Technical University of Crete
School of Electrical and Computer Engineering
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# Spatial light modulator based light source with controlled spectral emission

Diploma Thesis by
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Not forgetting my Love, my parents and my brother and my friends for sharing my thoughts, worries and expectations during these years of my studies. I dedicate this thesis to all of them for their understanding and support throughout my life.

# CONTENTS

# ABSTRACT

In this thesis, the development of a **Spatial light modulator based light source with controlled spectral emission** is presented, which is able to project any design spectrum that the user wants. Various Tunable-Spectrum 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 light source designed in this thesis is capable of projecting not only peaks spectrum like the above light sources but any available spectrum (in the shape of curve) there is in the world. The light source consists of a DLP (Digital light processing), optical fibers and variable filters. Also, a software development accompanies the light source to be fully PC controlled. Calibration of the light source and optical power was performed using a spectrometer. A series of laboratory tests have been conducted to evaluate the performance of the designed light source**.**

The intended applications of the innovative light source span a wide range of disciplines including but not limited as an achromatopsia tester, vision sensitivity tester, calibrator for optical instruments and for Metameric color reproduction and study etc.

# CHAPTER 1
# LIGHT SOURCES

## 1.1. Electromagnetic waves [1]

Electromagnetic waves were first postulated by James Clerk Maxwell and subsequently confirmed by Heinrich Hertz. Maxwell derived a wave form of the electric and magnetic equations, revealing the wave-like nature of electric and magnetic fields, and their symmetry. Because the speed of EM waves predicted by the wave equation coincided with the measured speed of light, Maxwell concluded that light itself is an EM wave. According to Maxwell's equations, a time-varying electric field generates a magnetic field and vice versa. Therefore, as an oscillating electric field generates an oscillating magnetic field, the magnetic field in turn generates an oscillating electric field, and so on. These oscillating fields together form an electromagnetic wave. In figure 1.1.1 an electromagnetic wave can be seen.

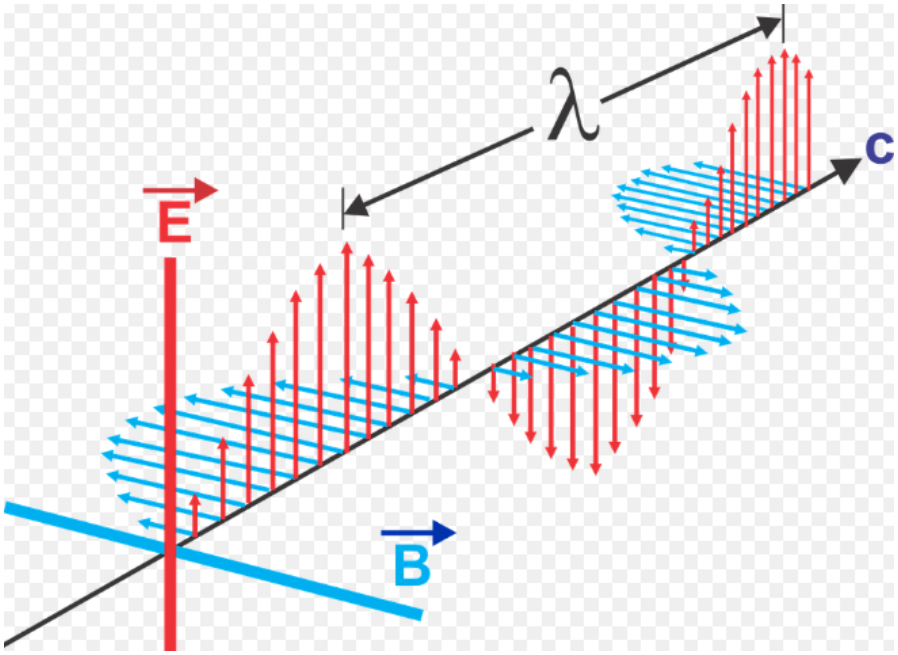


*Figure 1.1.1 – Electromagnetic wave*

In addition to electromagnetic theory, radiation can be treated as a flow of particles, discrete packets of energy called photons. One photon travel at the speed of light c and carries energy equal to:

$$E_{photon} = h \cdot v = \frac{h \cdot c}{\lambda},$$

where h = 6.626 × 10−34 J s is Planck's constant. Therefore, the energy content of radiation is quantized and can only be a multiple of hν for a certain frequency ν. While the energy per photon is given by $E_{photon}$ the total energy of radiation is given by the number of photons. It was this quantization of radiation that gave birth to the theory of quantum mechanics at the beginning of the twentieth century.

Although photons do not carry electrical charge this unit is useful in radiometry, as electromagnetic radiation is usually detected by interaction of radiation with electrical charges in sensors. In solid-state sensors, for example, the energy of absorbed photons is used to lift electrons from the valence band into the conduction band of a semiconductor. The bandgap energy Eg defines the minimum photon energy required for this process. As a rule of thumb the detector material is sensitive to radiation with energies Ev >Eg.

Electric and magnetic fields obey the properties of superposition, so fields due to particular particles or time-varying electric or magnetic fields contribute to the fields due to other causes. (As these fields are vector fields, all magnetic and electric field vectors add together according to vector addition.) These properties cause various phenomena including refraction and diffraction. For instance, a travelling EM wave incident on an atomic structure induces oscillation in the atoms, thereby causing them to emit their own EM waves. These emissions then alter the impinging wave through interference.

Since light is an oscillation, it is not affected by travelling through static electric or magnetic fields in a linear medium such as a vacuum. In nonlinear media such as some crystals, however, interactions can occur between light and static electric and magnetic fields - these interactions include the Faraday Effect and the Kerr Effect. In refraction, a wave crossing from one medium to another of different density alters its speed and direction upon entering the new medium. The ratio of the refractive indices of the media determines the degree of refraction, and is summarized by Snell's law. Light disperses into a visible spectrum as light is shone through a prism because of the wavelength dependent refractive index of the prism material (Dispersion).

Monochromatic radiation consists of only one frequency and wavelength. The distribution of radiation over the range of possible wavelengths is called spectrum or spectral distribution. Electromagnetic radiation covers the whole range from very high energy cosmic rays with wavelengths in the order of 10−16 m to sound frequencies above wavelengths of 106 m. Only a very narrow band of radiation between 380nm and 780nm is visible to the human eye. Each portion of the electromagnetic spectrum obeys the same principal physical laws. Radiation of different wavelengths, however, appears to have different properties in terms of interaction with matter and observability that can be used for wavelength selective detectors. In figure 1.1.2 the spectrum of electromagnetic radiation together with the standardized terminology separating different parts, is depicted.

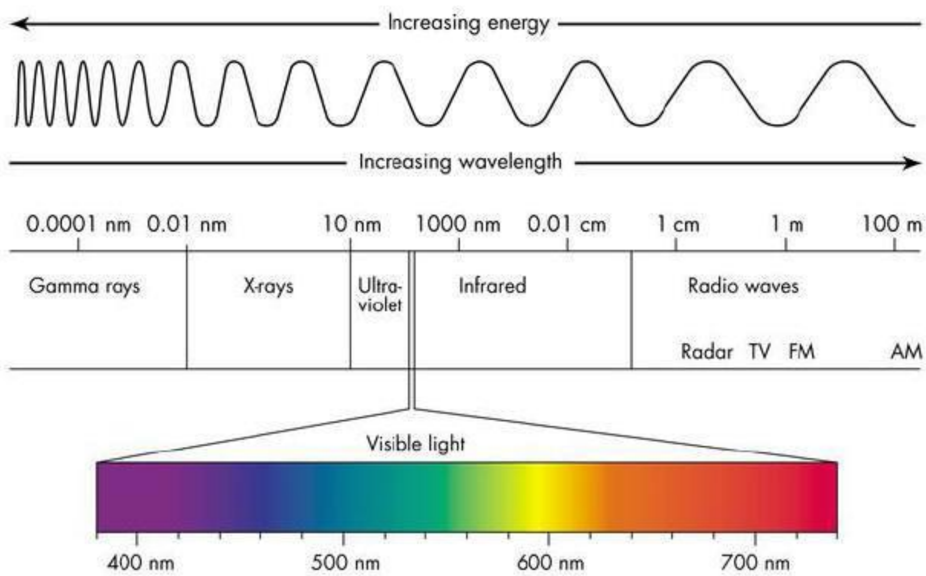



*Figure 1.1.2 Spectrum of electromagnetic (EM) radiation*

## 1.2. Continuous Spectrum Light Sources

In the previous section we discussed the basic principles of light. In this section will be described the light sources which are divided to discrete or continuous according to their 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. **Continuous light sources** are the sources that can produce extensive or limited continuous wavelength range.

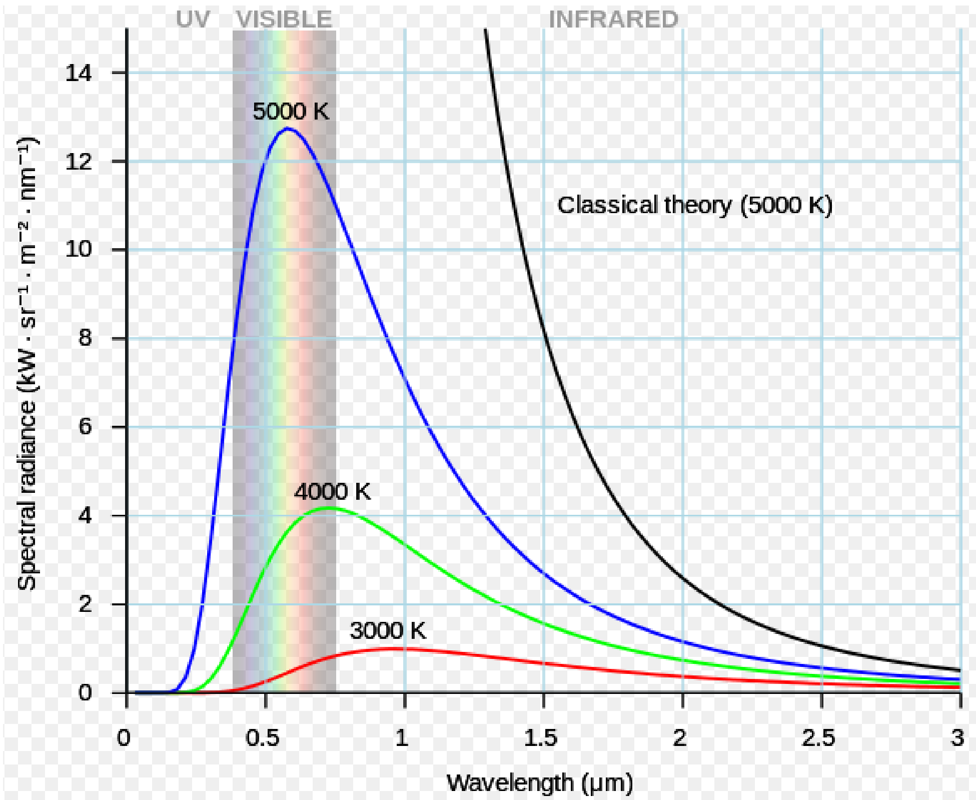
### 1.2.1. Black body sources [4]

Black body radiation is electromagnetic radiation that is emitted by an object that is in thermodynamic equilibrium. Every object radiates (and absorbs) electromagnetic waves. The spectrum of this radiation is not dependent on the chemical composition of the matter but it's only determined by its absolute temperature T. An object is considered a perfect black body when it absorbs all of the incoming light and does not reflect any. It appears perfectly black at room temperature. At ambient temperature the majority of the emitted spectrum is in the long wave infrared which is not visible. The spectrum shifts towards to shorter wavelengths when the temperature rises. As the temperature is rising the color of radiation will tent to yellow, white and white-blue. In figure 1.2.1 is depicted the temperature with the corresponding color.

| **Temperature** | **Color** |
|---|---|
| 1000 | Red |
| 1500 | Reddish orange |
| 2000 | Yellowish orange |
| 2800 | Yellow |
| 3500 | Yellowish white |
| 4500 | Warm white |
| 5500 | White |
| 6000 | Cold white |

*Figure 1.2.1 Temperature-Color*

The following plot shows the spectrum for temperatures 3000K, 4000K, 5000K from 0 to 3μm.




The spectrum is described by Plank's equation:

$$u\ (\lambda, T) = \frac{8\pi hc}{\lambda^2}\frac{1}{e^{\frac{hc}{\lambda k}} - 1}$$

Where:

$C = 2.99792458\ 10^{8}\ \frac{m}{s}$ , $k = 1.3806488\ 10^{-23}\ \frac{J}{K}$ $h = 6.62606957\ 10^{-34}$ JS

The wavelength of the peak of the blackbody radiation is proportional to 1/T and is called "Wien's shift" or "Wien's displacement law". In other terms, the hotter the body, the shorter the wavelength. The Wien's equation is given below:

$$\lambda_{max} = \frac{2.89776829 \cdot 10^{6}[nm \cdot K]}{T}$$

## 1.2.2 Gas-discharge lamps [5, 6, 7, 8]

**Gas-discharge lamps** are a family of artificial light sources that generate light by sending an electrical discharge through an ionized gas. 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/or 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.

There are three groups of gas discharge lamp, namely:

- Low pressure discharge
- High pressure discharge
- High intensity discharge

**Low pressure discharge**

Low-pressure lamps have working pressure much less than atmospheric pressure. These types of lamps include **Fluorescent lamps** which produces up to 100 lumens pew watt and is used mainly by office applications, **Neon lighting** which is used as advertising in neon signs and **Sodium lamps** which is the most efficient low pressure discharge lamp due to the production of up to 200 lumens. The disadvantage of the sodium lamp is that is the very poor rendering of colors. It has yellow monochromatic light and its usage is to luminate streets.

*Figure 1.2.2.1-Fluorescent lamps*


*Figure 1.2.2.2-Neon*

*Figure 1.2.2.3- Sodium lamps*

## High pressure discharge

High-pressure lamps have a discharge that takes place in gas under slightly less to greater than atmospheric pressure. They consist of Metal halide lamps, High pressure sodium lamps and mercury-vapor lamps. **The Metal Halide Lamps** produce almost white light, and attain 100 lumen per watt light output. Additionally, the used for illumination of stadium, parking area, airfield, etc. The **High Pressure Sodium Lamps** producing up to 150 lumens per watt produce a broader light at a characteristic wavelength near 589 nm. Their common usage is for street lighting and for the illumination of greenhouse helping the growing of plants. The last one lamp for this category is the **Mercury-Vapor Lamp** which uses an electric arc through vaporized mercury to produce light. Mercury vapor lamps provide about 50 lumens per watt and their color is a very cool blue/green white light. They are used for large area overhead lighting, such as in factories, warehouses, and sports arenas as well as for streetlights, due to the long bulb lifetime in the range of 24,000 hours and a high intensity, clear white light output.

*Figure 1.2.2.4- Metal halide lamp*

Figure 1.2.2.5- High pressure sodium lamps

Figure 1.2.2.6- the mercury-vapor lamp

**High-intensity discharge lamps**

**High-intensity discharge lamps** (**HID lamps**) are a type of electrical gas-discharge lamp which produces light by means of an electric arc between tungsten electrodes take placed inside a translucent or transparent fused quartz or fused alumina arc tube. This tube is filled with noble gas and often also contains suitable metal or metal salts. HID lamps are commonly used for outdoor lighting and in large indoor arenas.

Figure 1.2.2.7- HID lamp

## 1.3 Linear Spectrum Light Sources

Linear Spectrum Light Sources have got active element a gas at low pressure and at room temperature. The linear energy diagram and linear spectra is the result of the reset of the quantum nature of the systems. This happens because the broadening and overlapping of energy states of the electrons in the gas atoms are insignificant at the above conditions. An example of a linear spectrum source is the Geissler tube.

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

Incoherent sources emit light with frequent and random changes of phase between the photons. Two examples of incoherent light sources are Tungsten filament lamps and 'ordinary' fluorescent tubes. The transitions between energy levels in an atom is a completely random process and so we have no control over when an atom is going to lose energy in the form of radiation. In figure 1.3.1.1 the changes of phase between the photons can be seen.

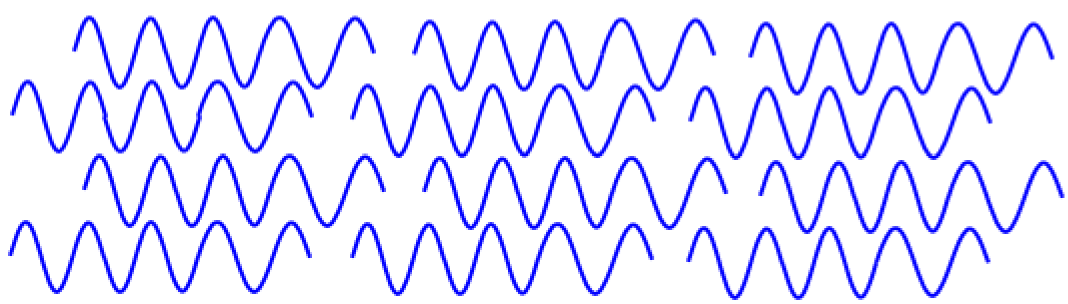


*Figure 1.3.1.1- Frequency of photons*

### 1.3.2 Coherent liner spectrum light sources (laser)

The word LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. Lasers differ from other sources of light because they emit light coherently. Laser not only amplifies or increases the intensity of light but also generates the light, which emits through a process called stimulated emission of radiation which amplifies or increases the intensity of light. Furthermore, is a device that amplifies or increases the intensity of light and produces highly directional light. Laser also have high temporal coherence which allows them to have a very narrow spectrum, viz produce a single color of light. Some lasers generate visible light but others generate ultraviolet or infrared rays which are invisible. Lasers are used in many sciences like Ophthalmology, Dermatology, surgery i.e.

### 1.3.2.1 Physics of Laser [ 34, 35]

**Laser consists of** a pair of mirrors at either end which the first one is a totally reflected mirror and the output mirror that is both reflect and transmit the light. 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. The **gain medium,** can be a solid, a liquid or a gas and is composed of atoms, molecules, ions or electrons whose energy levels are used to increase the power of a light wave during its propagation. The physical principle involved is called stimulated emission. 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. In the next figure a laser design is depicted.

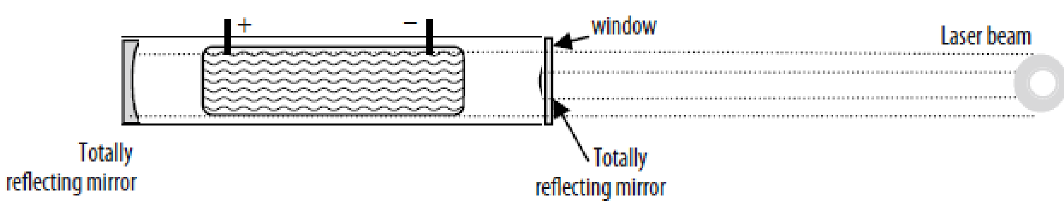



*Figure 1.3.2.1.1 – Laser design*

**Absorption of radiation or light**

It is well known that there are different energy levels in atoms. The electrons that are very close to the nucleus have lowest energy level. These electrons are also known as ground state electrons. To explain better and more easily the process it will be considered the energy state of ground state electrons is $E_1$ and the next higher energy state is $E_2$. When the lower energy state electrons ($E_1$) absorbs sufficient energy from photons, which this energy is equal to the energy difference between the two energy states $E_2 - E_1$, the electrons jump from the lower level ($E_1$) to the higher energy level ($E_2$). The electrons in the higher energy level are called excited electrons. written as $hv = E_2 - E_1$ where h is Planck's constant and v is the frequency of photons. This mechanism called **absorption** and can be seen in figure 1.3.2.1.2

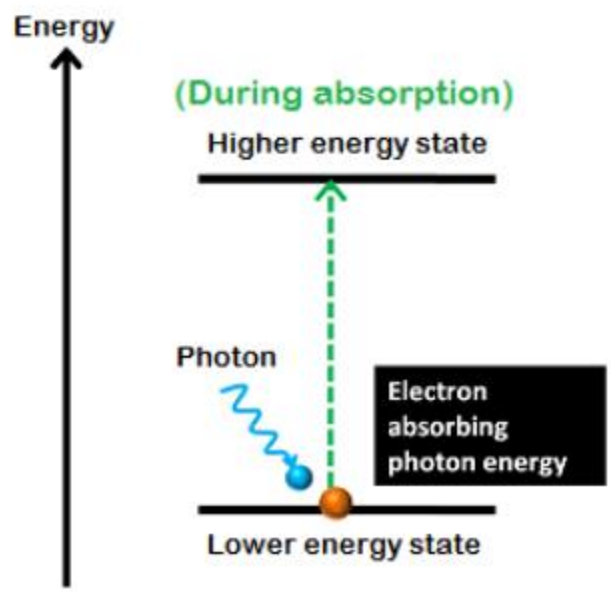



*Figure 1.3.2.1.2 – Absorption*

**Spontaneous emission**

When an electron is excited from a lower to a higher energy level, it does not stay there for a long period because the lifetime of electrons in the higher energy state or excited state is very small, of the order of $10^{-8}$ sec. Hence, after this short period, they fall back to the ground state by releasing energy in the form of photons or light, without external influence. The energy of the emitted photon is directed proportional to the energy gap of the material. The materials with large energy gap will emit high-energy photons whereas the materials with small energy gap will emit low energy photons. This mechanism is called spontaneous emission. In spontaneous emission, the electrons changing from one state (higher energy state) to another state (lower energy state) occurs naturally. The photons emitted due to spontaneous emission flow in random direction. The spontaneous emission is depicted in figure 1.3.2.1.3.

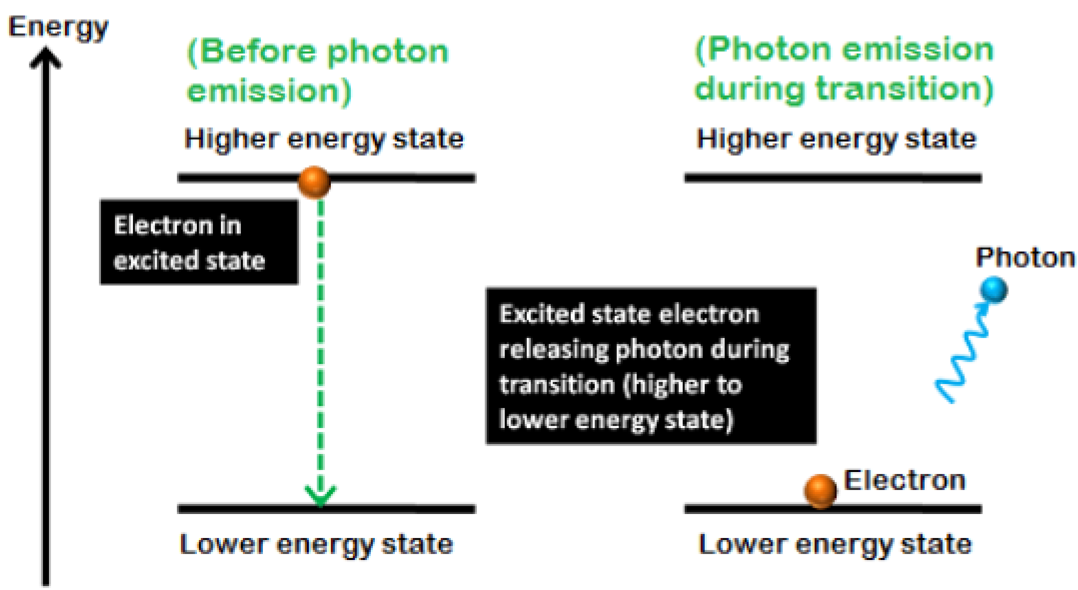



*Figure 1.3.2.1.3 – Spontaneous emission*

### Stimulated emission

In addition to spontaneous emission, the stimulated emission is not a natural process but an artificial process. In stimulated emission, the electrons in the excited state need not wait for natural spontaneous emission to occur because of an incoming photon of a specific frequency can interact with an excited atomic electron causing it to drop to a lower energy level. The incident photon stimulates or forces the excited electron to emit a photon and fall into a lower state or at the ground state. In this process, the excited electron releases an additional photon of same fre-

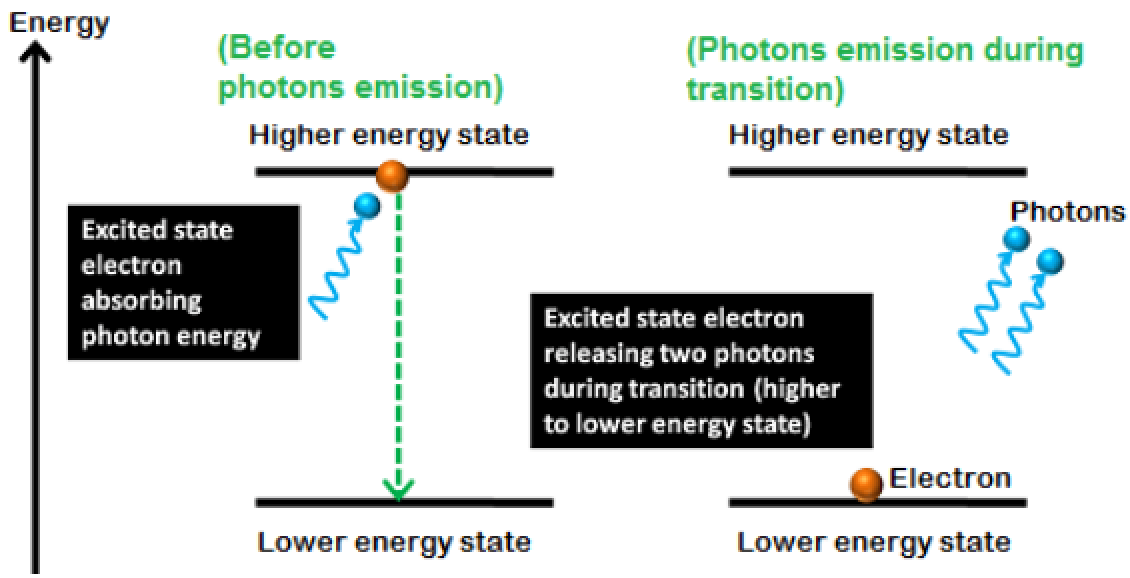



*Figure 1.3.2.1.4 – Stimulated emission*

quency, same phase, and the same direction while falling into the lower energy state. So, in this way when the electrons fall at the lower level energy, they release two electrons. All the photons in the stimulated emission have the same frequency and travel in the same direction. In figure 1.3.2.1.4 the stimulated emission can be seen.

