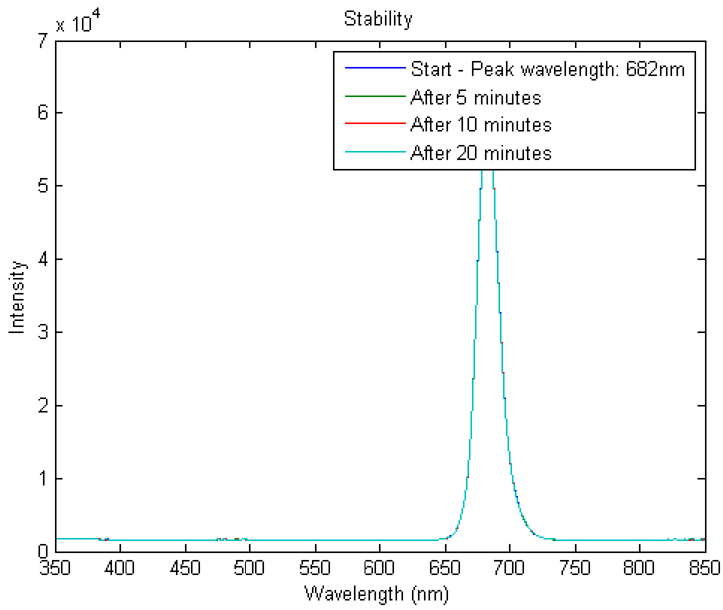


Figure 88 – Stability test, LED_peak=682nm

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

5.3 Lifespan of the 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 Tunable 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.

5.4 Emulation of a Flat Line Response Source

As we mentioned in Chapter 4, the user of the Tunable Light Source can adjust the intensity of each LED in 1024 steps. So, by powering on all 22 LEDs and adjusting each LED's spectrum to have the same intensity, we have a continuous spectrum flat response light source. For measuring the spectrums we used a spectrometer (Ocean Optics, USB400) and the relative software (Spectra Suite).

We can tune the TLS to have flat response in the wavelengths we choose.