**Population Inversion**

A population inversion occurs while a system (such as a group of atoms or molecules) exists in a state in which more members of the system are in higher, excited states than in lower, unexcited energy states. More detail, if there are more atoms in the upper state ($E_2$) than in the lower state ($E_1$), the system is not at equilibrium. In fact, at thermodynamic equilibrium, the distribution of the atoms between the levels is given by Boltzmann's Law:

$$N_2 = N_1 exp - \frac{(E_2 - E_1)}{kT}$$

In this case, $N_2$ is always less than $N_1$. A situation not at equilibrium must be created by adding energy via a process known as "pumping" in order to raise enough atoms to the upper level. This is known as population inversion and is given by $\Delta = N_2 - N_1$. Light is amplified when the population inversion is positive. Pumping may be electrical, optical or chemical.

For example, a 3-level laser is a system consisting of three energy levels $E_1$, $E_2$, $E_3$ with N number of electrons. It is considered that the energy level of $E_1$ is less than $E_2$ and $E_3$, the energy level of $E_2$ is greater than $E_1$ and less than $E_3$, and the energy level of $E_3$ is greater than $E_1$ and $E_2$. It can be simply written as $E_1 < E_2 < E_3$. That means the energy level of $E_2$ lies in between $E_1$ and $E_3$. Additionally, it is assumed that N1 is the number of electrons in the energy state $E_1$, $N_2$ is the number of electrons in the energy state $E_2$ and $N_3$ is the number of electrons in the energy state $E_3$. To get laser emission or **population inversion**, the population of higher energy state ($E_2$) should be greater than the population of the lower energy state ($E_1$). **Pumping** is the process in which the electrons in the lower energy state ($E_1$) gains sufficient energy and jumps into the higher energy state ($E_3$). This can be occurred when the supply of light energy is equal to the energy difference of $E_3$ and $E_1$. Because of the short lifetime of electrons in the energy state $E_3$ they quickly fall to the middle state $E_2$ releases radiation less energy instead of photons. In this way, only a small number of electrons accumulate in the energy state $E_3$. As a result, the population of middle state will become greater that the population of energy states $E_3$ and $E_1$ ($N_2 > N_1 > N_3$). In a three-level energy system, we achieve population inversion between energy levels $E_1$ and $E_2$. In figure 1.3.2.1.5 a population inversion of a 3-level laser is depicted.

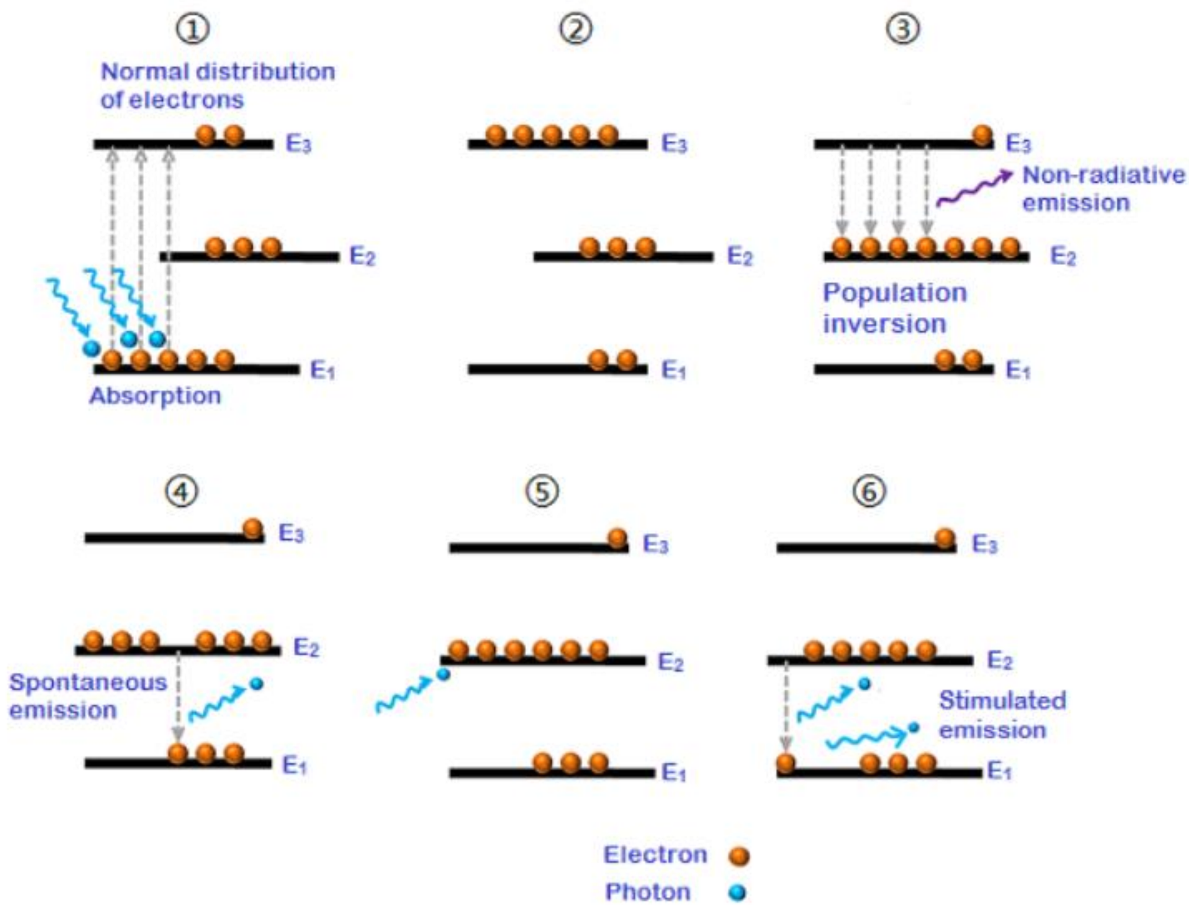



*Figure 1.3.2.1.5 - Population inversion of a 3-level laser*

### 1.3.2.2 Gas Lasers [15, 16]

A gas laser is a laser in which an electric current is discharged through a gas inside the laser medium to produce laser light. In gas lasers, the laser medium is in the gaseous state. Gas lasers are used in applications that require laser light with very high beam quality and long coherence lengths. In gas laser, in the gain medium there is a glass tube which inside this is the mixture of gases. The tube of gas has mirrors on either end, one fully reflective, and the other partially reflective. When the tube is excited by an electric field, the electrons in the atoms of the gas jump to a higher energy level. When they fall to their original state the produce light because the excess energy is given off as photons. This light bounces between the two mirrors, which act as a resonant cavity for the light. Each pulse increases the intensity of the light, and when the light is intense enough, it shines through the less reflective mirror. There are several types of gas lasers and they are presented in the following table.

| GAS | Wavelength (nm) |
| --- | --- |
| He – Ne | 632.8 nm |
| $CO_2$ | 10600, 9600 |
| Krypton | 406.7, 413.1, 415.4, 468, 476.2,482.5, 520.8, 530.9, 568.2, 647.1, 676.4 |
| Argon | 351.1, 363.8, 454.6, 457.9, 465.8, 476.5, 488.0, 496.5, 501.7, 514.5, 528.7, 1092.3 |
| Nitrogen | 337.1 nm |

*Table 1 - Gas lasers and their wavelengths*

#### 1.3.2.3 Solid-state Lasers [15]

Solid-state lasers have the active medium held in an insulating dielectric crystal or glass rod. This rod, is "doped" with ions that provide the required energy states. The laser beam comes from energy jumps between discrete these energy levels. Rare earth elements such as cerium (Ce), erbium (Eu), terbium (Tb) i.e. are most commonly used as dopants. Materials such as sapphire ($Al_2O_3$), neodymium-doped yttrium aluminum garnet (Nd:YAG), Neodymium-doped glass (Nd:glass) and ytterbium-doped glass are used as host materials for laser medium. Out of these, neodymium-doped yttrium aluminum garnet (Nd:YAG) is most commonly used which can produce high power in the infrared spectrum at 1064 nm. In figure 1.3.2.3.1 the first solid state (Ruby laser) can be seen.

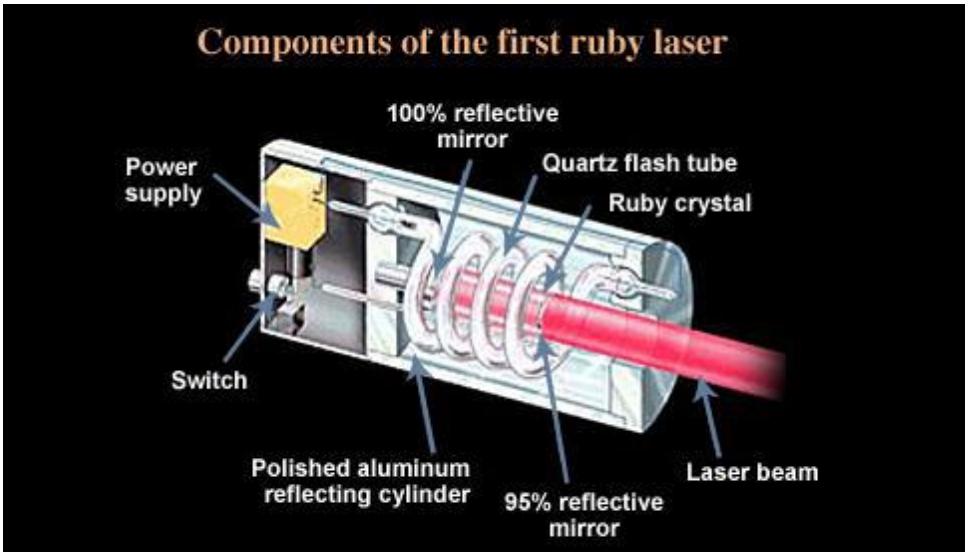



*Figure 1.3.2.3.1 – Ruby laser*

### 1.3.2.4 Liquid Lasers [12, 13]

**Liquid lasers** are optically pumped lasers in which the gain medium is a liquid at room temperature. In liquid lasers, light supplies energy to the laser medium. The advantage of a liquid laser is the feasibility of cooling the liquid by circulation. This permits production of higher energy both in pulsed and continuous operation. The most successful of all liquid lasers are dye lasers. In dye lasers the liquid material can be rhodamine B, sodium fluorescein and rhodamine 6G and is uses as active medium which produces laser beam. These lasers generate broadband laser light from the excited energy states of organic dyes dissolved in liquid solvents. Output can be either pulsed or CW and spans the spectrum from the near-UV to the near-IR, depending on the dye used (390nm to 1000nm). The dye lasers used as research tool in medical applications. Some of their advantages are that they are available in visible form, the beam laser is very less and their construction isn't so complex. On the other way, dye lasers are very expensive and there aren't suitable for all cases. In figure 1.3.2.4.1 the construction of a dye laser (Liquid laser) is depicted.

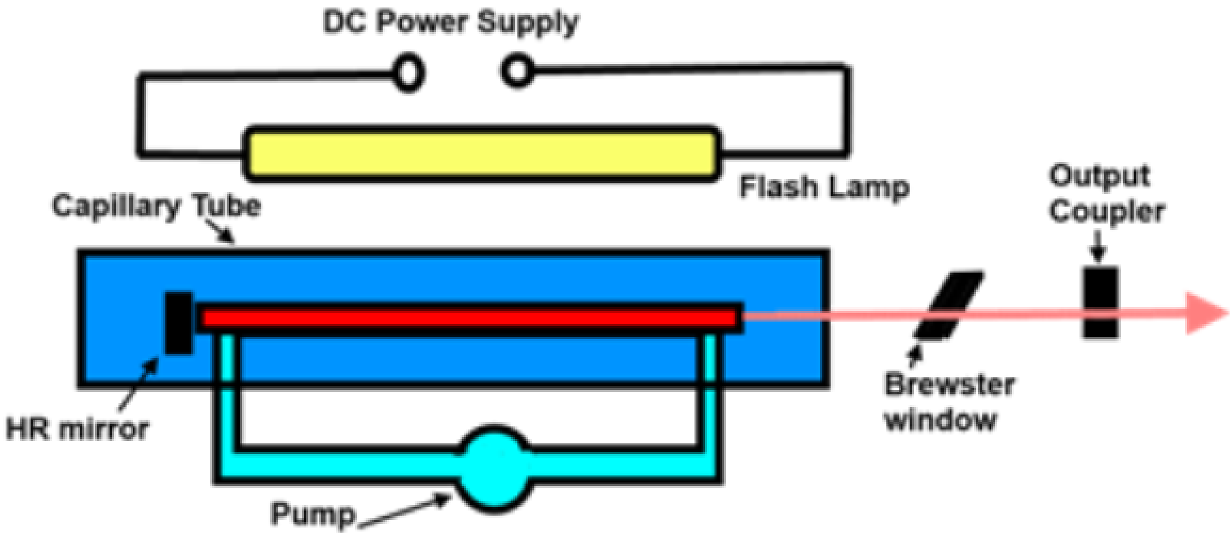



*Figure 1.3.2.4.1 – Dye laser*

### 1.3.2.5 Semiconductor Lasers [17, 18]

The **semiconductor laser** is very small both size and appearance and play important role to the everyday life because of they are cheap and consume low power. Semiconductors lasers are also known as laser diodes. Their wavelengths cover a wide area of the visible and near infrared spectrum. The active medium of the semiconductors lasers is a junction of a P-N diode. In figure 1.3.2.5.1 a P-N diode can be seen. In general, holes are injected from the p-doped (positive terminal), and electrons from the n-doped (negative terminal), semiconductor. A light beam with a photon energy slightly above the bandgap energy can excite electrons into a higher state in the conduction band,

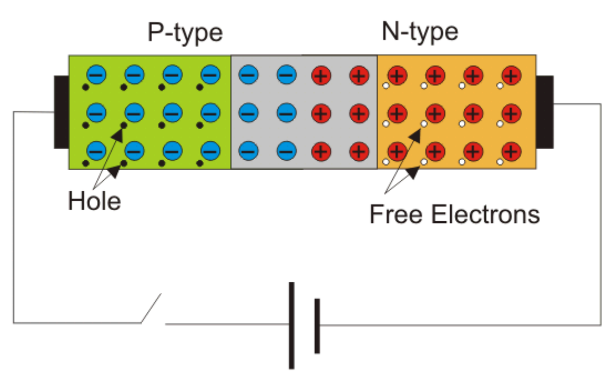



*Figure 1.3.2.5.1 – P-N diode*

from where they rapidly decay to states near the bottom of the conduction band. At the same time, the holes generated in the valence band move to the top of the valence band. This means that there is a reverse population between the vane and conductivity zone. The light emission is then achieved by re-coupling an electron from the conduction zone with a hole from the valence zone. In addition, both ends of the active layer act as a reflecting mirror where the light bounces in the active layer. Then, the light is amplified by the stimulated emission process and laser oscillation is generated. There are several types of semiconductor lasers like Double Heterostructure Lasers, Quantum Well Lasers, Quantum Cascade Lasers. In figure 1.3.2.5.2 the basic construction of a semiconductor laser is depicted and in figure 1.3.2.5.3 is presented a diode laser.

*Figure 1.3.2.5.2 – Diode laser*

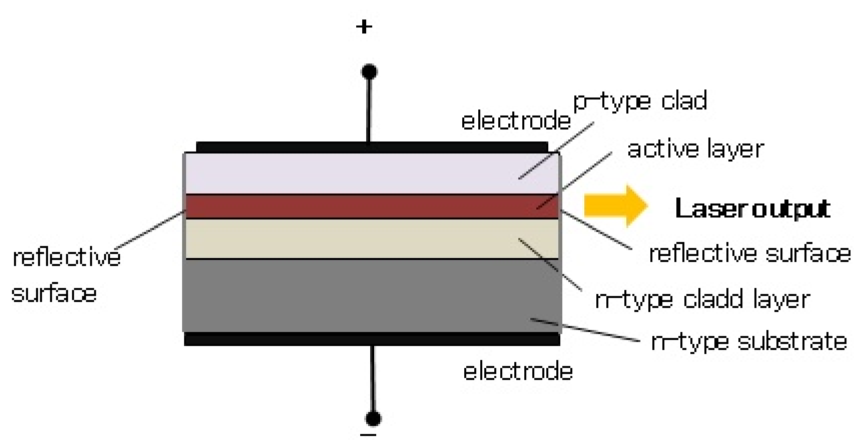
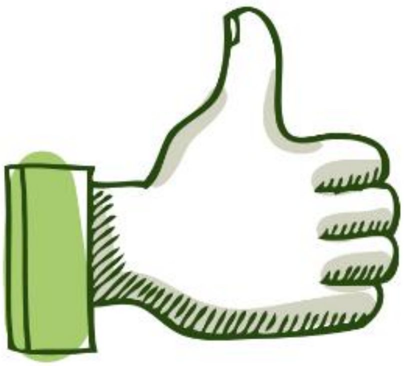


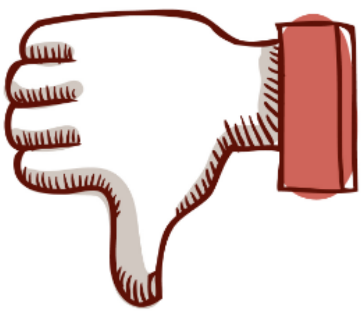

*Figure 1.3.2.5.3 – Basic construction of a semiconductor laser*

The main advantages and disadvantages of semiconductors lasers are:



**Advantages**

- Small size and appearance make them good choice for many applications
- Less expensive
- Much less power
- High efficiency



**Disadvantages**

- Diode laser beams are highly divergent
- Dependent on temperature
- Cooling system required in some cases

# 1.4 Light Emitting Diode (LED) [19, 20, 21, 22, 23, 24]

A Light Emitting Diode (LED) is an electronic device that emits light when current is passed through it. Furthermore, LEDs are small, extremely efficient, bright, and very cheap and these make them used as indicator lamps in many devices and are increasingly used for general lighting. **Captain Henry Joseph Round** observed first an electroluminescence from a diode and couple of years later **Nick Holonyak, Jr.** invented the first visible-spectrum (red) LED in 1962.

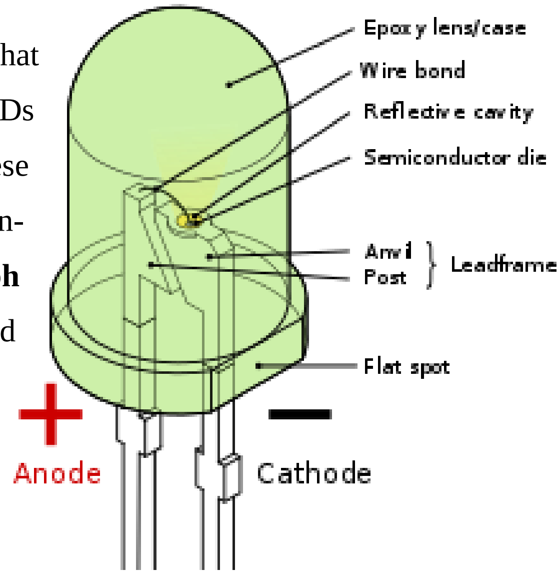
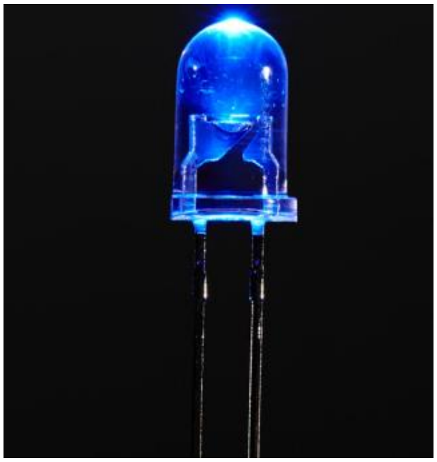



*Figure 1.4.1 - LED*

**Physics**

LED is a type of diode that converts electrical energy into light. The electricity flows through in one direction, from the Anode (positive side) to the Cathode (negative side), but not in the reverse direction. An interdiffusion of electrons and holes will occur in the region adjacent to the p-n-junction, driven by their concentration gradients. When an electron recombines with a hole, releases energy in the form of a photon due to the transfer of the electron to a lower energy level. The wavelength of emitted light depends on the band-gap energy of the semiconductor, which varies for different materials. The materials used for the LED have a direct band gap with energies corresponding to near-infrared, visible, or near-ultraviolet light. Some of the materials that LEDs are made are gallium arsenide, gallium nitride, yttrium aluminum garnet.

## 1.4.1 Blue LED



Blue LEDs were first developed by Herbert Paul Maruska at RCA in 1972 using gallium nitride (GaN) on a sapphire substrate. GanN is a semiconductor with a Wurtzite crystal structure and a direct bandgap of 3.4 eV, which directly corresponds to the wavelength of light in the ultraviolet range. Nowadays, blue leds have an active region consisting of one or more InGaN material made of a mix of gallium nitride (GaN) and indium nitride (InN).

*Figure 1.4.1.1 – Blue led*

## 1.4.2 White LED

There are two approaches that a led emits high brightness white light. One approach is to mix the light from several colored LEDs (blue, green, red) to create a spectral power distribution that appears white. By locating red, green and blue LEDs adjacent to one another and mix them, the resulting light is white in appearance. In figure 1.4.2.1 a white LED, by mixing red, green and blue LEDs, is illustrated.

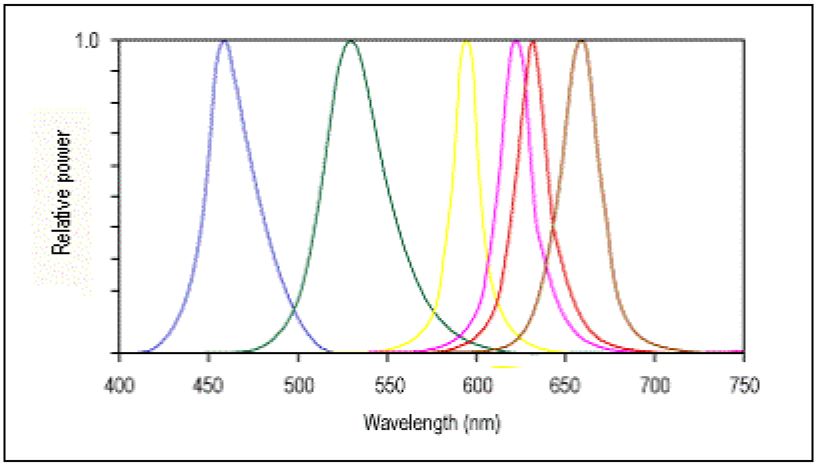



***Figure 1.4.2.1** - white LED by mixing red, green and blue Leds*

The other way to generate white light through led is via a phosphor material. This material can convert a blue led to white led. This phenomenon called phosphorescence. The mixing spectrum of the blue led and the spectrum caused by phosphorescence, is the final total spectrum, white light. In figure 1.4.2.2 the total spectrum of a white LED is depicted.

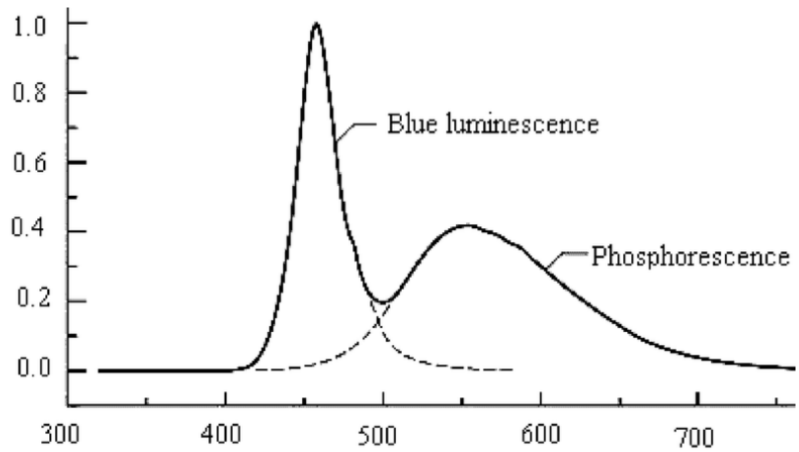



*Figure 1.4.2.2 – Spectrum of a white LED*

## 1.4.3 RGB LEDs

In fact, an RGB LED is a combination of 3 separate LEDs in just one package consists of one Red, one Green and one Blue LED. The color produced by the RGB LED is a combination of the colors of each one of these three LEDs. In figure 1.4.3.1 an RGB LED can be seen. There are two types of LED RGB, the common cathode (-) and the common anode (+) and their diagrams are presented at the next figure (1.4.3.2)

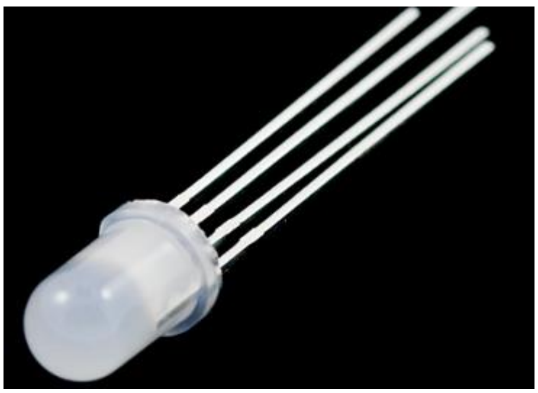


*Figure 1.4.3.1 – RGB LED*

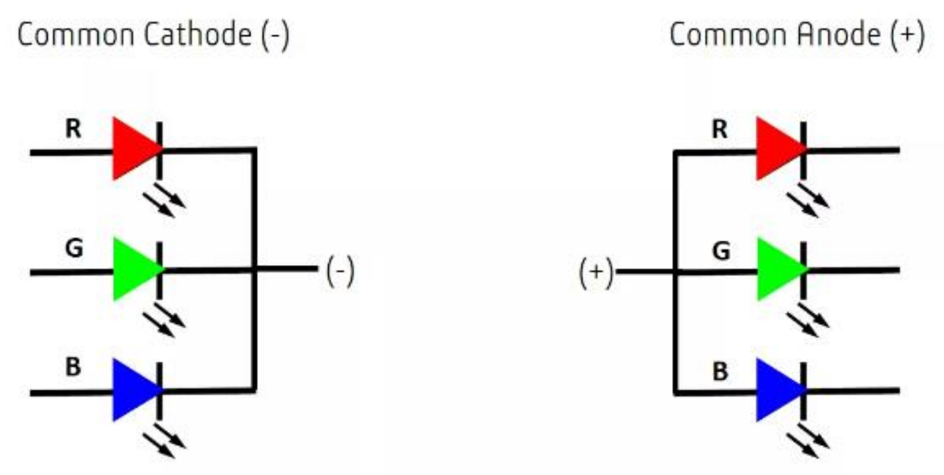



*Figure 1.4.3.2 – Common Anode, common Cathode*

Common anode means that the anode (positive) side of all of the LEDs are electrically connected at one pin, and each LED cathode has its own pin. Common cathode means that the cathodes of all of the LEDs are common and connected to a single pin. In figure 1.4.3.3 the total spectrum of an RGB LED is depicted.

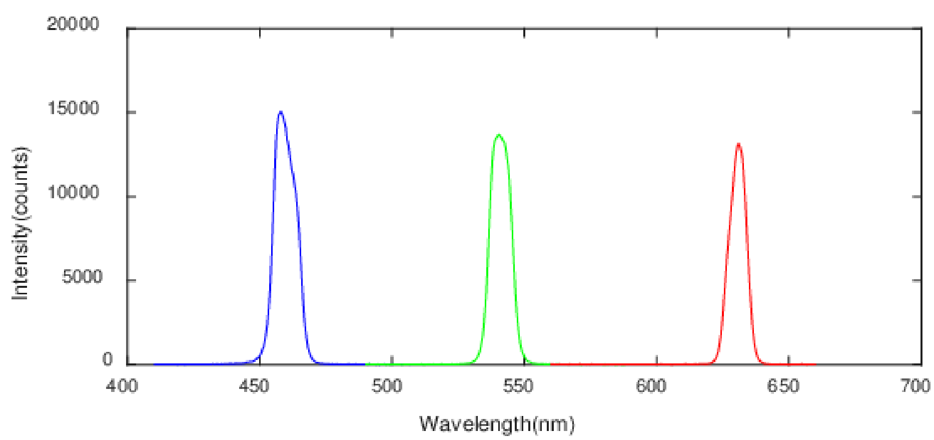



*Figure 1.4.3.3 – RGB Spectrum*

## 1.4.4 LED TYPES

There are several types of LEDs like miniature LEDs, mid-range LEDs, high power LEDs that are used in different applications according to the applications' needs**.**

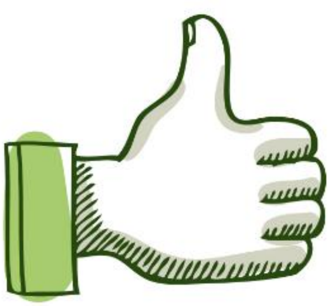
Figure 1.4.4.1 – High power LED

**Miniature LEDs** are mostly single-die LEDs used as indicators, and they come in various sizes from 2 mm to 8 mm and their typical current ratings range from around 1 mA to above 20 mA. **Medium-power LEDs** are mostly utilized when an output of just a few lumens 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). **High-power LEDs** can be driven at currents from hundreds of mA to several Amperes. Some of them can emit over a thousand lumens. In figures 1.4.4.1, 1.4.4.2 and 1.4.4.3 these types of LEDs are depicted.

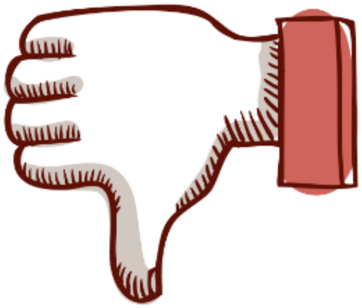
Figure 1.4.4.2 – Miniature LED

Figure 1.4.4.3 – Medium-power LED

The main advantages and disadvantages of LEDs are:



- **Size -** They are very small in size (smaller than 2mm) which makes it easier to place them on boards or places where the space is limited
- They are not fragile
- **Fast response**
- **Energy efficient -** produce more light per watt (135 lumens/watt)
- **long lifetime** - 50,000 hours or more if properly engineered.
- **Environmentally friendly** – LEDs contain no mercury or other hazardous substances
- **No warm-up period** - LEDs light instantly – in nanoseconds



- **high initial cost -** LEDs today is more expensive, price per lumen, than common lighting technologies
- **Voltage sensitivity -** Resistance series or power control sources are often used
- **sensitivity to temperatures -** The LEDs are made up of these tiny lamps and a circuit that allows them to function properly. All of them, although not usually warm, are sensitive to high temperatures. If for some reason it gets hot, there is a risk that some part of the circuit will fail and so the entire circuit does not work, so it needs to be replaced

# CHAPTER 2
# LIGHT SOURCES

In the previous chapter, there was an introduction to the physics of light 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, with these light sources we can't control the spectrum that we want to project.

In this chapter, will be mentioned light sources that are tunable. This means that they give to the user the possibility to control the spectrum that is projected. Tunable Light Sources (TLS) are used to illumine objects with a specific range of wavelength. TLS are extremely utilitarian in many sciences like optics, biology, chemistry i.e. The most common Tunable Light Source assembly is a white light source (halogen, Xe) and a monochromator.

## 2.1 Discrete LEDs

One way to control the projected spectrum, is the light source that consist of several discrete LEDs. These devices can be tuned in wide spectral range, usually (380nm-1000nm) with specific spectral peaks in this range. Through a software, the user can choose which exactly spectrum(peak) want to project. The disadvantage of these light sources is the complexity of their format and that can project only "peaks". In figure 2.1.1 the projection spectrum of the light sources that consist of discrete LEDs can be seen.

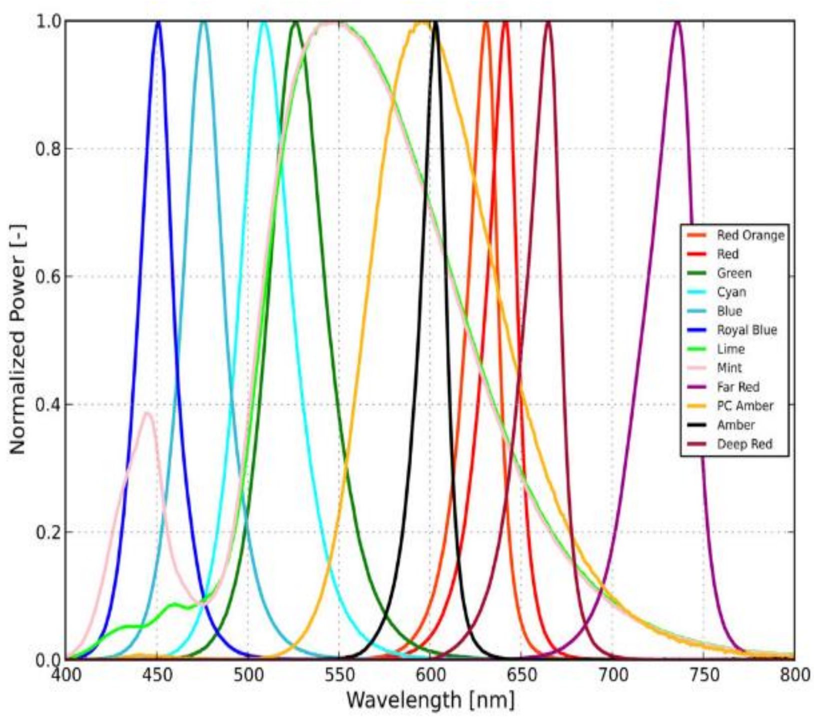



*Figure 2.1.1 – Peaks of discrete LEDs light sources*

## 2.2 Liquid-crystal tunable filter [25, 26, 27, 28]

**Liquid crystal tunable filters** (LCTFs) are optical filters that use electronically controlled liquid crystal (LC) elements to transmit a selectable wavelength of light. Often, the basic working principle is based on the Lyot filter but many other designs can be used. The main difference with the original Lyot filter is that the fixed wave plates are replaced by switchable liquid crystal wave plates. LCTFs are known for enabling very high image quality and allowing relatively easy integration with regard to optical system design and software control but having lower peak transmission values in comparison with conventional fixed-wavelength optical filters due to the use of multiple polarizing elements. This can be mitigated in some instances by using wider bandpass designs, since a wider bandpass result in more light traveling through the filter. Some LCTFs are designed to tune to a limited number of fixed wavelengths such as the red, green, and blue (RGB) colors while others can be tuned in small increments over a wide range of wavelengths such as the visible or near-infrared spectrum from 400 to the current limit of 2450 nm. The tuning speed of LCTFs varies by manufacturer and design, but is generally several tens of milliseconds, mainly determined by the switching speed of the liquid crystal elements. Higher temperatures can decrease the transition time for the molecules of the liquid crystal material to align themselves and for the filter to tune to a particular wavelength. Lower temperatures increase the viscosity of the liquid crystal material and increase the tuning time of the filter from one wavelength to another. LCTFs are often used in multispectral imaging or hyperspectral imaging systems because of their high image quality and rapid tuning over a broad spectral range Multiple LCTFs in separate imaging paths can be used in optical designs when the required wavelength range exceeds the capabilities of a single filter, such as in astronomy applications.

## 2.3 Diffraction grating [29, 30]

When there is a need to separate light of different wavelengths with high resolution, then a diffraction grating is most often the tool of choice. This "super prism" aspect of the diffraction grating leads to application for measuring atomic spectra in both laboratory instruments and telescopes. The **diffraction grating** is an optical component with a periodic structure that splits and diffracts light into several beams travelling in different directions. The emerging coloration is a form of structural coloration. The directions of these beams depend on the spacing of the grating and the wavelength of the light so that the grating acts as the dispersive element. Because of this, gratings are commonly used in monochromators and spectrometers. The light sources based on diffraction grating can rotate it to allow only a few nm of light to pass through the fiber optic adapter or cable. In figure 2.3.1 a light source based on diffraction grating is depicted

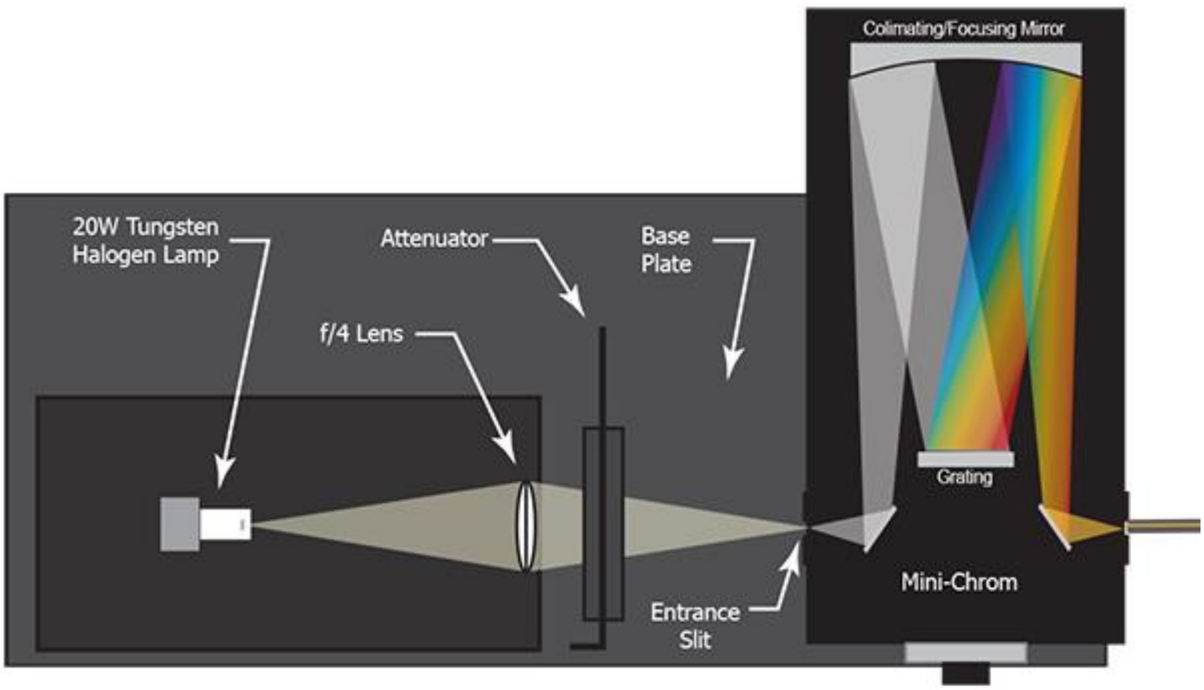
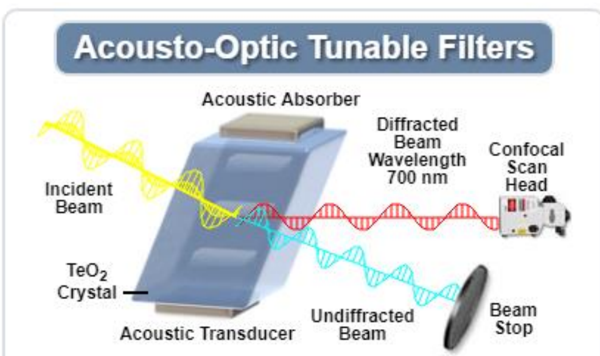
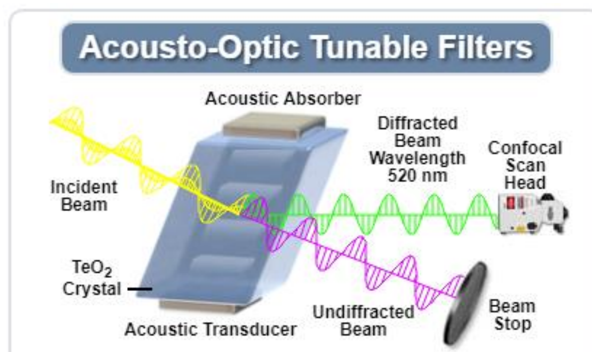


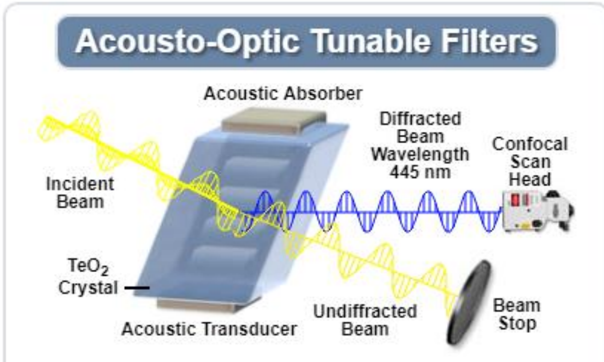

*Figure 2.3.1 – Diffraction grating technology*

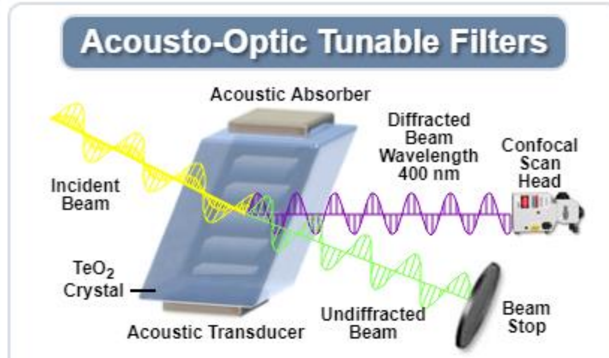
## 2.4 Akousto – Optic Tunable filter (AOTF) [31, 32]

Wavelength selection is of fundamental importance in many arenas of the optical sciences, including fluorescence spectroscopy and microscopy. Electro-optic devices, such as the acousto-optic tunable filter (AOTF), are increasingly being employed to modulate the wavelength and amplitude of illuminating laser light in the latest generation of confocal microscopes. These filters do not suffer from the mechanical constraints, speed limitations, image shift, and vibration associated with rotating filter wheels, and can easily accommodate several laser systems tuned to different output wavelengths. In addition, acousto-optic filters do not deteriorate when exposed to heat and intense light as do fluorescence interference filters. Upon encountering the standing wave in the tellurium dioxide crystal, a portion of the incident light beam is diffracted into the Confocal Scan Head while the remainder of the beam passes through the crystal and is absorbed by a Beam Stop. In an acousto-optic tunable filter, a piezoelectric transducer bonded to a crystal of tellurium dioxide or quartz generates high-frequency acoustical compression waves that alter the refractive index of the crystal in a periodic pattern. This lead, in effect, to the generation of a diffraction grating so that an orthogonal beam of polarized and collimated light incident at the Bragg angle is diffracted with high efficiency into the first order beam. Variations in the frequency of the acoustic waves alter the spacing pattern in the crystal and, hence, the wavelength of the diffracted. Likewise, altering the amplitude of the acoustic wave determines its relative intensity. The diffraction efficiency can reach levels of 85 percent and the switching speed for both wavelength and power is in the megahertz range. In the next figures some examples of Acousto-Optic Tunable Filters are presented.






## 2.5 Central purposes

Regarding the tunability, some of the tunable light sources and configurations which described in previous sections can project only specific monochromatic spectrum range (curve peaks**).** Our goal is to construct a computer controlled Light Source that will be able to project any desired spectrum that the user wants. Any spectrum, in the scientific world that is described by a curve, our light source is suitable to created it and projected the corresponding color. The spectrum range that can cover our light source is in visible light and is able for future work to cover infrared too. It is very important to refer the cost of this. **The main innovation of our Light Source is that it is able to produce any desired spectral line requesting by user.** Also, it is characterized by low cost and high throughput. These characteristics are not found in another light source in entire world.

# CHAPTER 3
# HARDWARE AND SOFTWARE CONFIGURATION

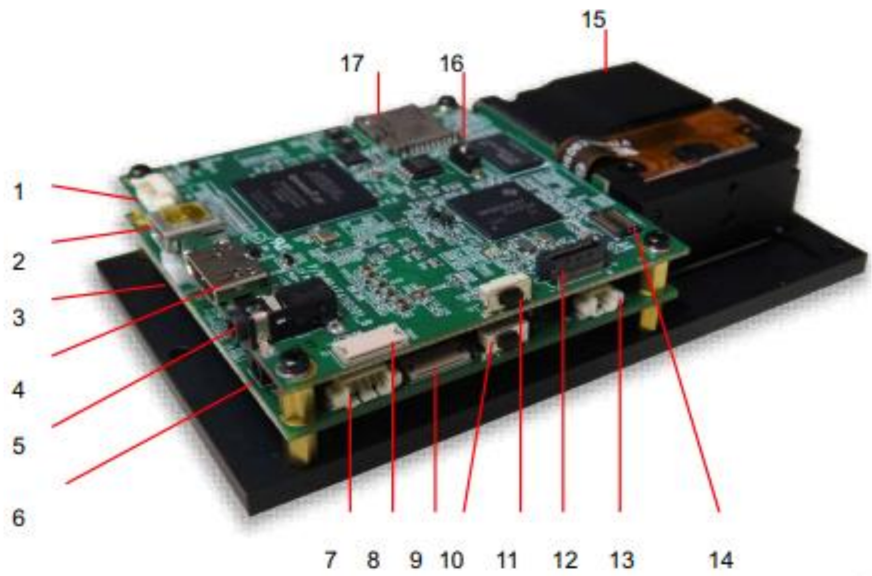
## 3.1 Architecture of the experiment

In the context of this diploma thesis, after the searching and finding of light sources which exist in the science, was created a spatial light modulator based light source with controlled spectral emission.

In this section will be explained the architecture of the light source in detail and will be presented its function, as well as the modules that consists of. Furthermore, in the text there are multiple figures to understand better and easier the experiment.

### 3.1.1 DLP lightcrafter 3000 evaluation module [36]

Digital Light Processing (DLP) is a display device based on optical micro-electro-mechanical technology that uses a digital micromirror device. It was originally developed in 1987 by Larry Hornbeck of Texas Instruments. For the creation of light source used a DLP 3000 LightCrafter which, as a compact module, evaluates the integrating projected light and it is applicable into industrial, medical, and other scientific needs. Its size is 117mm x 65mm x 23mm and it is able to display images and videos up to WVGA resolution (854 x 480). Lightcrafer offers connectivity options with cameras, sensors, mini-HDMI, micro-SD, mini USB, UART mini plug, $I^2C$. In the figure 3.1.1.1 the lightcrafter 3000 Evaluation module with the connector locations can be seen. Inside it there is an engine which produce light and consists of a digital micromirror device (DMD), a red LED, a green LED, a blue LED, an NTC thermistor. Additionally, it has Optics with 1.66 throw ratio ($throw\ ratio = \frac{\text{distance from projector lens to screen}}{\text{screen width}}$).




1. Trigger input and output
2. Mini USB
3. Power connector
4. Mini HDMI
5. UART
6. Power socket
7. $I^2C$
8. FPGA SPI flash programming interface
9. MSP430 or DLPC300 flash programming interface
10. On or off button – Do not turn off while the Linux system is booting
11. Input selection button (DM365, internal test pattern, or HDMI input)
12. Ethernet PHY
13. Fan
14. Camera
15. Focus control
16. Boot mode selection switch
17. Micro-SD card

*figure 3.1.1.1 - DLP LightCrafter 3000 Evaluation Module with connector locations*

**1.DLP 3000**

The DLP3000 digital micromirror device (DMD) is a digitally-controlled micro-opto-electromechanical system (MOEMS) spatial light modulator (SLM) optimized for small form-factor applications. The dlp 3000 is characterized by speed accuracy and high performance and is able to modulate the amplitude and direction of incoming light. The size of DMD is 0.3 Inch (7.62mm) and contains 415872 mirrors arranged in 608 × 684 Array of Aluminum. It is highly efficient in Visible Light with spectral range 420nm to 700nm. It has low power consumption of about 200MW and the temperature that supports is 0° to 70° C. There are several applications that Dlp300 can be used like machine vision, face recognition, 3D scanning, spectroscopy, chemical Analyzers and medical Instruments. In figure 3.1.1.2 a DLP3000 can be seen.