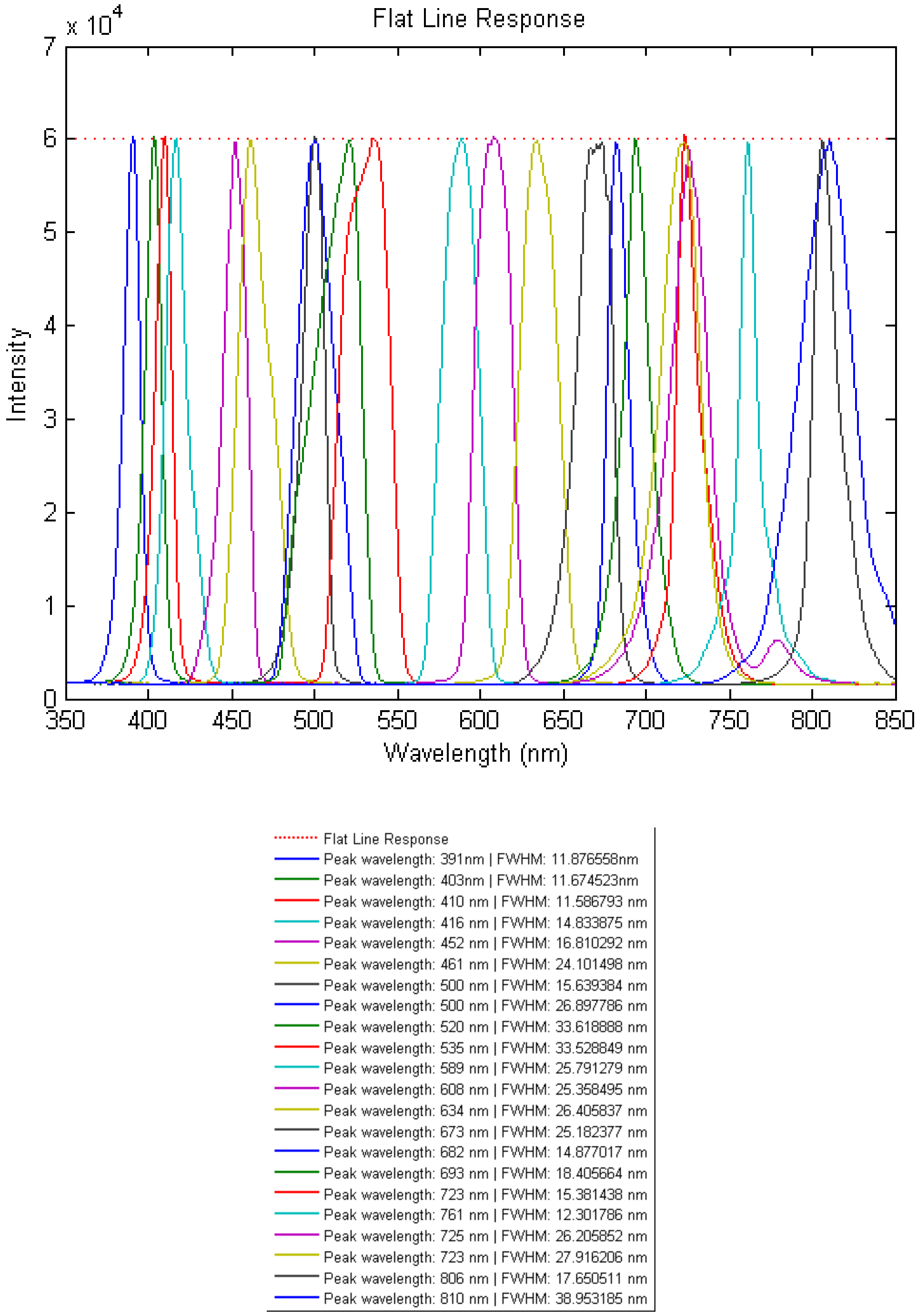


Figure 89 – Flat Line Response

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.

5.5 Emulation of Random Source

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.