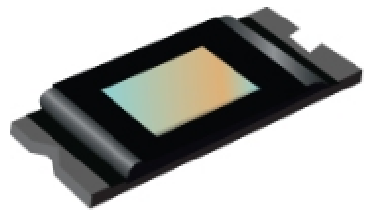


*Figure 3.1.1.2- DLP3000*

**2. Blue LED - Green LED - Red LED**

OSRAM Opto Semiconductors are high power LEDs-single color and are used in specific applications that need projection. They have been developed specifically for use in slim designs and because of this their size is very small. There are three embedded LEDs inside the DLP3000 Light crafter, particularly a blue (465nm), a green (550nm) and a red (624nm). One of their characteristics is their very low thermal resistance. Likewise, they are characterized by high brightness and fast switching times. Their usage is quite common in Pico projectors, general Lighting applications, RGB floodlights and effect lighting. In figure 3.1.1.3 a high-power LED is depicted. For the experiment, these three LEDS replaced by a halogen lamp, to get more output power and be able to project in the infrared spectrum.

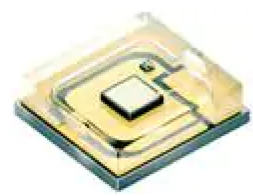


*Figure 3.1.1.3- LED-single color*

**3. NTC thermistor**

Thermistor is a type of resistance which the value of which is affected by temperature, much more than the usual resistances. At NTC thermistors the value is decreasing when the temperature is increasing. Usually they are used to protect the circuit from sudden increases in currents. Inside DLP3000 LightCrafter there is one NTC thermistor which has been developed by

Murata. Some of their features are the excellent solderability and high stability in environment, the excellent long-time aging stability. In figure 3.1.1.4 a NTC can be seen.

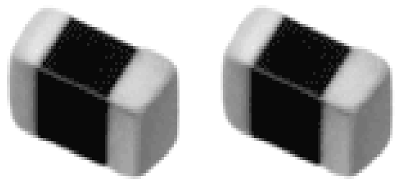


*Figure 3.1.1.4-NTC thermistor*

**4. Items needed for the operation**

The user to operate the DLP3000 evaluation module needs a power supply which is not include in the package, and it will provide 5V. The inner plug diameter must be 0.7mm, the outer diameter 2.35mm and the female shaft length 9.5mm. Furthermore, the package doesn't include any cable or additional hardware component.

## 3.1.2 Optical fiber cables [38]

An optical fiber is a flexible, transparent fiber made by glass or plastic with very thick diameter. The optical fibers transmit light toward the ends of the fiber and are more useful instead of metal wires because the signals that arrive at final destination have less losses. At one end of the optical fiber, there is the transmitter and at the other, the receiver. The transmitter converts a computer's digital information into digital light waves. The receiver decodes the digital waves of light in digital data. The digital waves of light travel at the speed of light through the optical fiber with successive reflections on the walls of the optical fiber. These reflections take place in the walls, at an angle of less than 42 degrees, as a result the walls are operated like mirrors. This phenomenon is called total reflection and that's the reason why light waves stay inside the optical fiber, and continue their journey to the other end without coming out of the fiber. In figure 3.1.2.1 fiber optics are depicted.

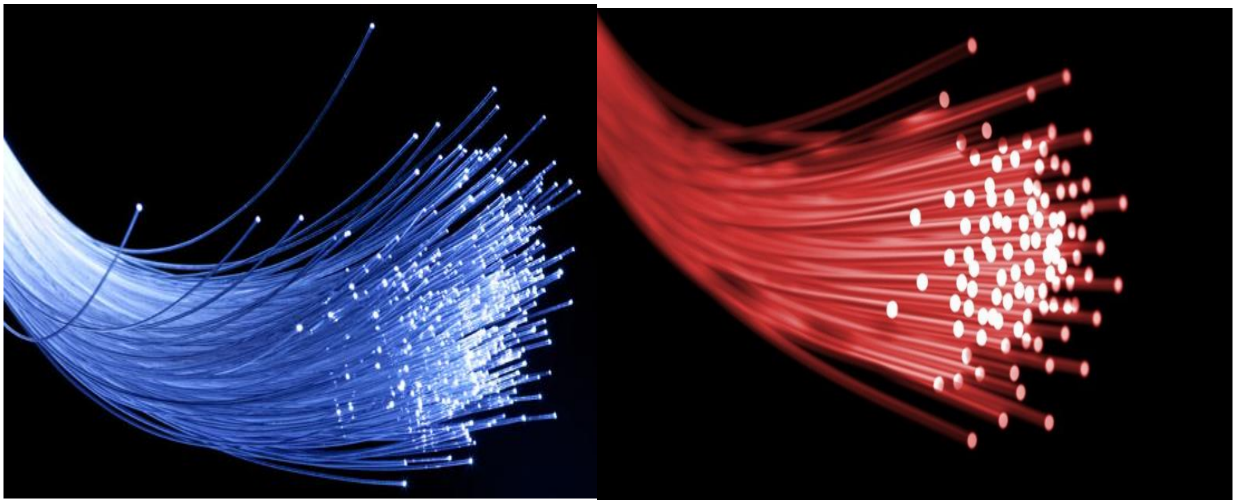


*Figure 3.1.2.1-Optical fibers*

For the experiment were used two optical fiber cables which on one side are arranged a lot of optical fibers next to each other, and at the other end they are all gathered together in a round mount to transmit the photons. In figure 3.1.2.2 the Optical Fiber Cables can be seen.

*Figure 3.1.2.2-Optical Fiber Cable*

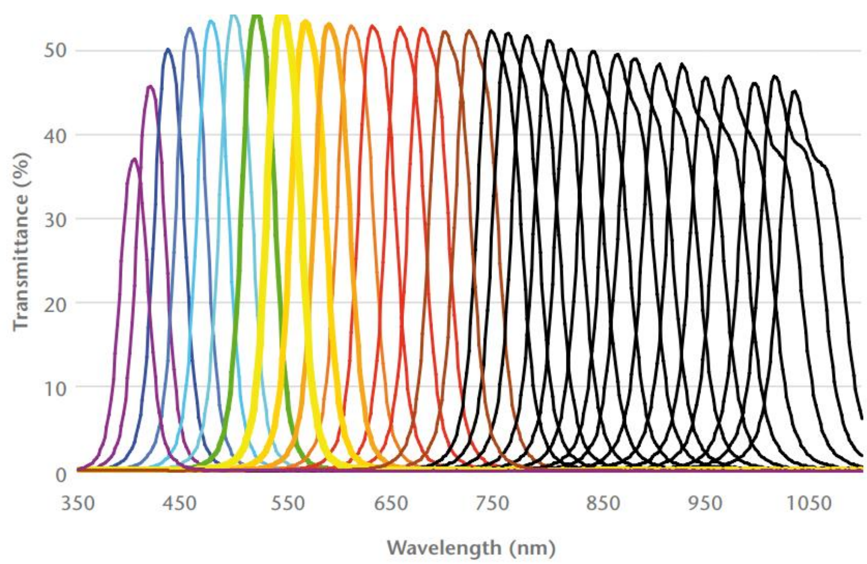
## 3.1.3 Spectrometer [37]

In optoelectronics, a spectrometer is a scientific device which the main operation in visible light is to analyze, separate and measure the light properties of an illuminated object or reflected light. Particularly, determine the wavelength and the intensity of light. In general, a spectrometer can applied in several sciences like astronomy, chemistry. A Spectrometer consists of Illumination source, interference filters, a detector or photodiode and a readout device. A spectrometer that is manufactured by Ocean Optics was used for the needs of the experiment. The spectral range which can cover is about 200 to 1100nm. In figure 3.1.3.1 the spectrometer is depicted.


*Figure 3.1.3.1-Spectrometer USB4000*

### 3.1.4 Linear Variable Filters [39]

Another component of the architecture experiment is one filter glass that manufactured by Schott. The tunability of our light source depends on two components; the linear variable filters used to produce (ideally) monochromatic light and the Optical fibers which are arranged in specific positions behind the filters.




In this way, the black and white image illuminates different areas behind the filters and gives a different wavelength each time. Its length is about 50mm and its spectral range is 400-700nm. A linear variable bandpass filter where the center wavelength of the filter shifts linearly across the length of the filter. When used with a slit, the bandwidth

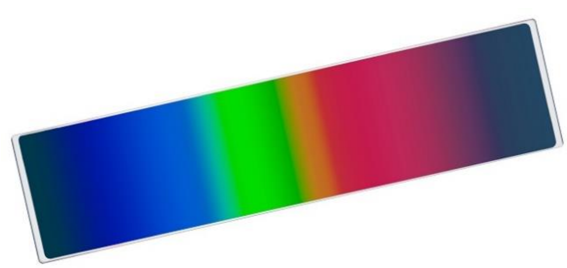


**Figure 3.1.4.2 – Schott filter**

of the filter can be verified. Filters like this can be used in several applications like spectroscopy, immunology, pharmaceutical analysis i.e.

### 3.1.5 Camera sensor

The last component of the architecture is a Back-illuminated CMOS Image Sensor with 14bit ADC. ASI178MC has a 1/1.8″ and 6.4M pixels sensor IMX178 with SONY STARVIS and Exmor R Technology. For this experiment, its usage was to take pictures of the final projected results.

## 3.2 Software development

For the purposes of this Experiment two different software programs were used:

### 3.2.1 MATLAB

The functionality of MATLAB for this experiment is to create images that consists of black and white vertical lines. These lines are defined from a curve which is given from the user. The curve is a plot that in X-axis is the wavelength (380nm-720nm) and Y-axis is the intensity which is from white (0) to black (255). So, for each wavelength corresponds an intensity and created the line at new image for the specific wavelength. The inserted curve is created with the MATLAB' s method "Spline" and the arguments of this method are points that given by user. This method was used because it creates more evenly the curve we need, without creating sharp peaks between the points and better suited to describing a spectrum. For example, if the user wants to create the red color then choose two points before and after 700 nm and one point at 700nm so in this way will be created a curve with peak at 700nm. The given points and the curve resulted from these points:

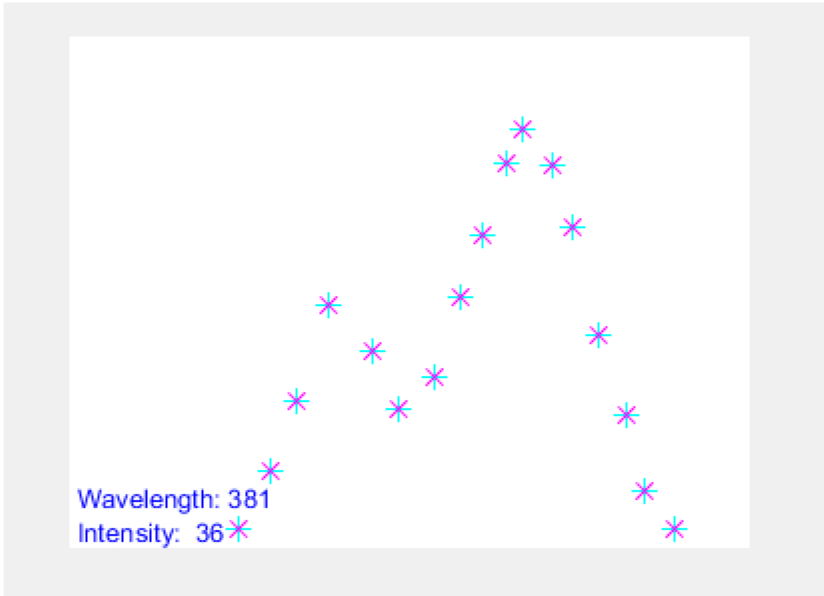



*Figure 3.2.1.1 - Given points of the curve*

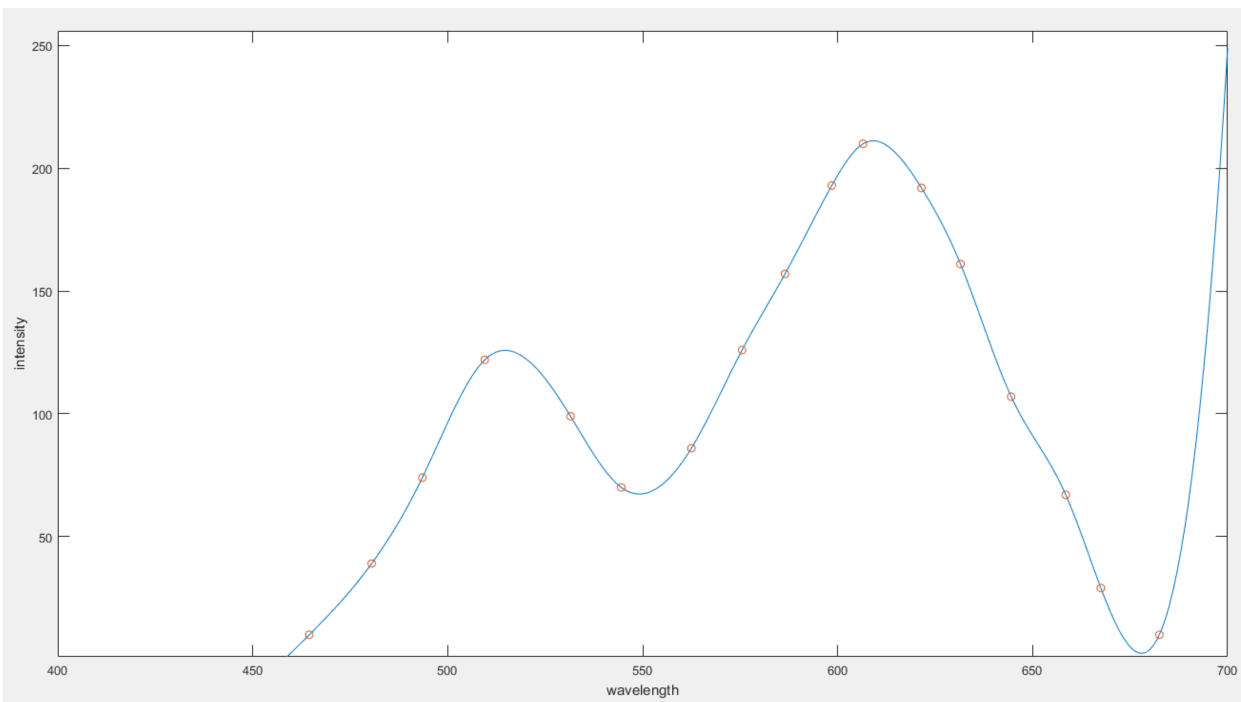



*Figure 3.2.1.2 - Design curve*

The final projected image:

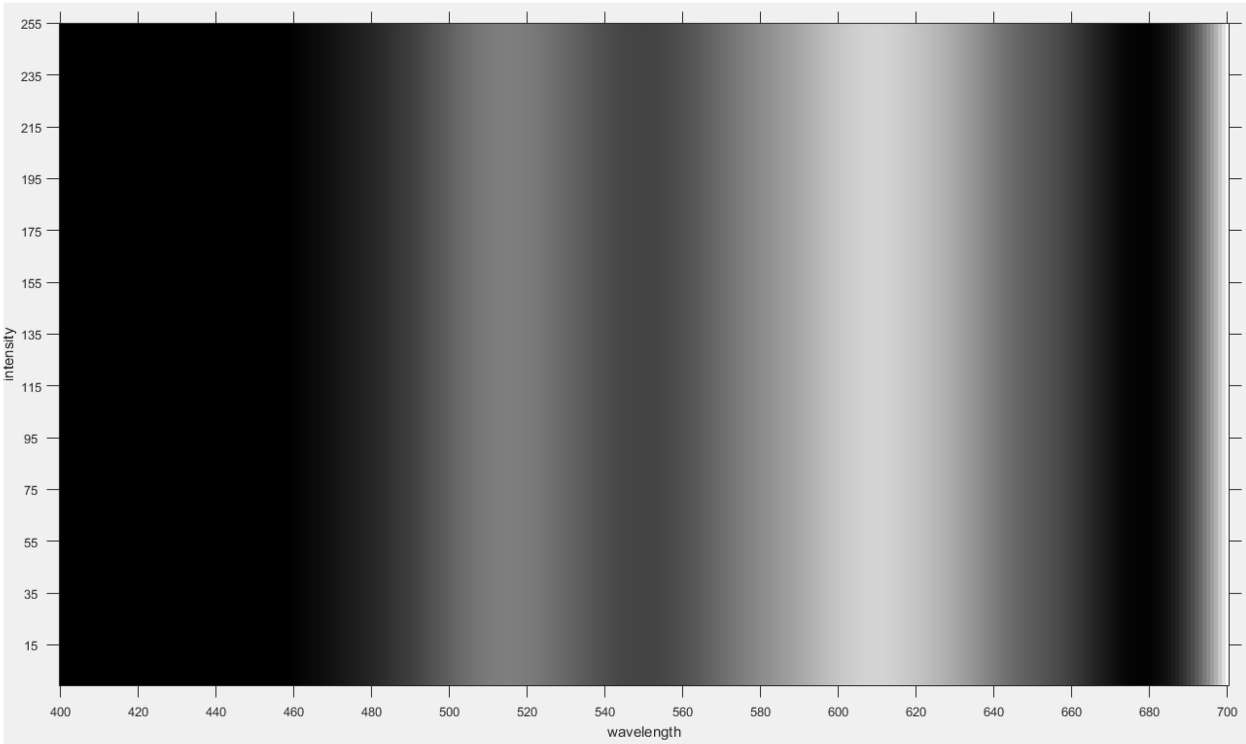



*Figure 3.2.1.3-Final image*

Because of, the final image will be sent at DLP via HDMI it was necessary to be created another one same image but in resolution of the DLP (854 x 480).

### 3.2.2 Spectra suite

For measuring the spectrums, it used a spectrometer (Ocean Optics, USB4000) and the relative software (Spectra Suite).

## 3.3 Experiment Description

With this light source, the user firstly desires whatever spectrum he wants and then are created the black and white images which are the pattern of the desired curve. Then, the image is sent to the DLP via USB and is projected towards to the linear filter. The result light from the filter insert in optical fiber which there is behind the filter. Finally, the fiber project the specific color described by the initial curve given by user. With the resulted color we are able to do several experiments which are described in the next chapter. Additionally, there are various variations of the software for the needs of the experiments. The initial setup of the light source to test the system is depicted in the next figures (3.3.1, 3.3.2).

*Figure 3.3.1 – Front initial setup*

*Figure 3.3.2 – Back initial setup*

After this setup we decided to change it to take better results. The first change was to remove the light engine of the DLP (3 RGB LEDS) and replace them with a halogen lamp to get more optical power and be able to project in the infrared spectrum but also because it has more "continuous" spectrum than the 3 LEDs, which leave a gap between them as they don't have overlapping. The second change, was to do the system more stablish so in this way we construct at printer a design scheme to union the DLP with the filters-Fibers. Because of the halogen lamp gives a lot of infrared light was placed a cooler to protect the optical engine from overheat. Additionally, the light is projected on optical diffuser which are used to evenly diffuse light. More specifically, optical diffusers cause light to spread evenly across a surface, minimizing or removing high intensity bright spots. In this way the final results are more understandable. In the next figure the final setup is presented.