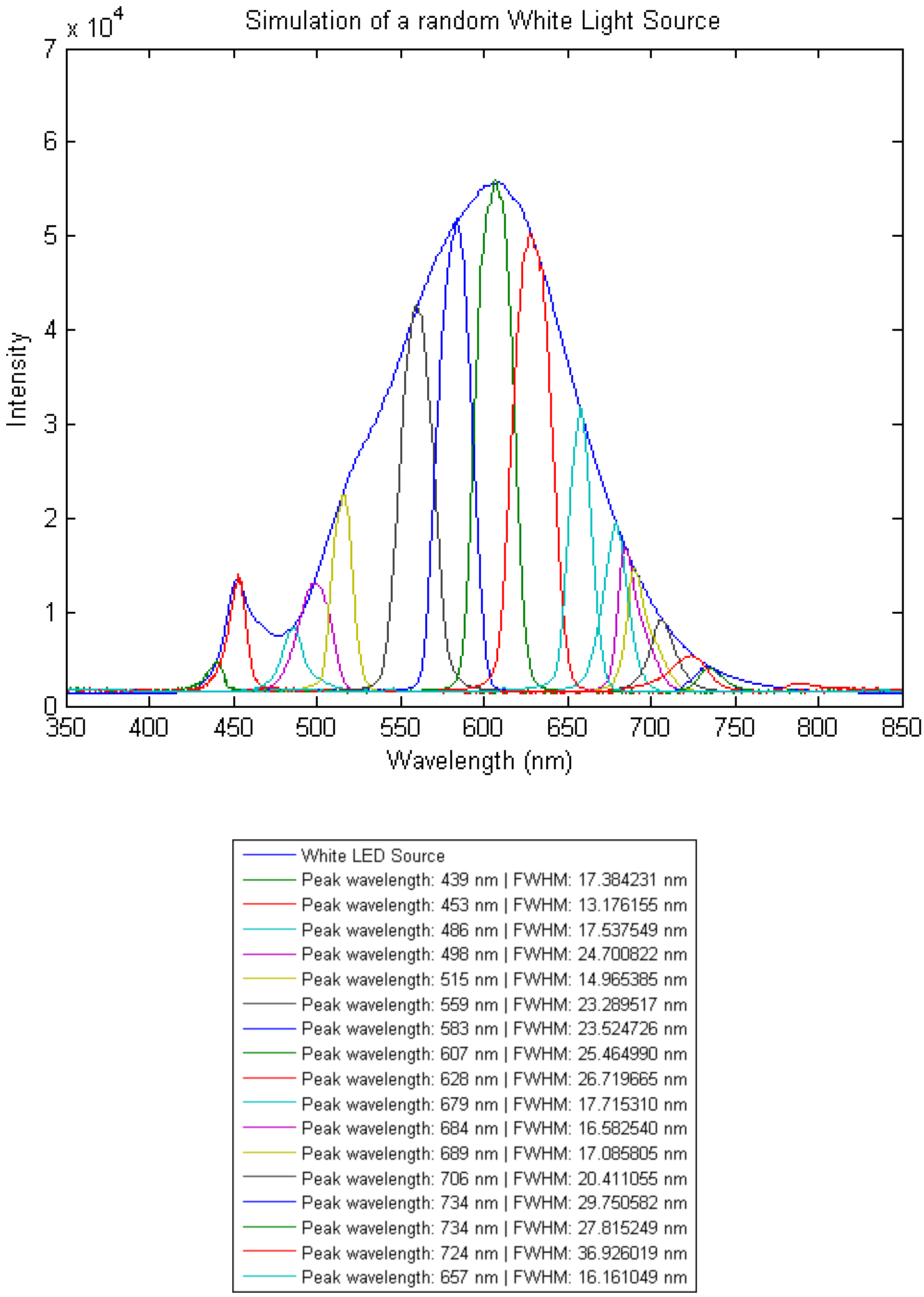


Figure 89 – Emulation of a White Light Source

For measuring the spectrums we used a spectrometer (Ocean Optics, USB400) and the relative software (Spectra Suite). As presented above, the experimental points fit excellent the given spectrum of the Random Source. This is due to many reasons such as the great number of available wavelengths (LEDs) and the high PWM resolution that adjusts the intensity of each LED in small steps.

5.6 Emulating a source for fluorescence

Fluorescence is the emission of light by a substance that has absorbed light. In most cases, the emitted light has a longer wavelength, and therefore lower energy, than the absorbed radiation. By having more available excitation wavelengths, more substances can fluorescence by emitting a corresponding wavelength. The TLS has up to 22 individually controlled wavelengths from UV to IR, so it is an excellent source for fluorescing imaging.