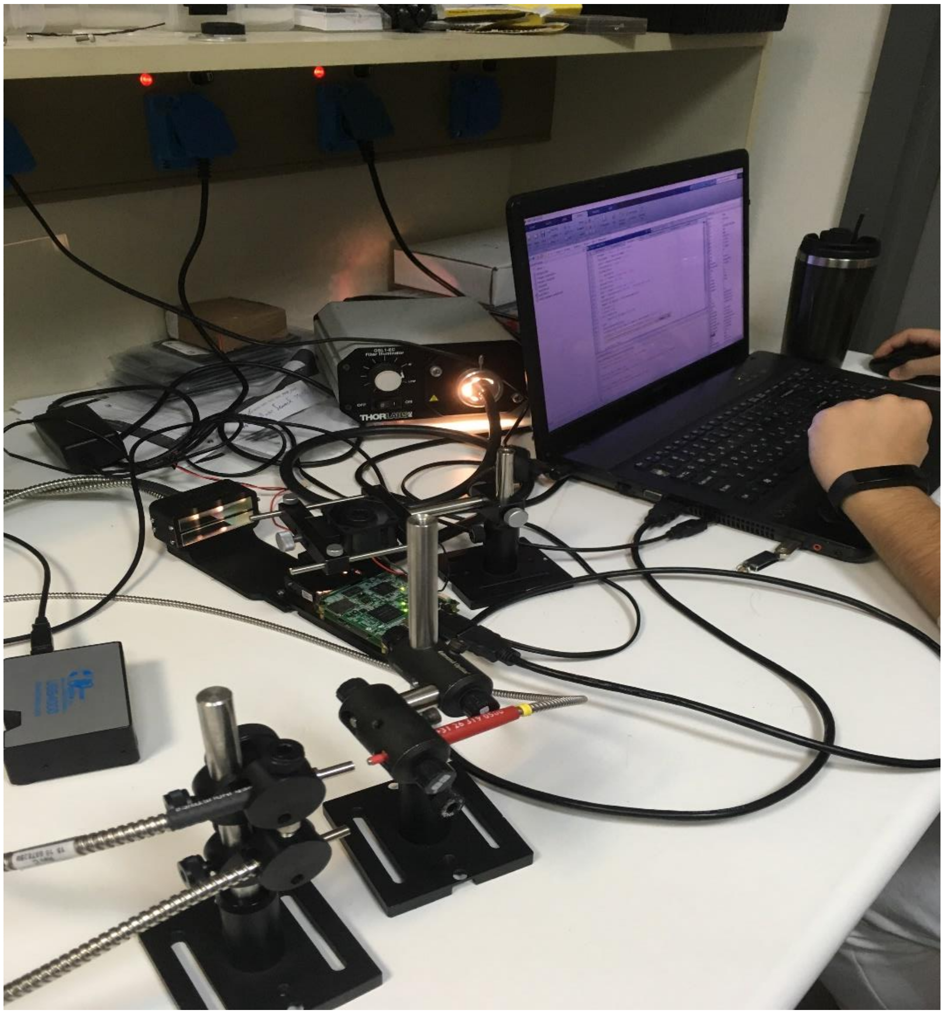


*Figure 3.3.3 – Final Setup*

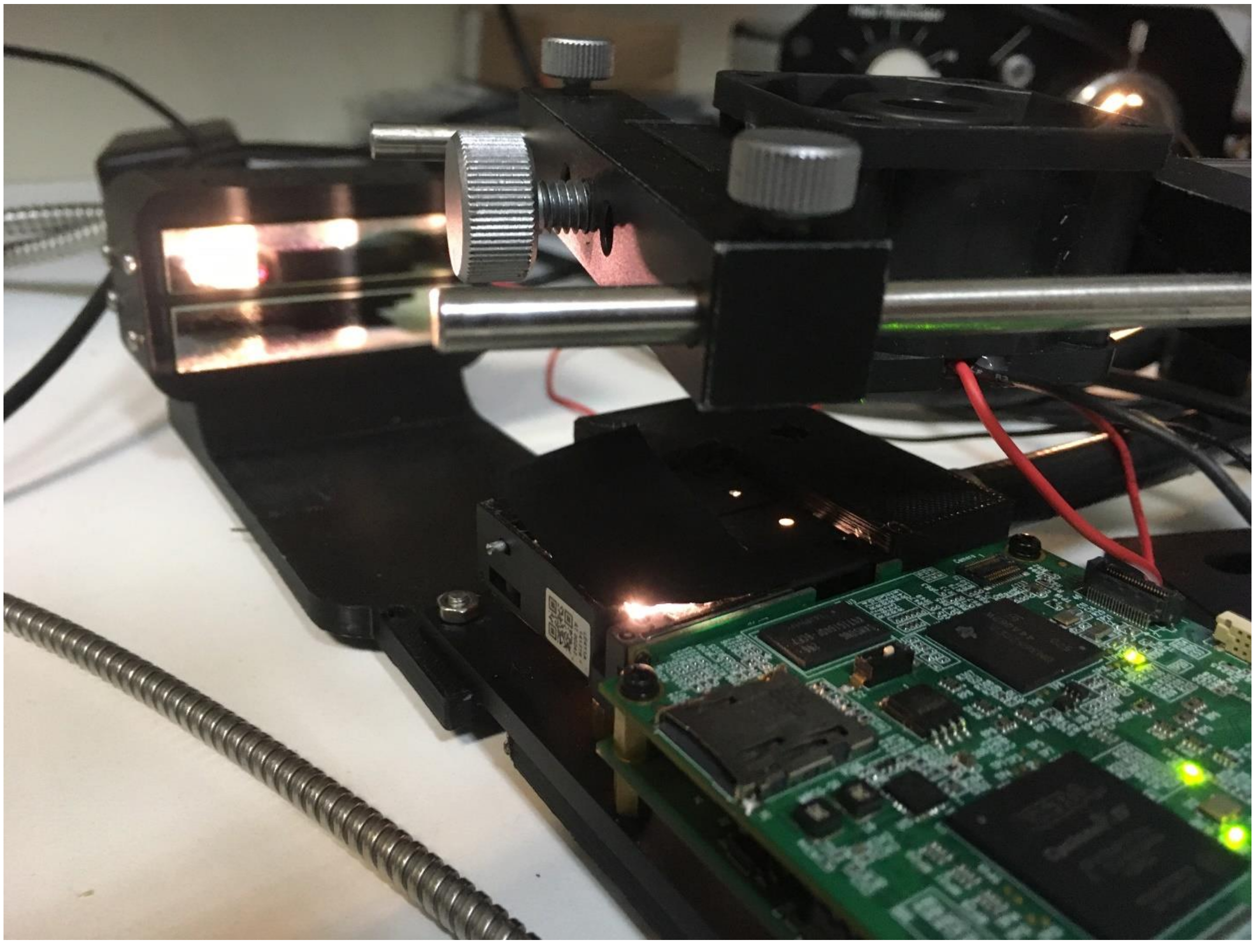


*Figure 3.3.4 – Final setup (detailing)*

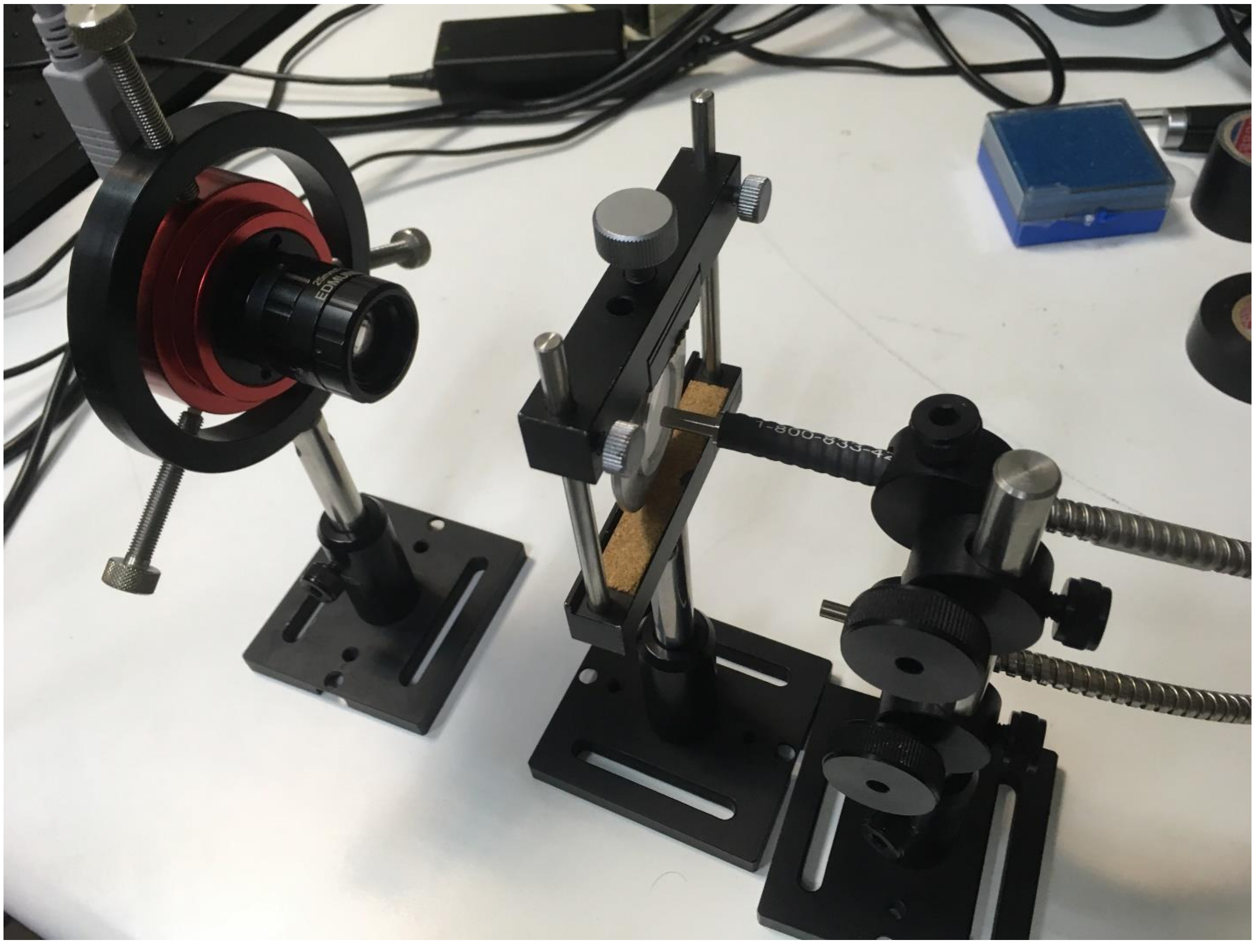


*Figure 3.3.3.5 – Final setup (Detailing 2)*

Additionally, there is an extra figure for better understanding of the system (figure 3.3.3.6)

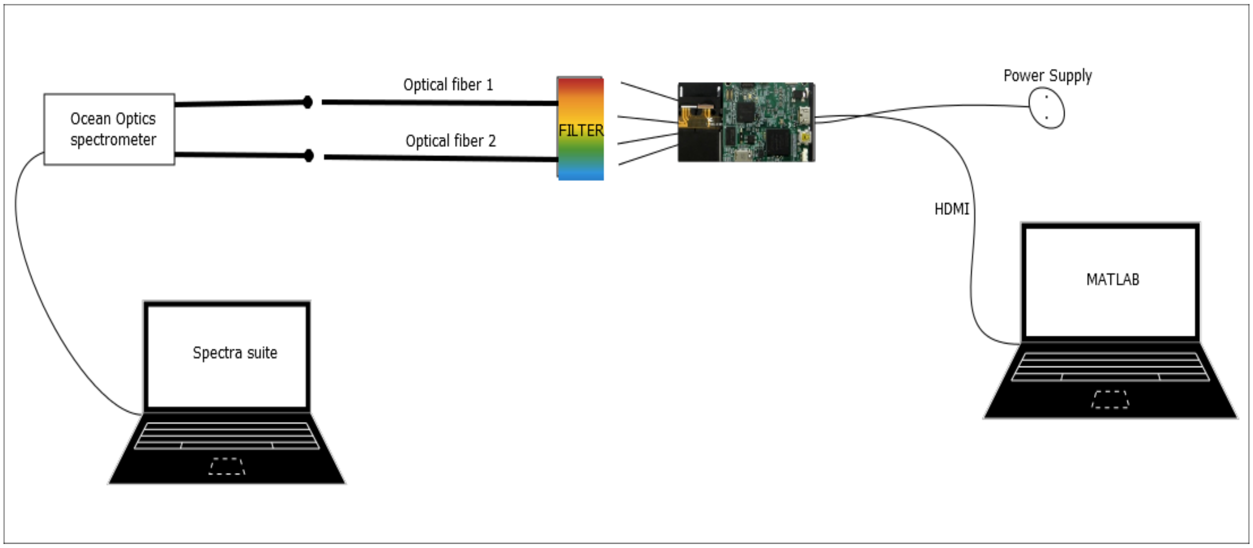



*Figure 3.3.3.6 – Block diagram of the system*

# CHAPTER 4
# TECHNICAL EVALUATION

In this Chapter we will elaborate on the technical evaluation of the system we built. The aspects of evaluation will be the reproducibility test, accuracy, the projection of the chlorophyll spectrum and a skin spectrum, the creation of a pair of metameric colors and flatten the light source. All the aforementioned parameters are important to define the stability and quality of operation of our Tunable Light Source.

## 4.1 Reproducibility test

The first test performed was about the reproducibility of the system. Ten different spectra were designed and each was measured 10 times with the spectrometer. The first measure was at 470nm and the last one at 650nm with steps 20nm each time. Also, for each measurement, has been calculated the deviation between the curve that is the result of the spectrometer and the initial design curve.

### 4.1.1 470nm peak

The initial design curve, the display image and the resulting curve of ten different measurements are:

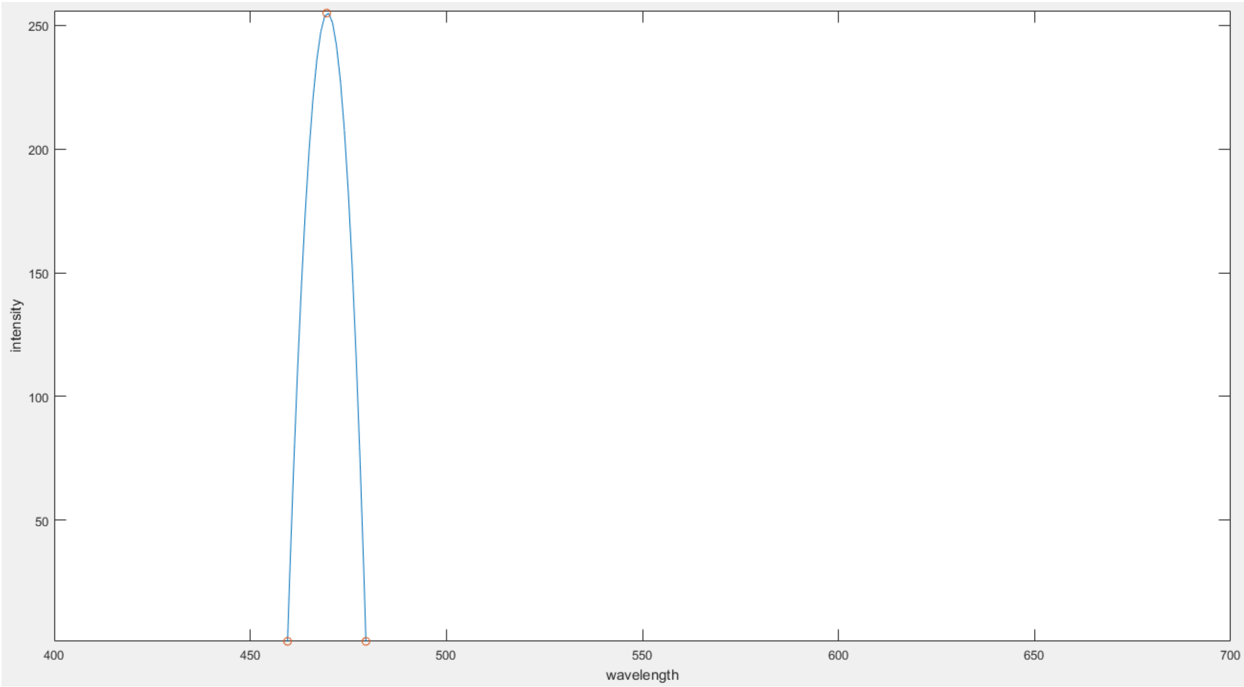



*Figure 4.1.1.1 – Initial Design of 470nm*

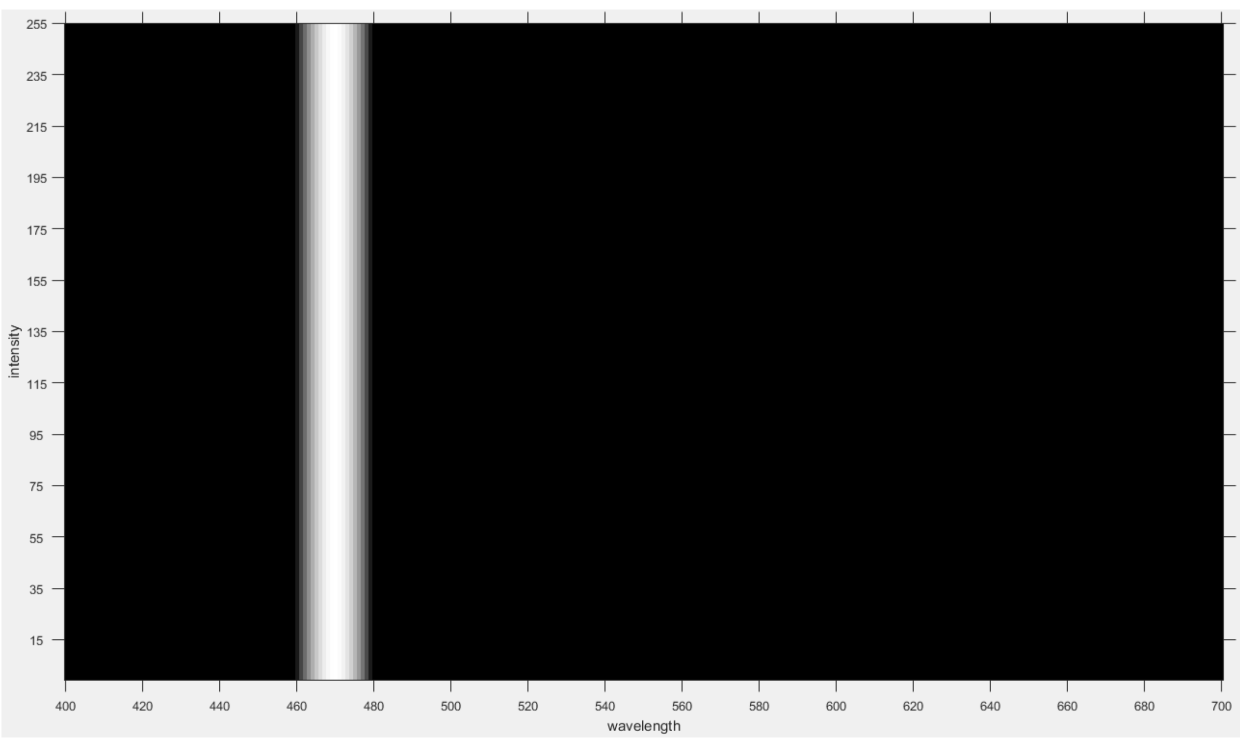
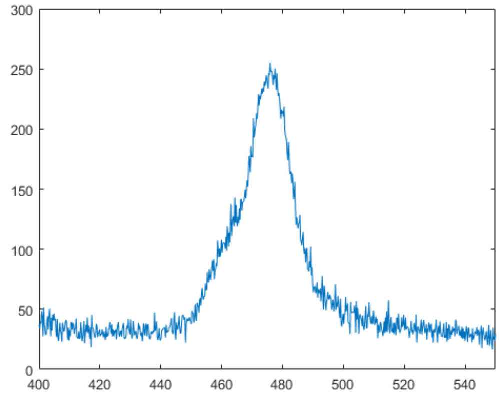



*Figure 4.1.1.2 – Displaying image*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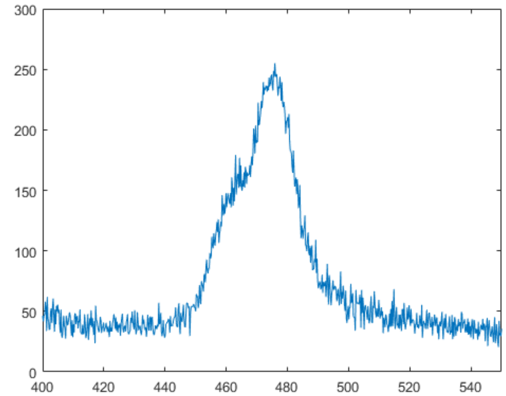
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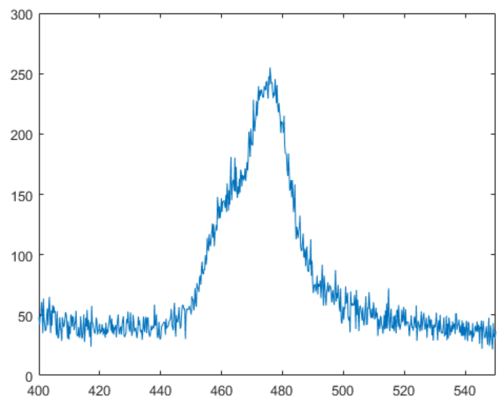
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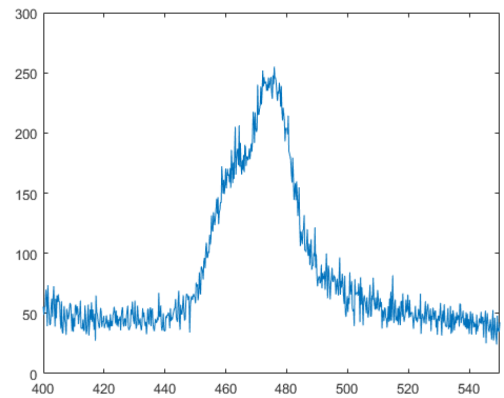
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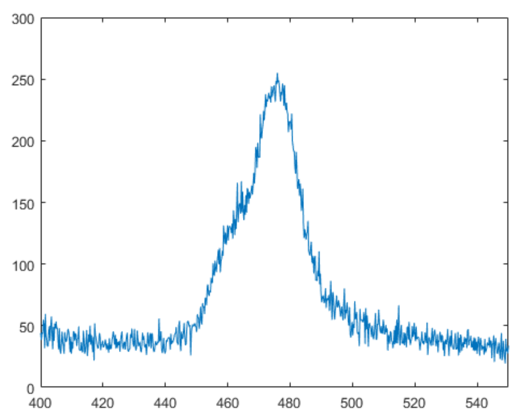
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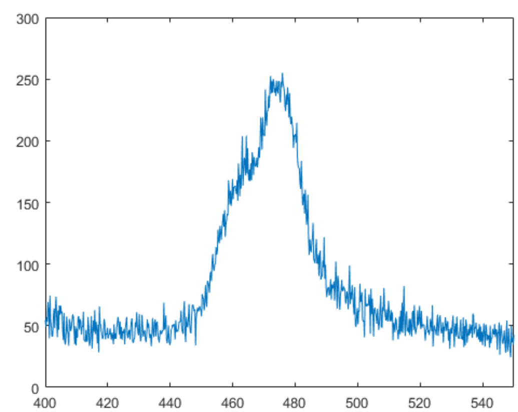
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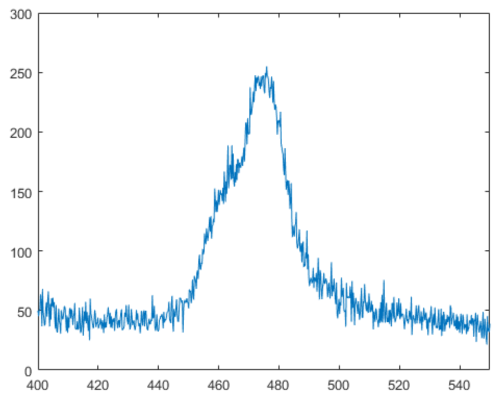
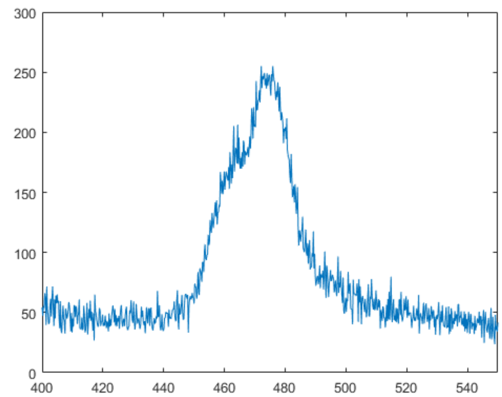
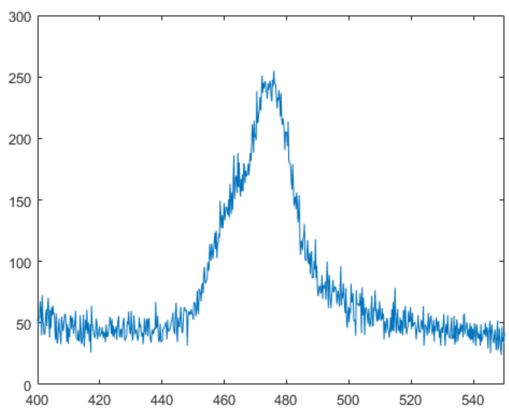
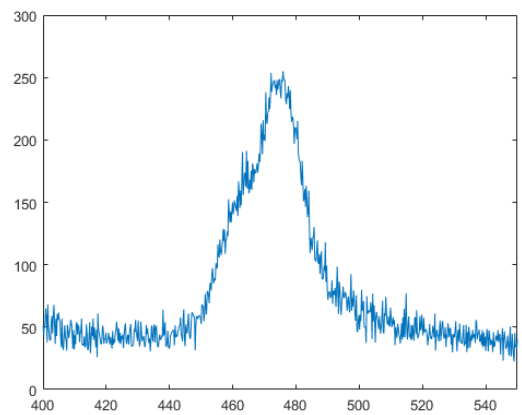



The average peak value executed from spectrometer was 474.8 so, the deviation is **4.8nm**

## 4.1.2 490nm peak

The initial design curve, the display image and the resulting curve of ten different measurements are

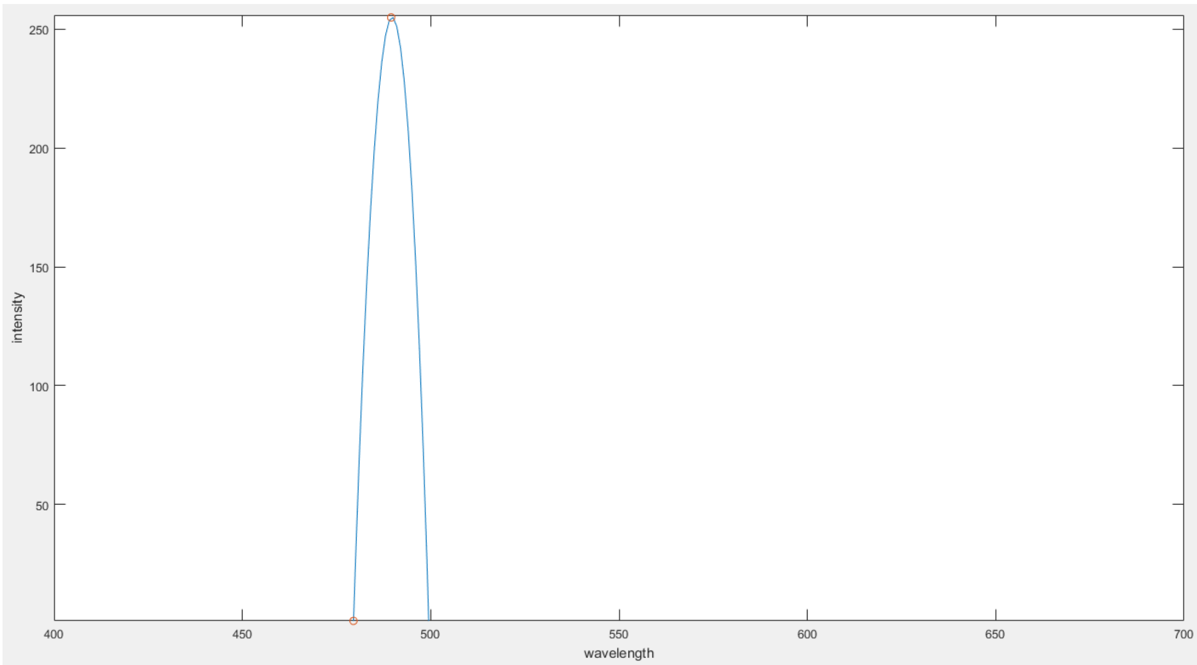



Figure 4.1.2.1 – Initial Design of 490nm

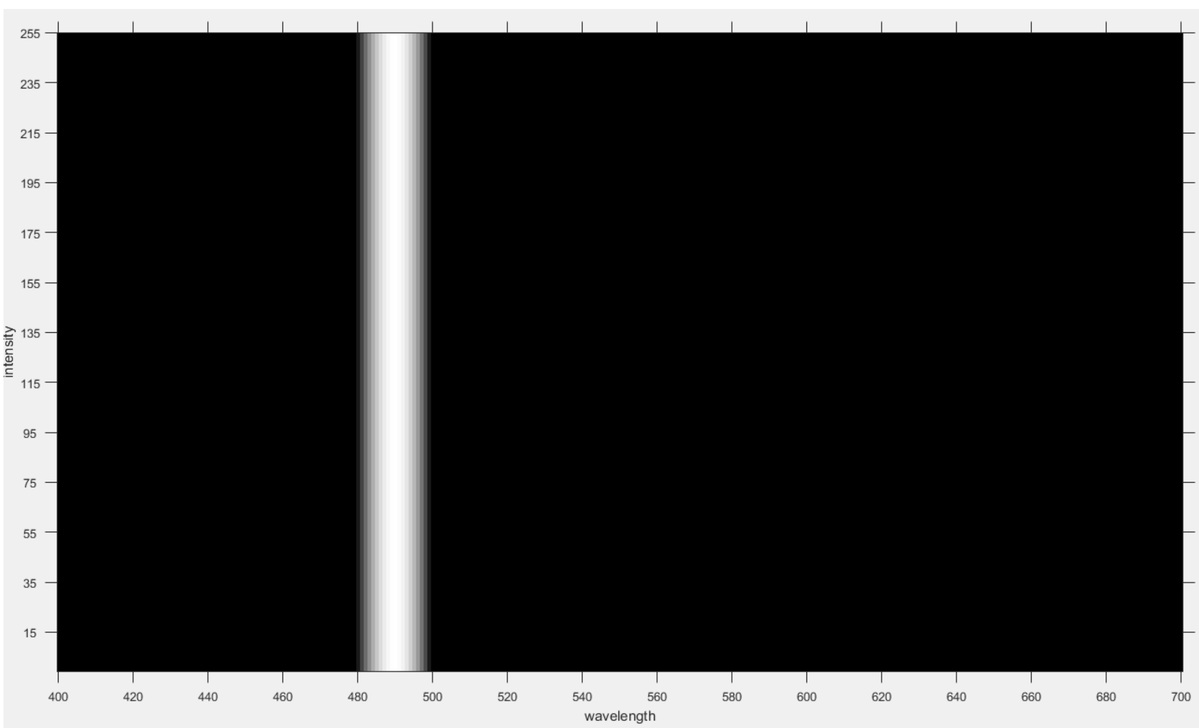
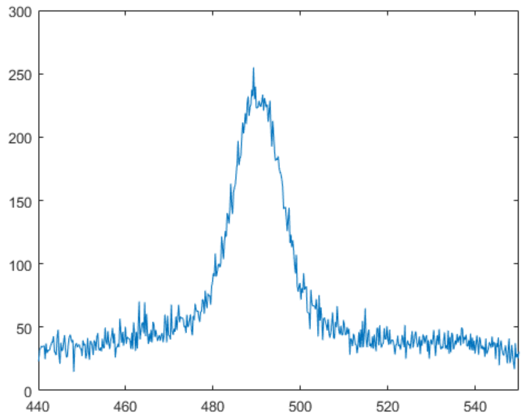