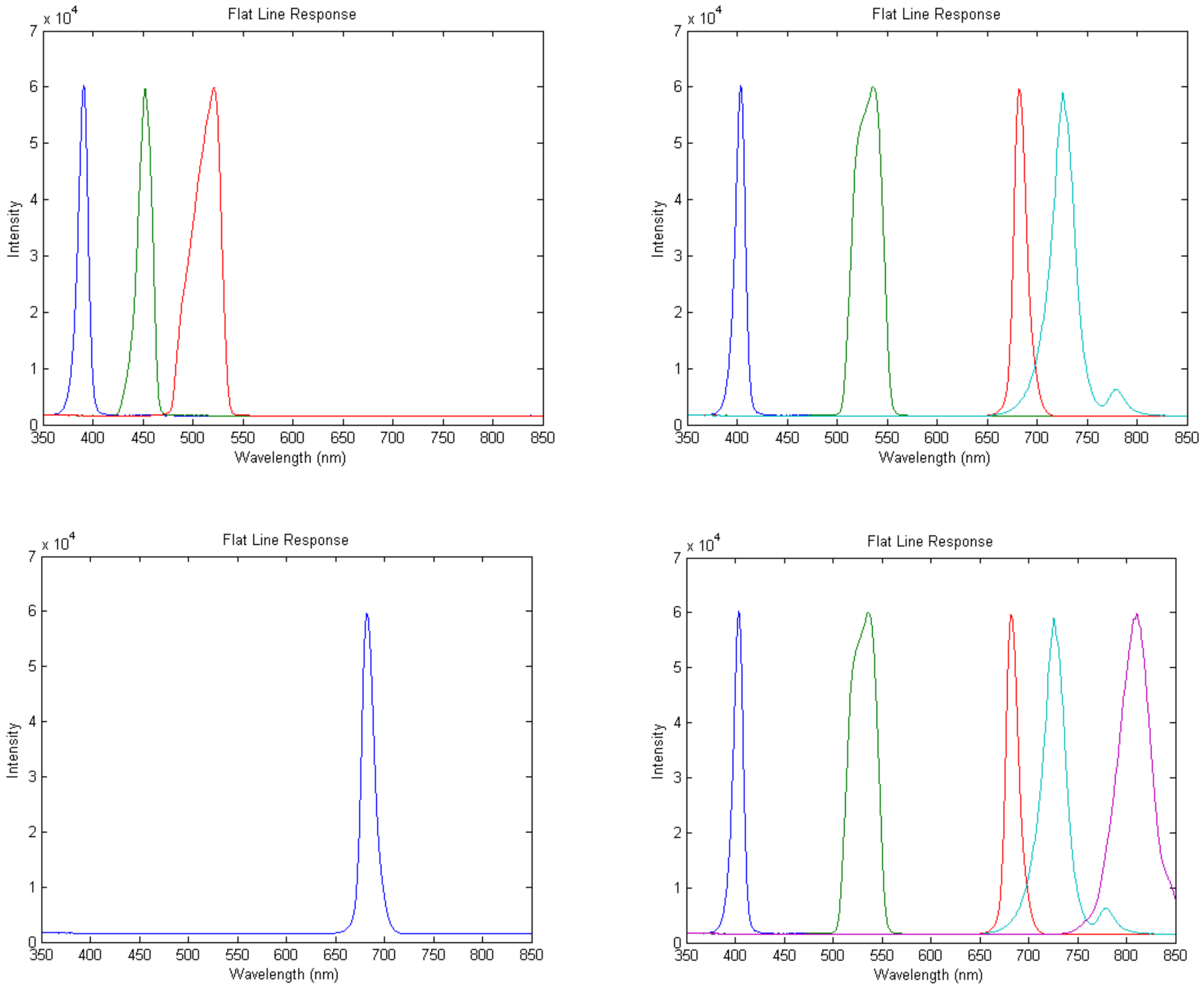


Figure 90 – Excitation Wavelengths

6 CONCLUSIONS AND FUTURE WORK

In this diploma thesis a Tunable Wavelength Light Source is presented. The system is built on two key ideas. First, the use of a long-wavelength and a short-wavelength pass filter which combined to create a band-pass filter. This band pass filter acts as monochromator, i.e. selects narrow band of wavelengths of light from a wider range of wavelengths available at the input. Second, the use of monochromatic and white LEDs which act as individual light sources. LEDs are arranged in specific positions behind the filters so as the current LED to be behind the appropriate central wavelength of the 'custom' band pass filter. The reason we did not use only white LEDs is because the white LED has very low intensity in bands 380-430nm, 470-520nm and 650-810nm. So, in order to have enough light intensity in these bands we used monochromatic LEDs, which can achieve a satisfactory light intensity.

Our configuration is a cost-effective approach in hardware and software demanding areas of biomedicine. The device presented has accurate and high tunability over a wide range of spectral bands, high output light and high quality of spectral data. It is evident that the characteristics presented above have a trade-off relation, but the balance of our configuration among these parameters seems to be very efficient for the purposes used.

The device can be tuned in wide spectral range (380-810nm) and is able of emitting up to 22-wavelengths simultaneously, unlike other configurations which are able to emit only one wavelength at a time. 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.

The intended applications of the innovative TLS spans a wide range of disciplines including but not limited to microscopy, ophthalmology, endoscopy, quality control, calibration etc.

A future work, there are a lot of improvements to made hardware and software-wise. The available wavelengths can be increased by adding more LEDs and redesigning the LED board. This way, the tunability of the Tunable

Light Source will also improve as the available wavelengths would be more. Also, an improvement on the power throughput would be the replacement of some LEDs with more powerful and efficient LEDs. Probably one last important improvement in terms of hardware would be the redesign of the whole system to a smaller size.

In terms of software, several features could be developed as a way to highlight the utility and functionality of the Tunable 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 Tunable Light Source will be able to simulate the user-defined source automatically, without the use of a spectrometer.

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