Figure 4.1.2.2 – Displaying image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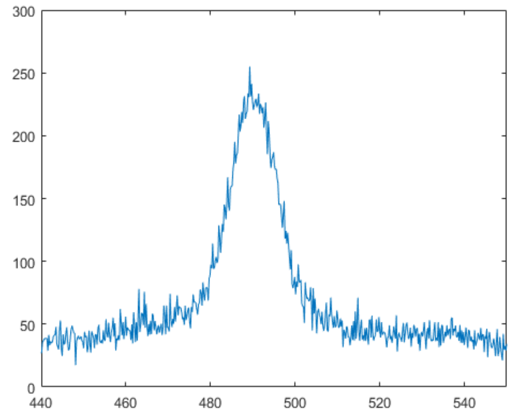
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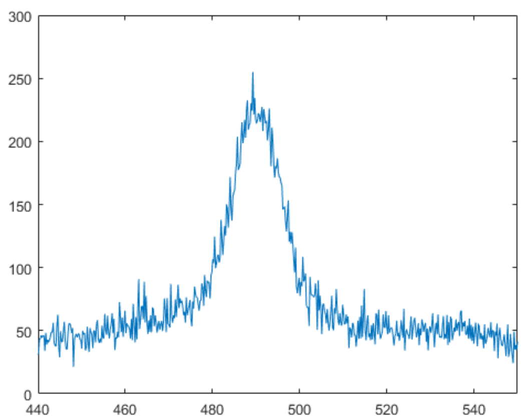
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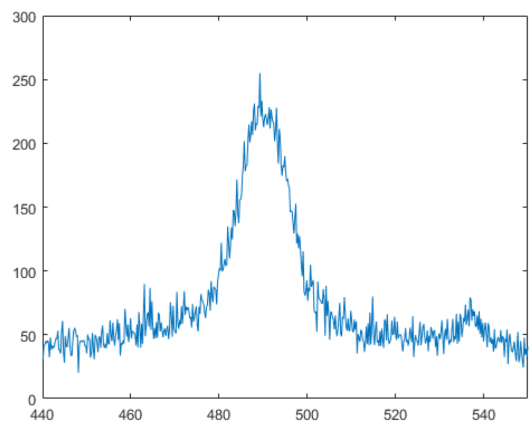
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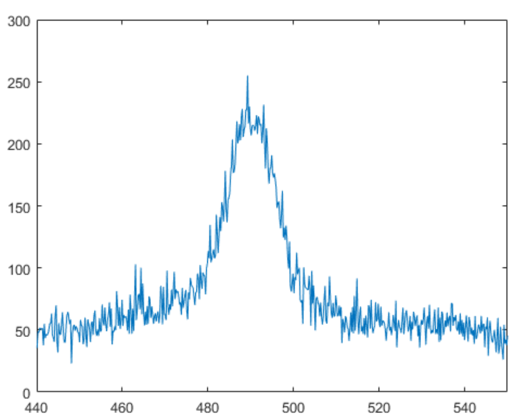
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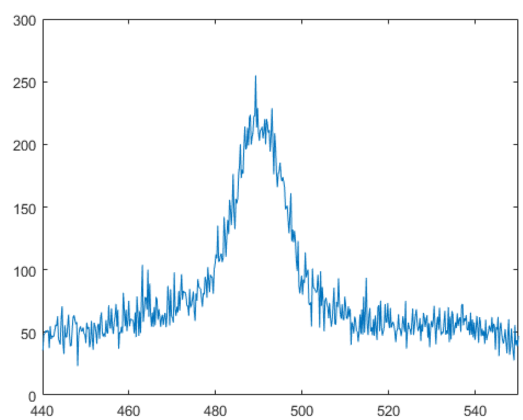
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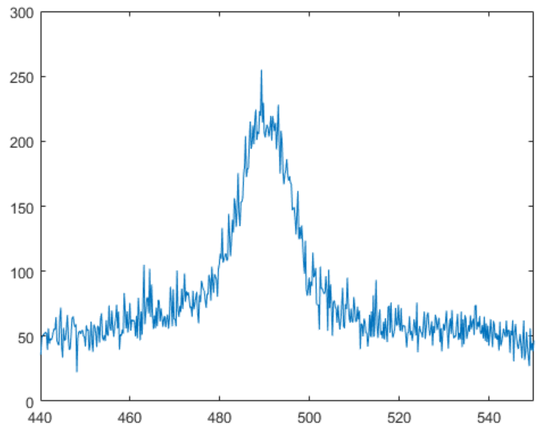
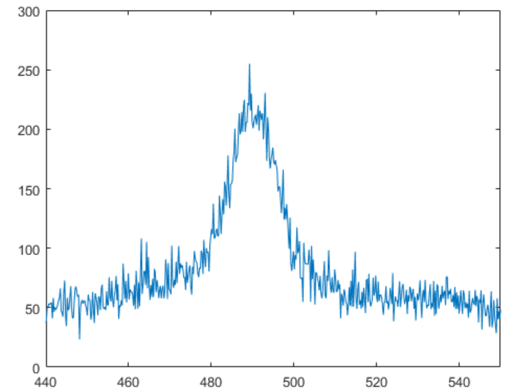
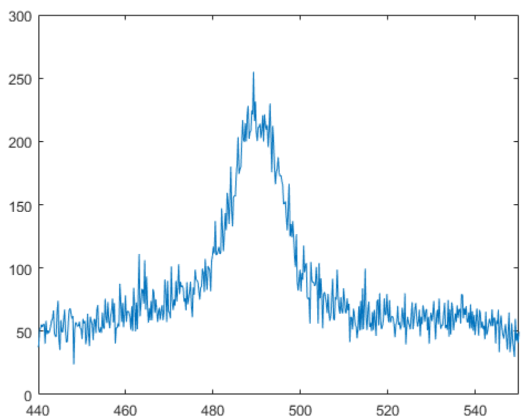
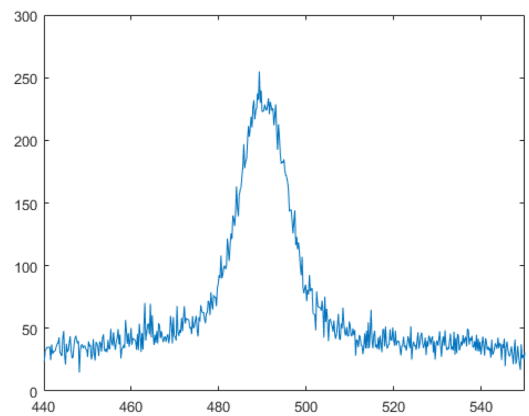









The average peak value executed from spectrometer is 489.28 so, the deviation is **0.72nm**

### 4.1.3 510nm peak

The initial design curve, the display image and the resulting curve of ten different measurements are

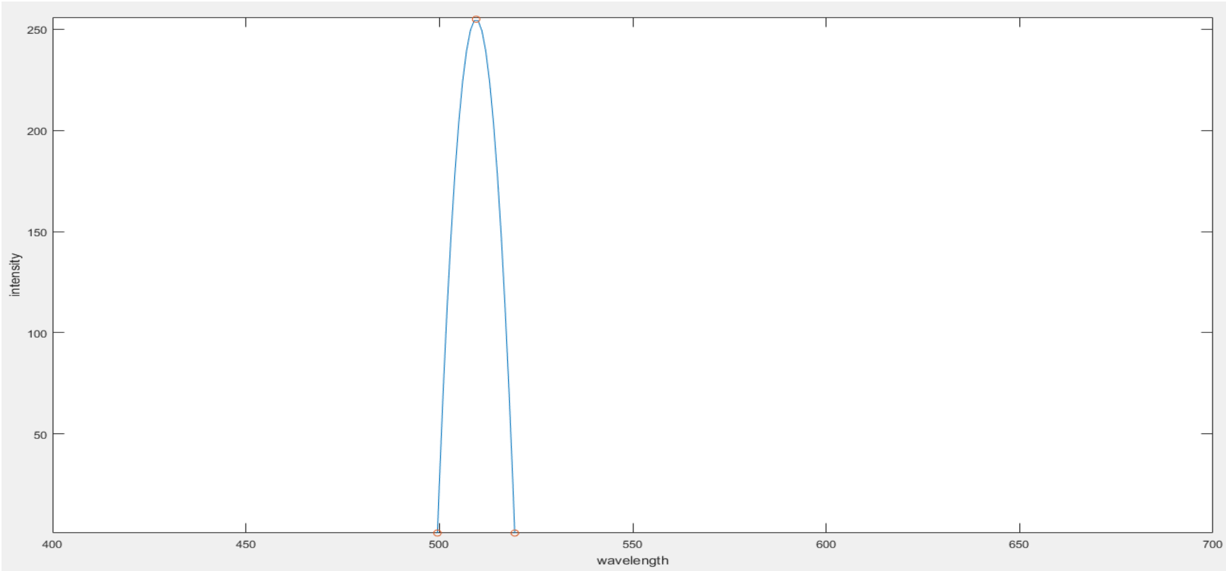



**Figure** ***4.1.3.1 – Initial Design of 510nm***

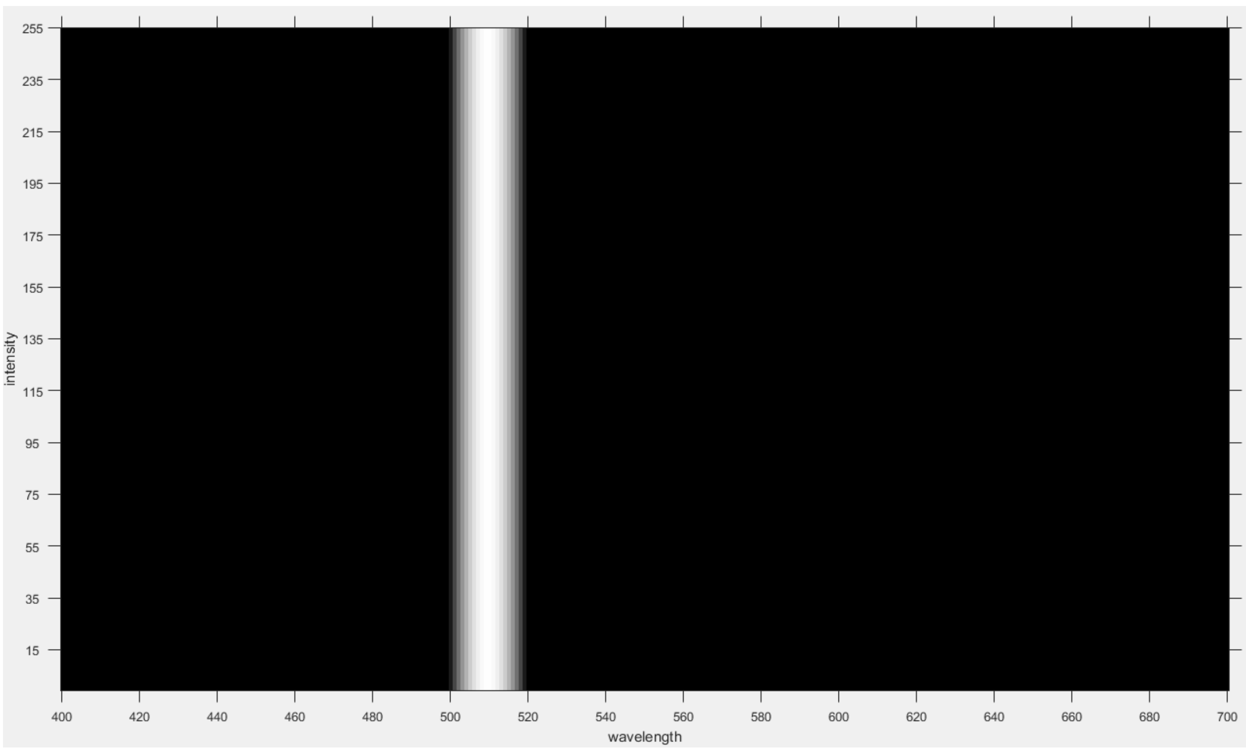
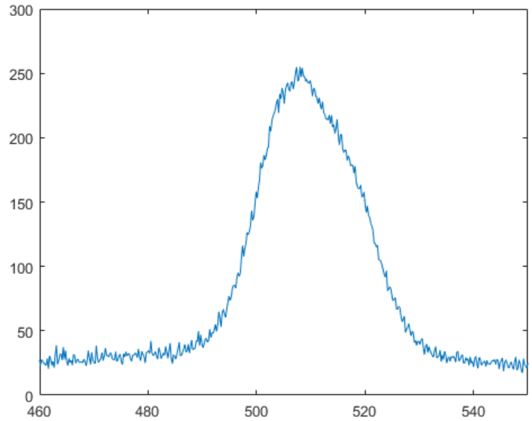



**Figure** ***4.1.3.2 –displaying of 510nm***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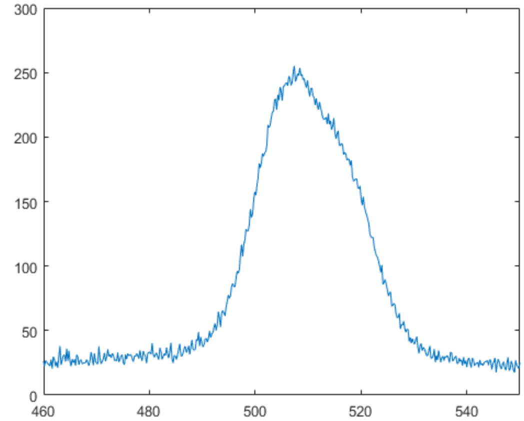
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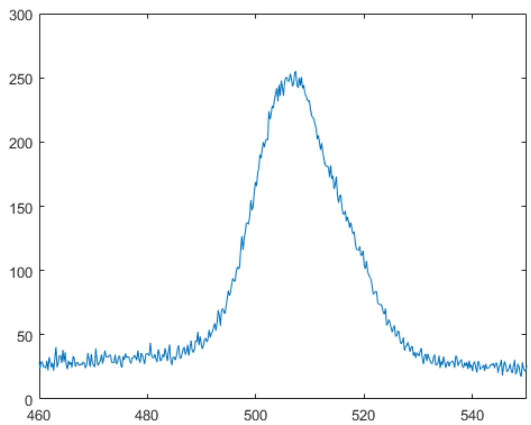
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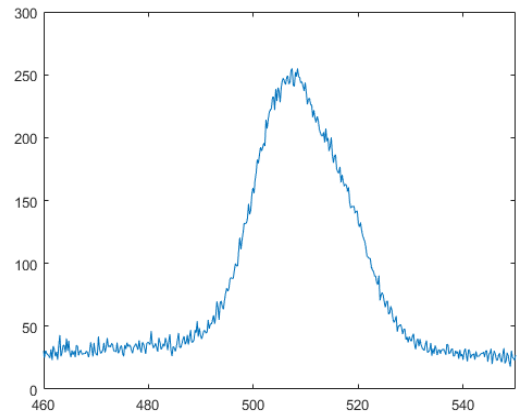
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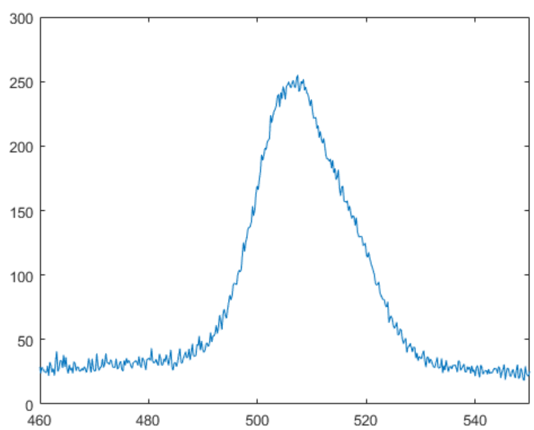
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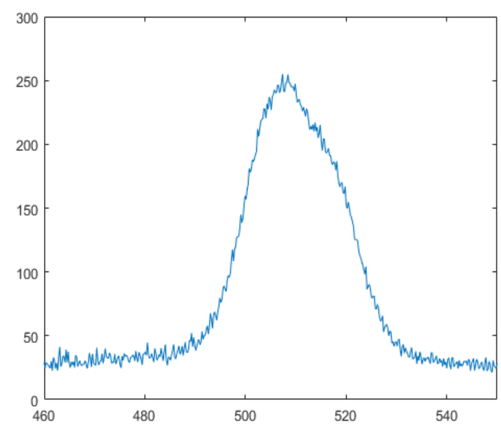
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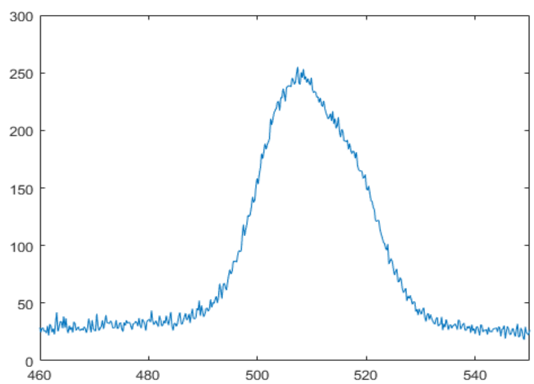
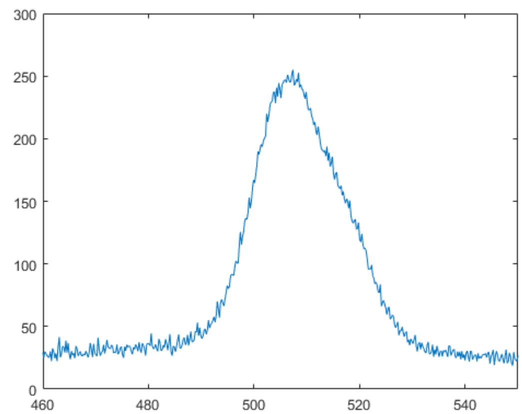
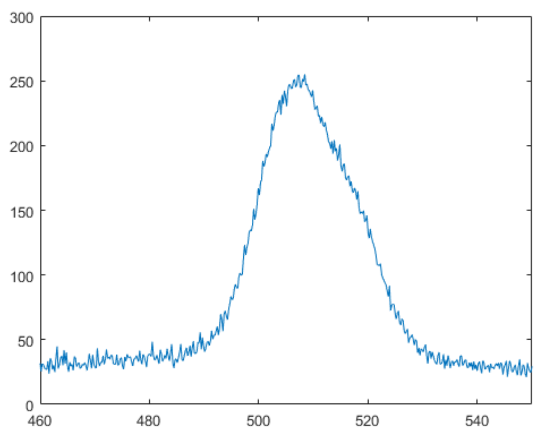
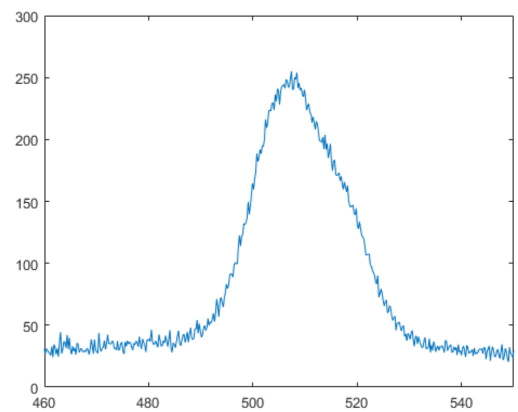



The average peak value executed from spectrometer is 507.94 so, the deviation is **2.06nm**

### 4.1.4 530nm peak

The initial design curve, the display image and the resulting curve of ten different measurements are:

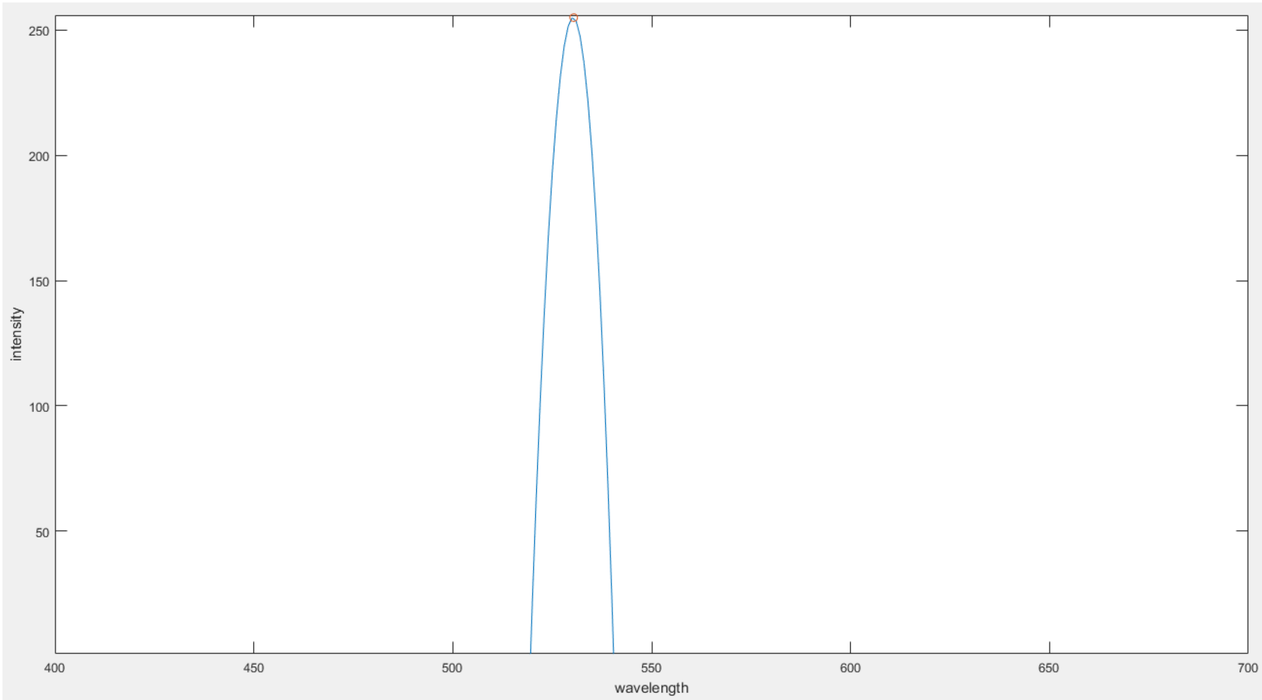



Figure 4.1.4.1 – *Initial Design of 530nm*

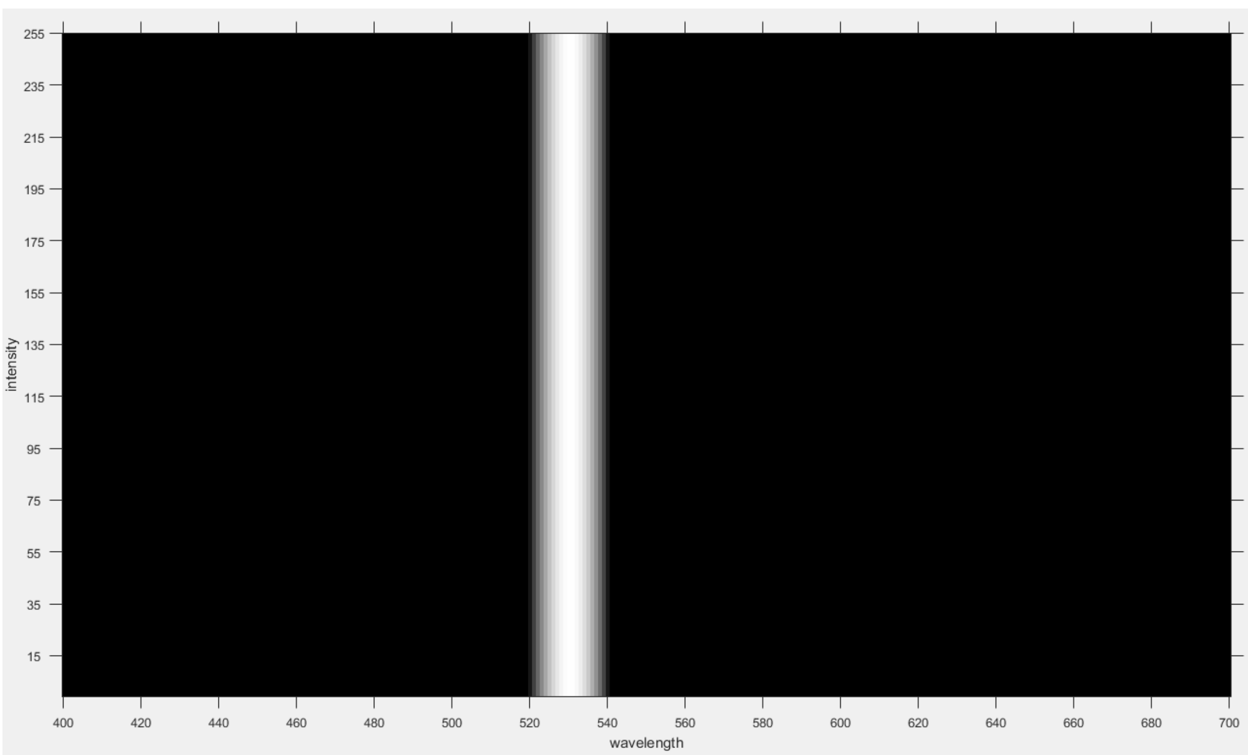
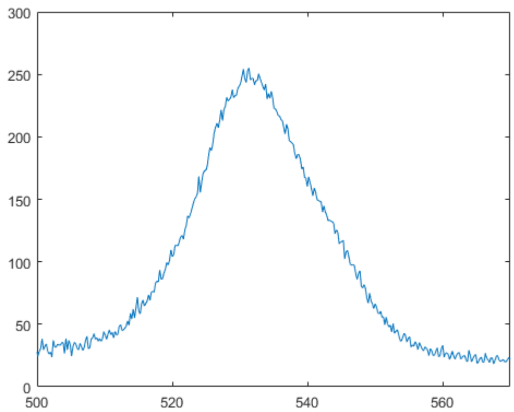



Figure 4.1.4.2 –*displaying of 530nm*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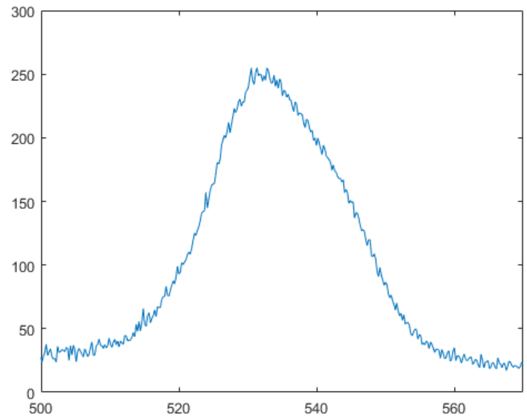
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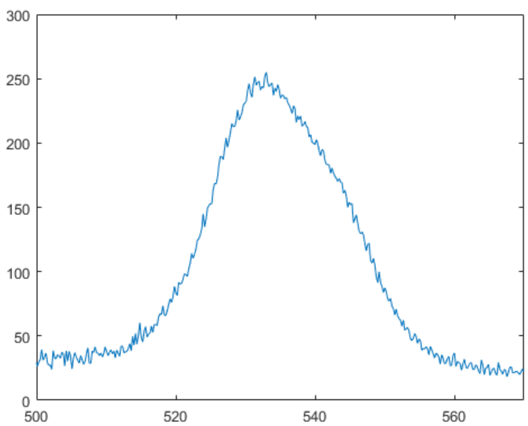
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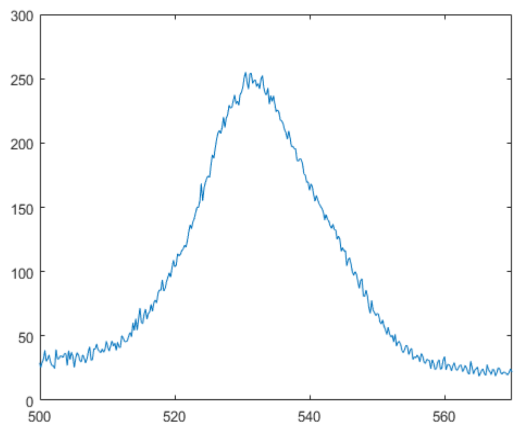
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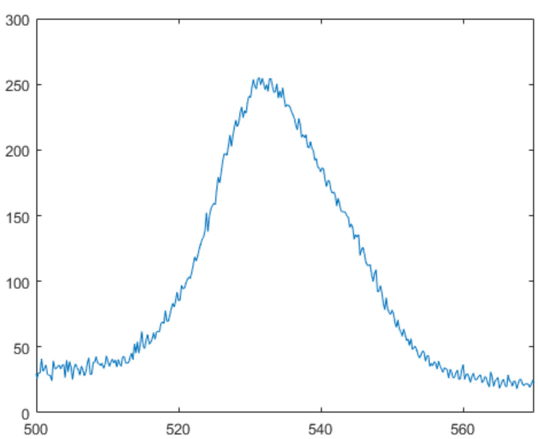
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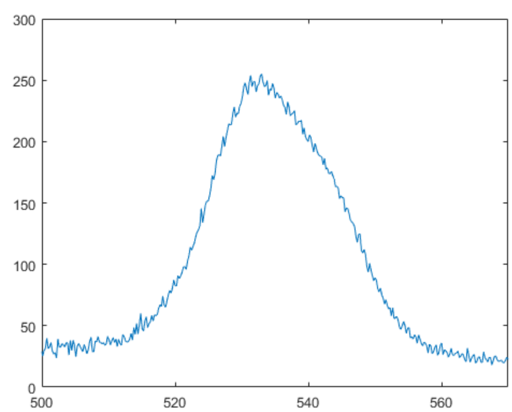
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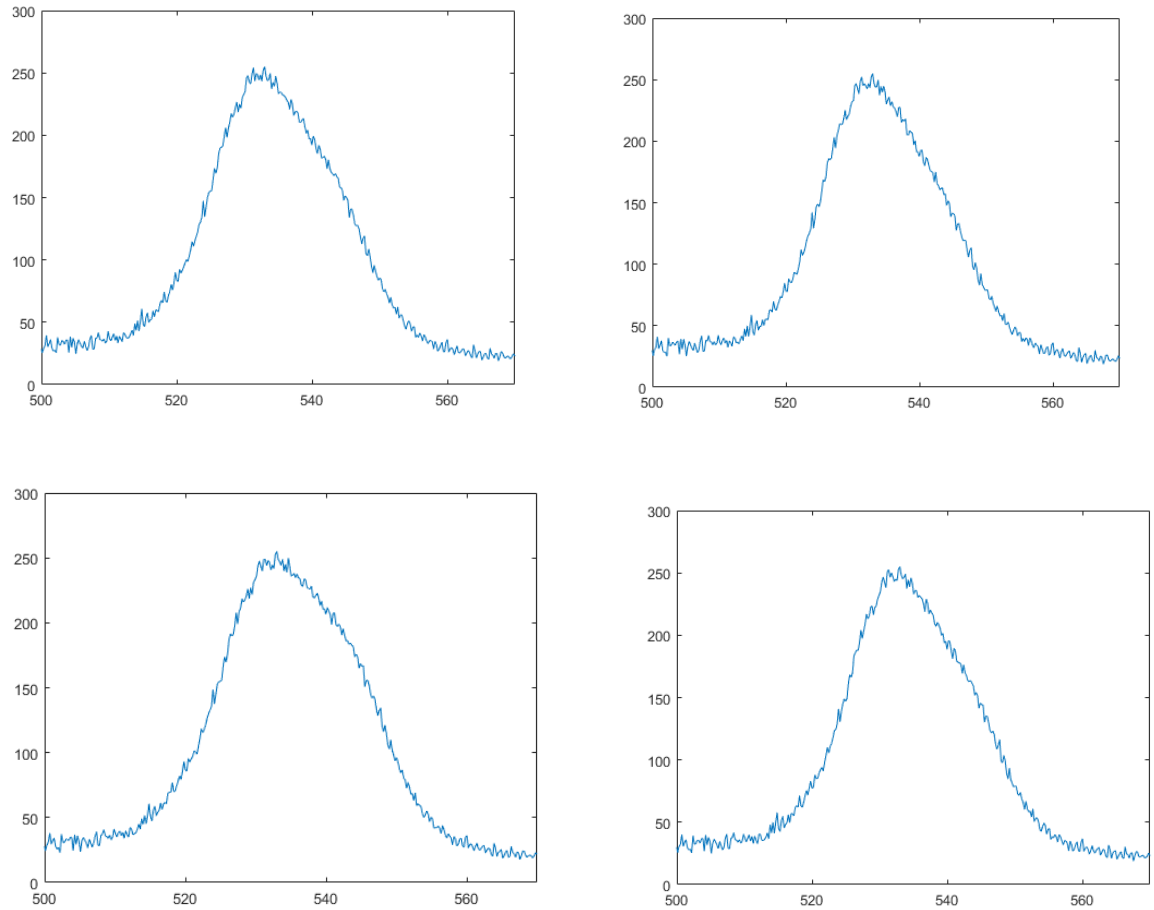



The average peak value executed from spectrometer is 531.56 so, the deviation is **1.56nm**

## 4.1.5 550nm peak

The initial design curve, the display image and the resulting curve of ten different measurements are:

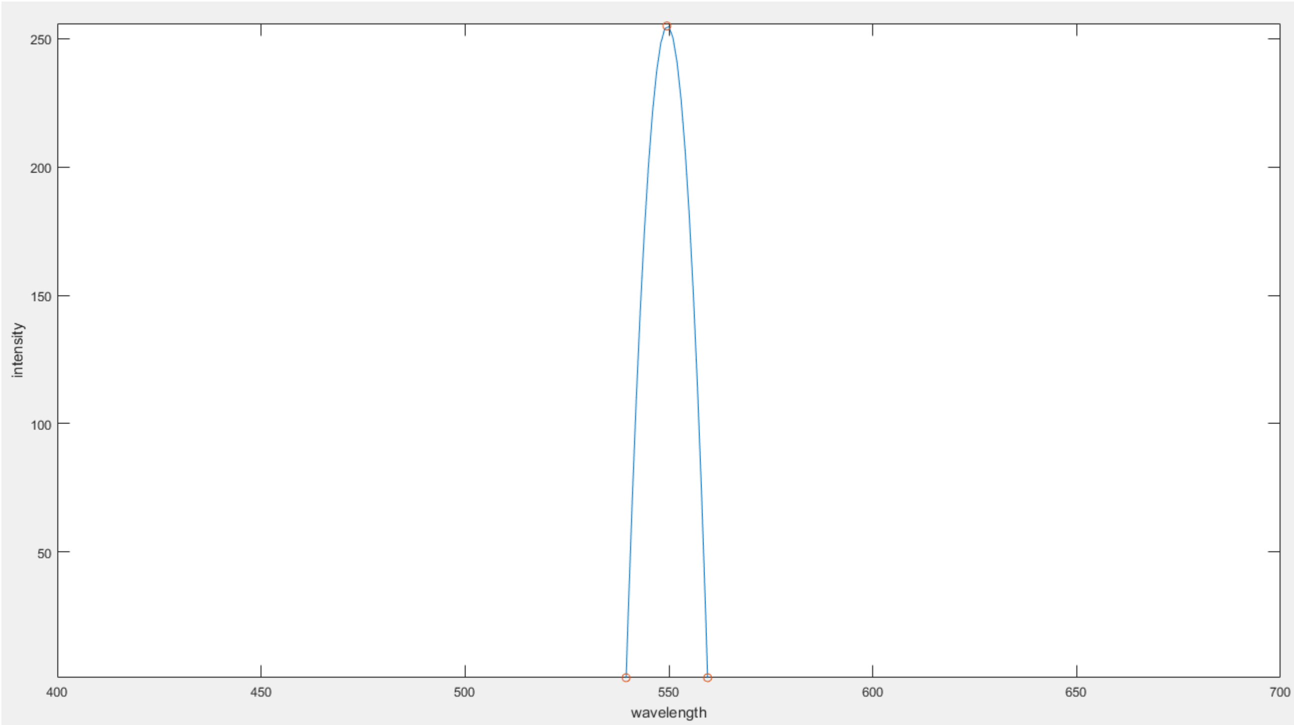



**Figure 4.1.5.1 – *Initial Design of 550nm***

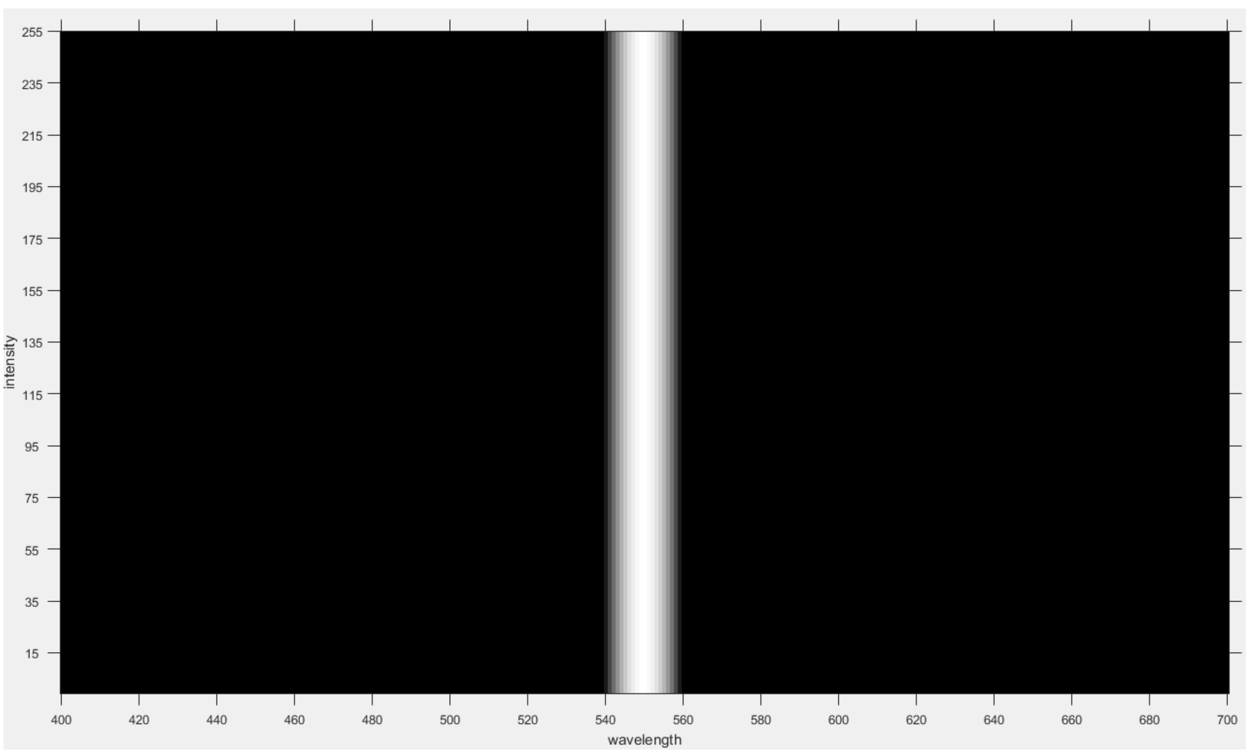
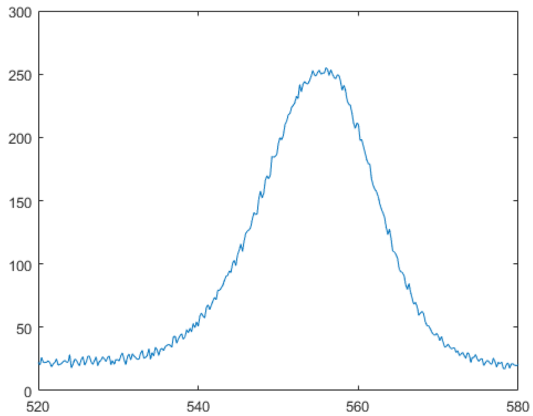



**Figure *4.1.5.2 –displaying of 550nm***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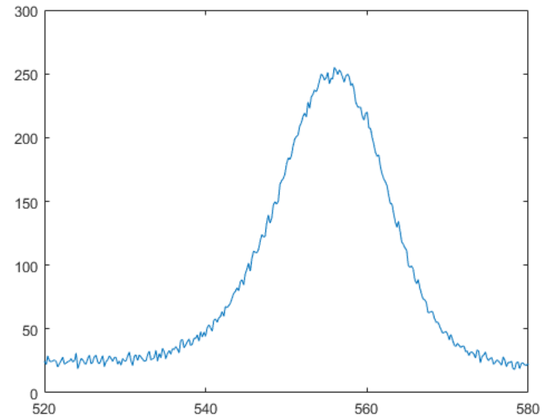
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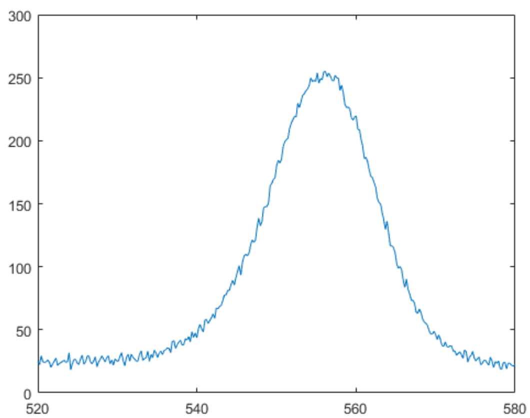
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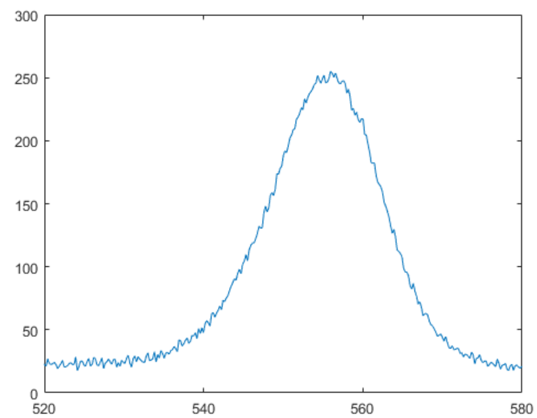
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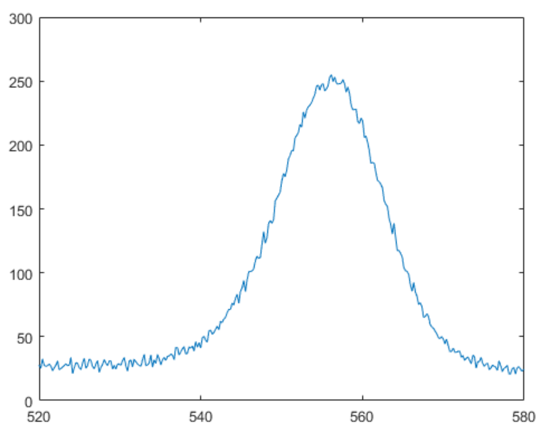
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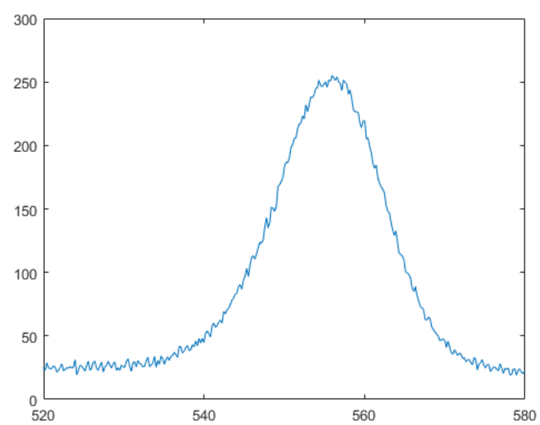
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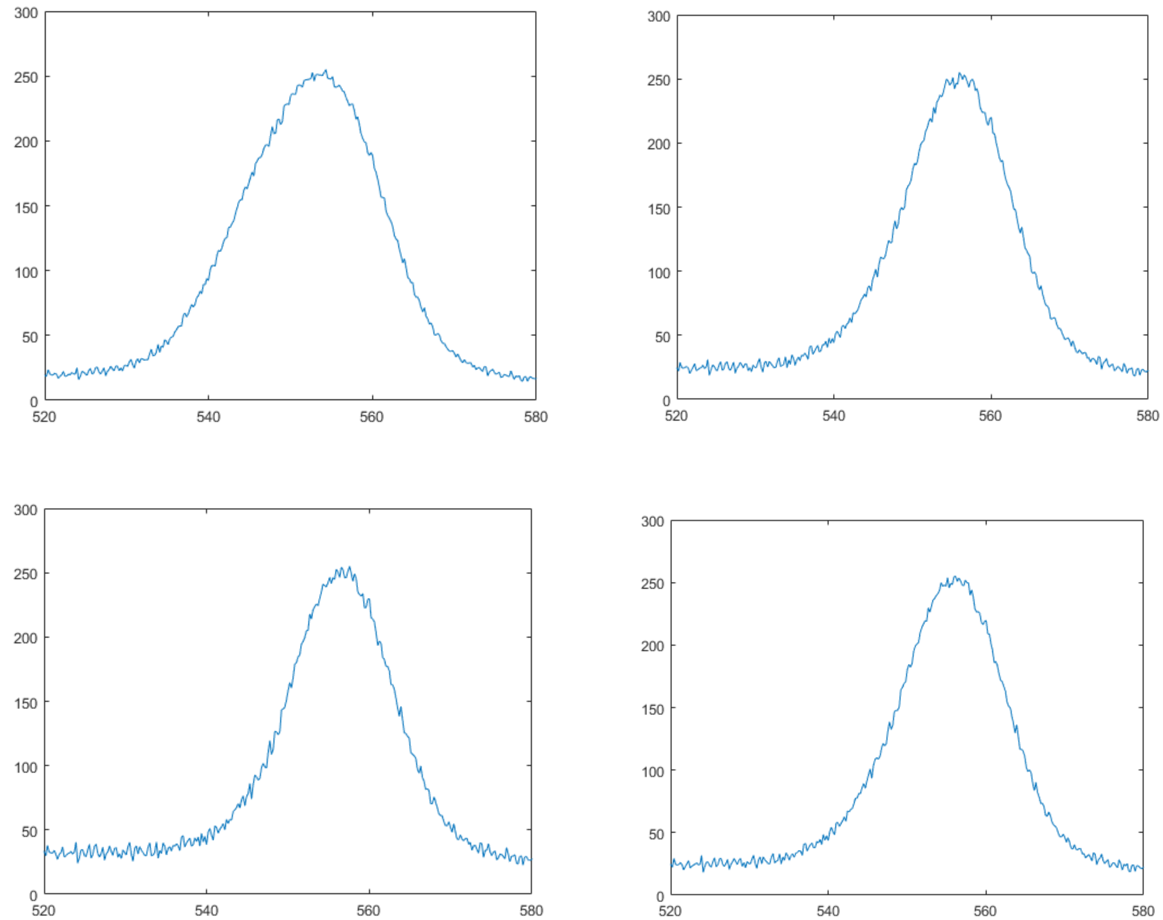



The average peak value executed from spectrometer is 554.06 so, the deviation is **4.06nm**

### 4.1.6 570nm peak

The initial design curve, the display image and the resulting curve of ten different measurements are:

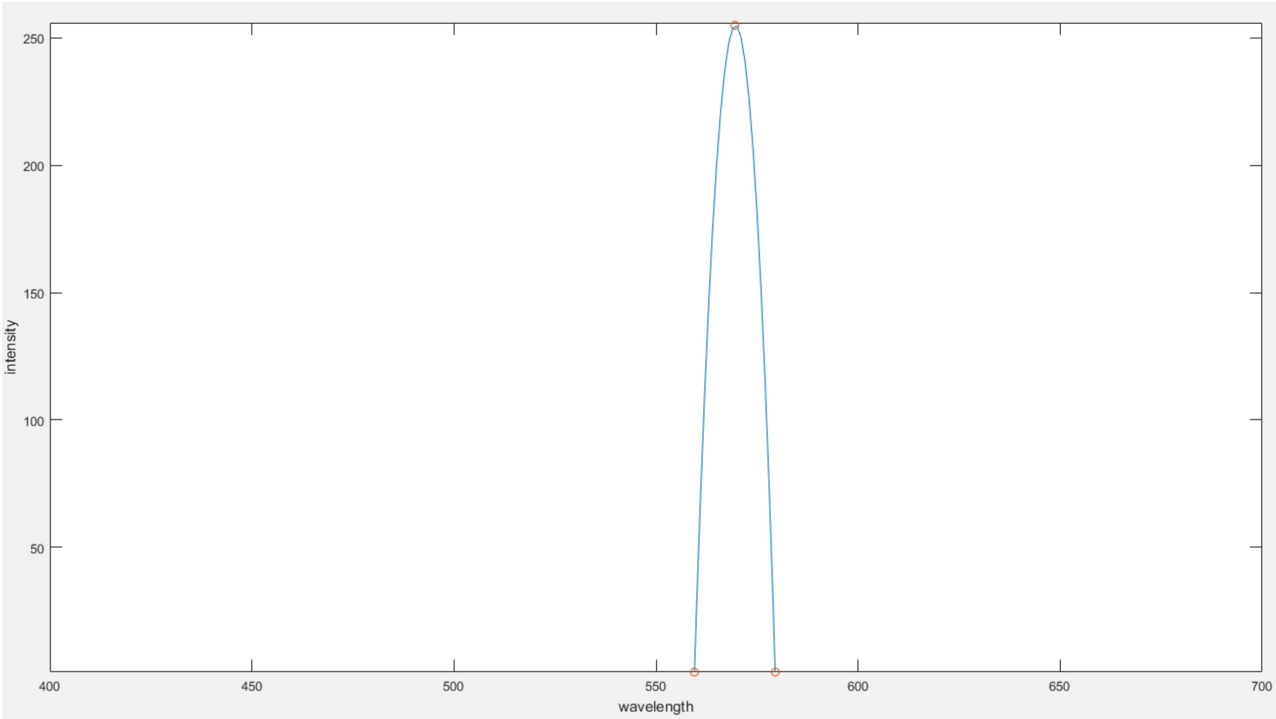



*Figure 4.1.6.1 – Initial Design of 570nm*

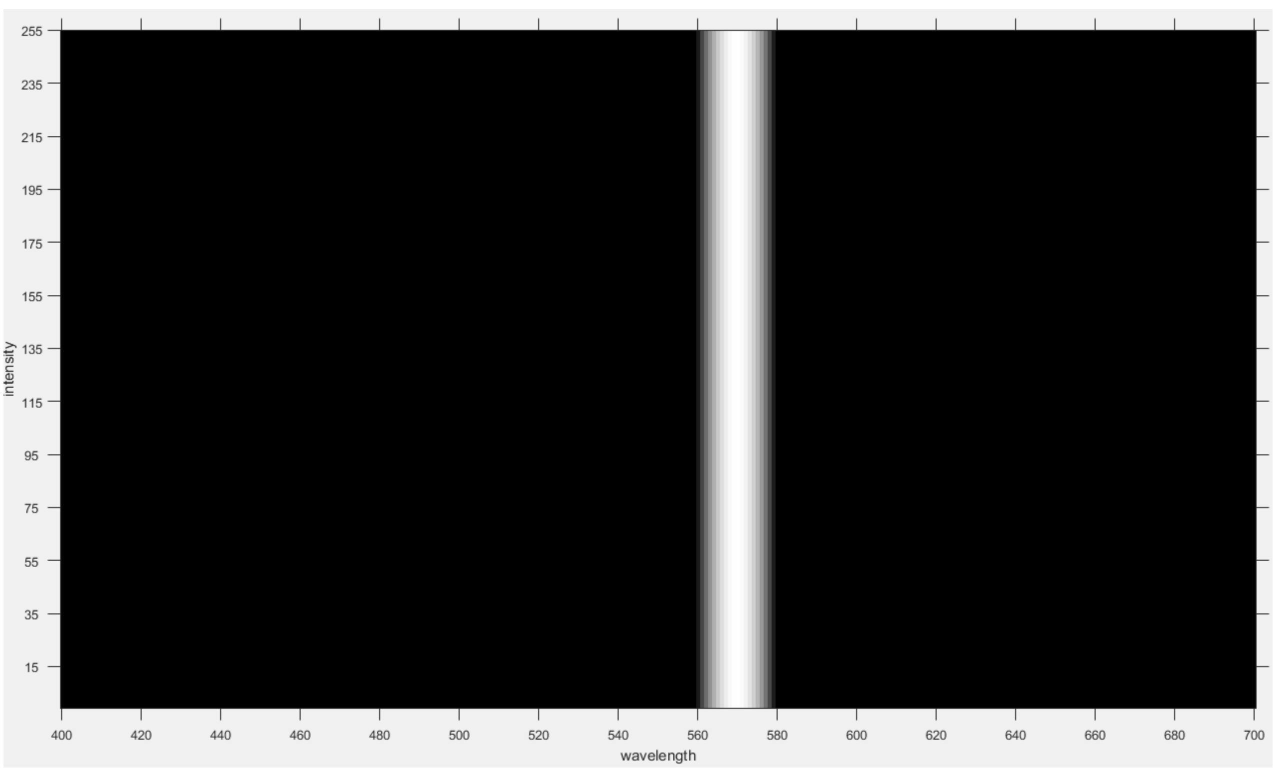
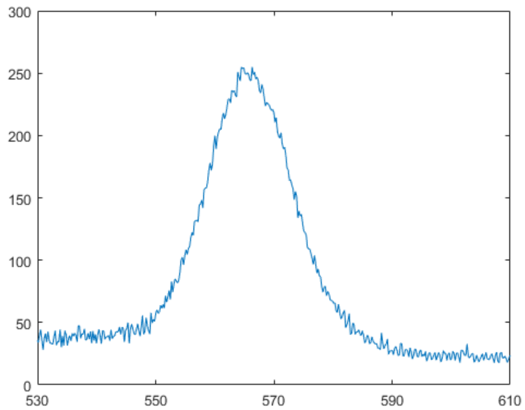



*Figure 4.1.6.2 – Displaying image of 570nm*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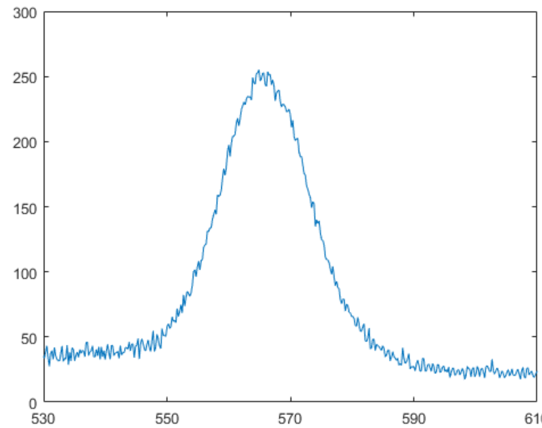
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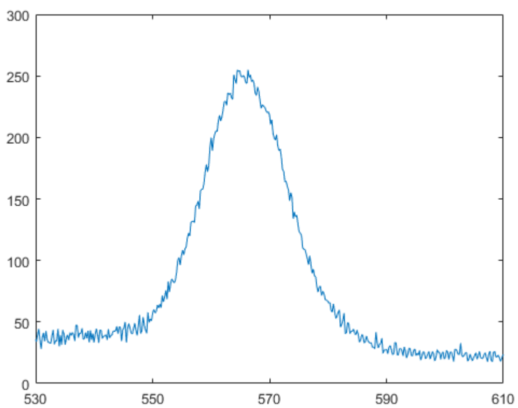
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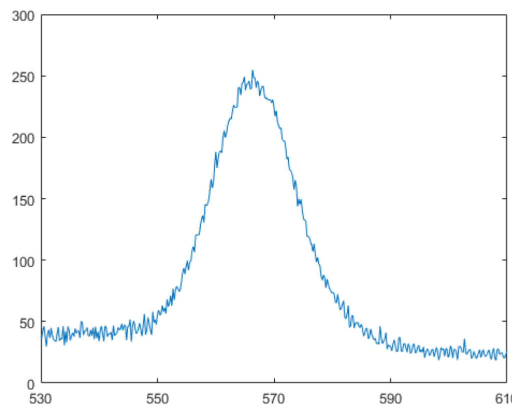
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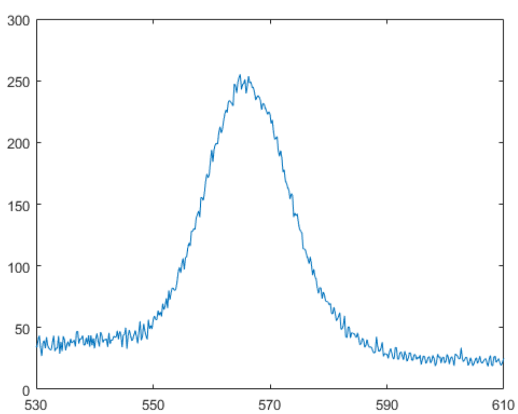
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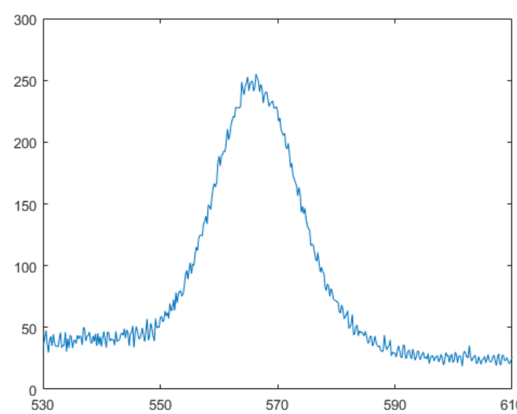
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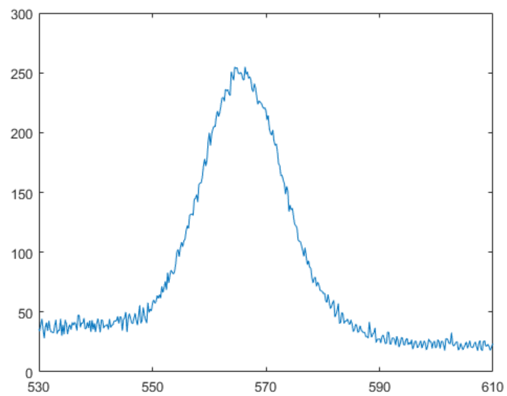
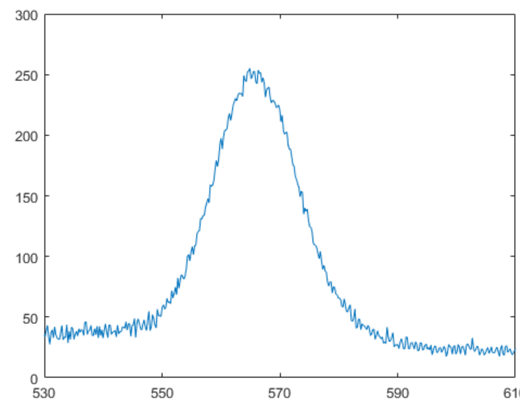
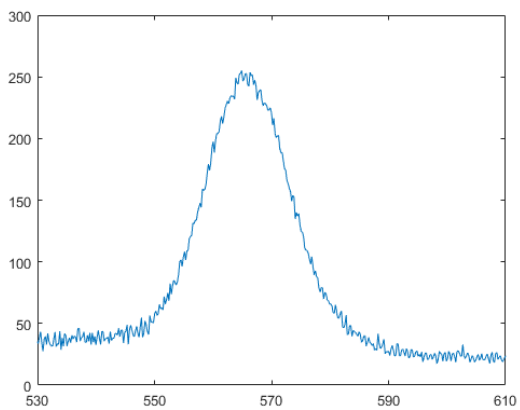
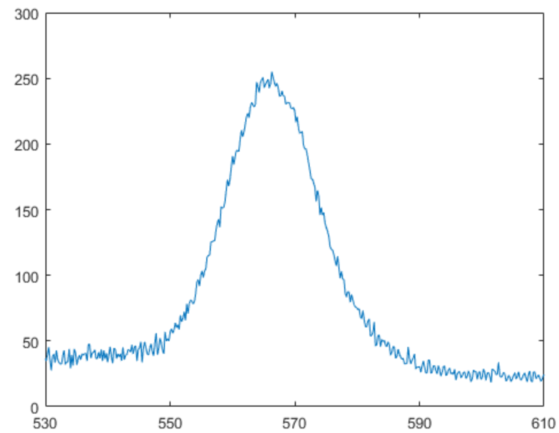



The average peak value executed from spectrometer is 565.62 so, the deviation is **4.38nm**

### 4.1.7 590nm peak

The initial design curve, the display image and the resulting curve of ten different measurements are:

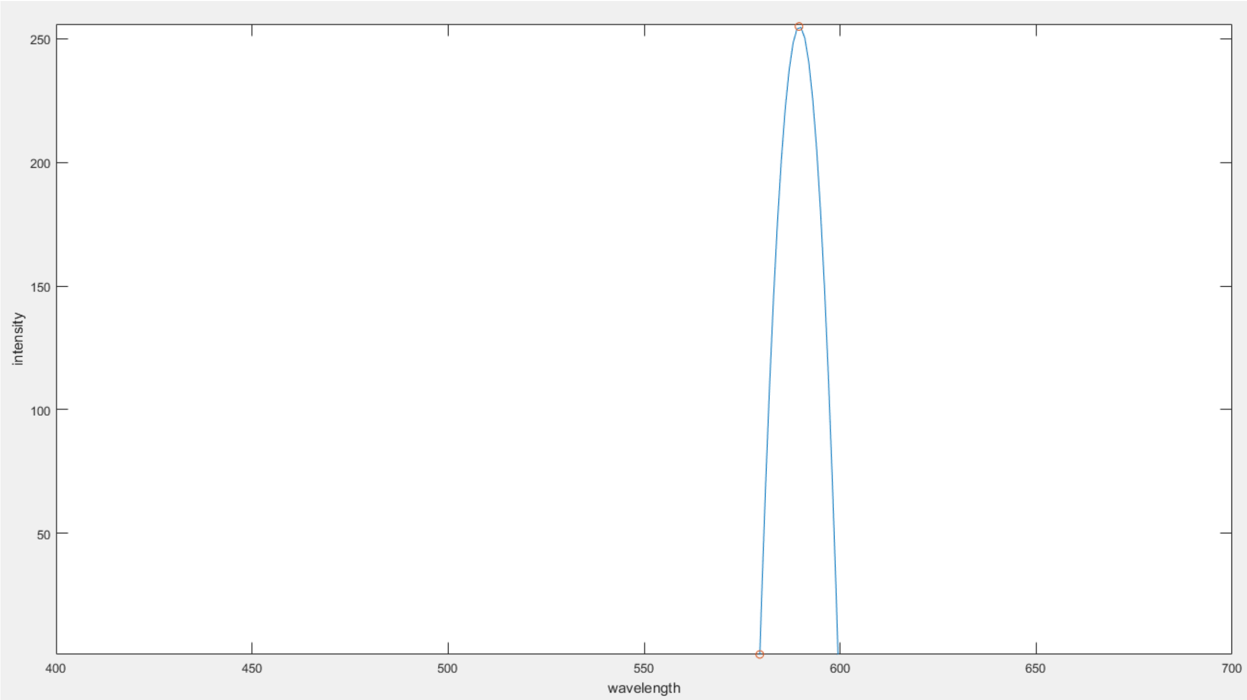



*Figure 4.1.7.1 – Initial Design of 590nm*

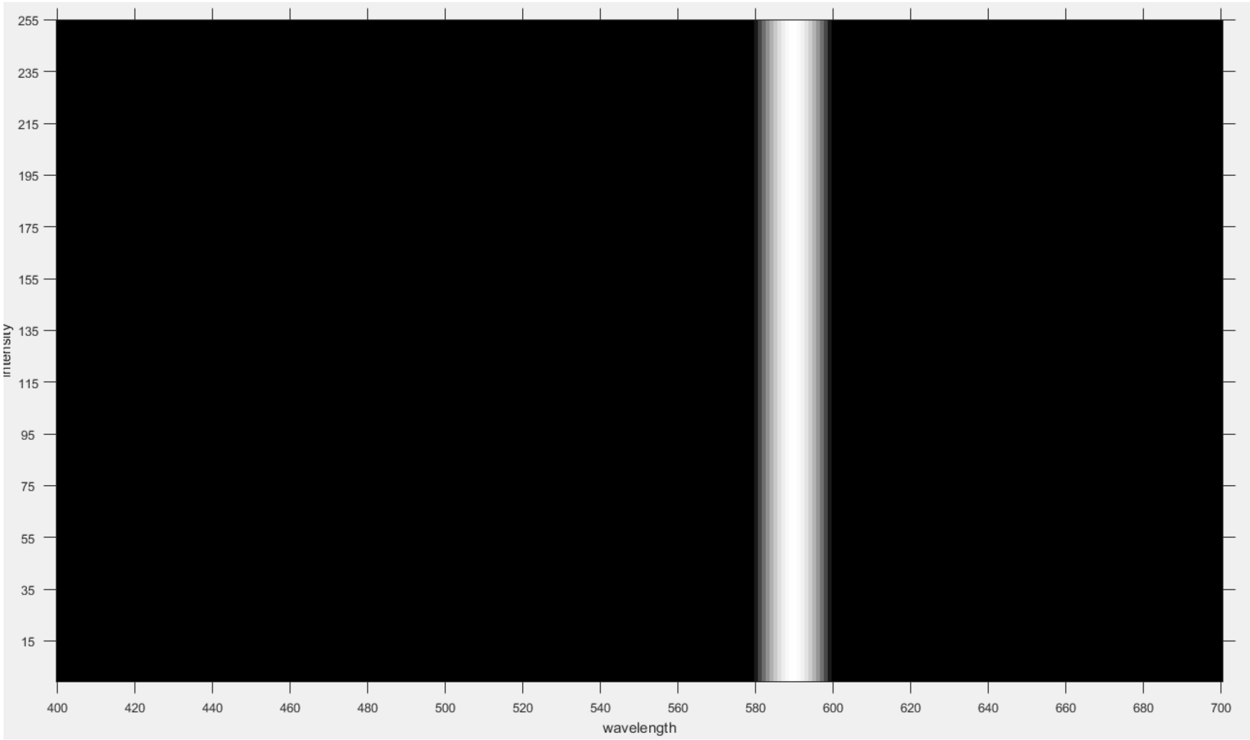
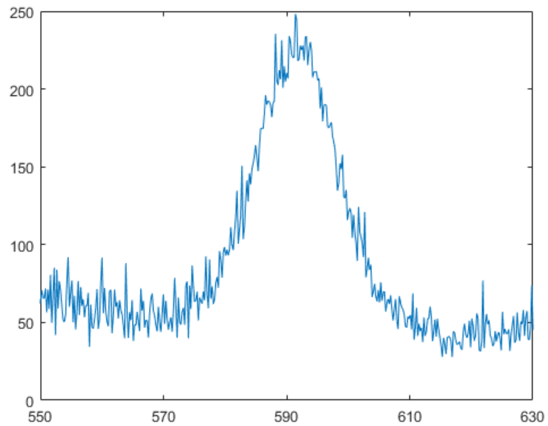



*Figure 4.1.7.2 – Displaying image of 590nm*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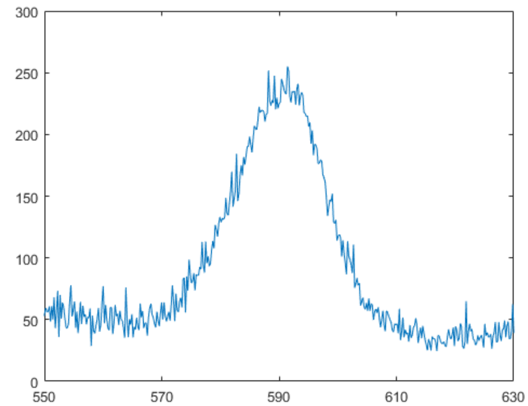
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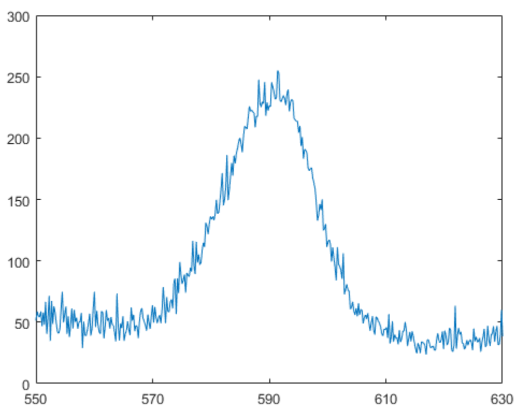
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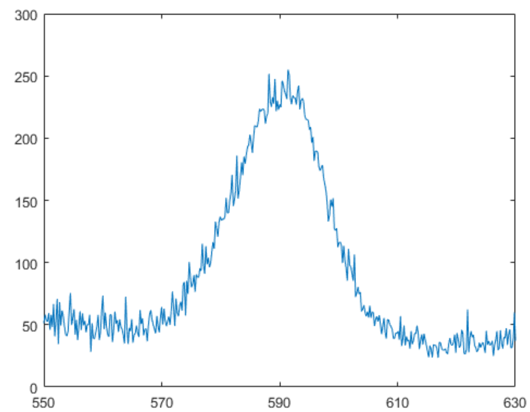
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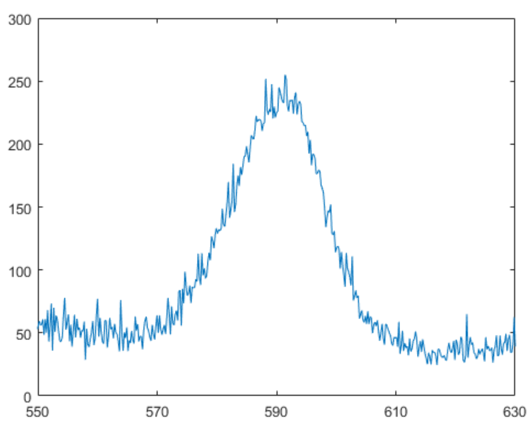
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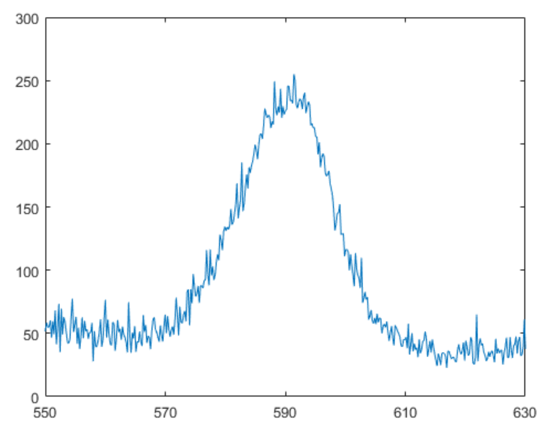
630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250
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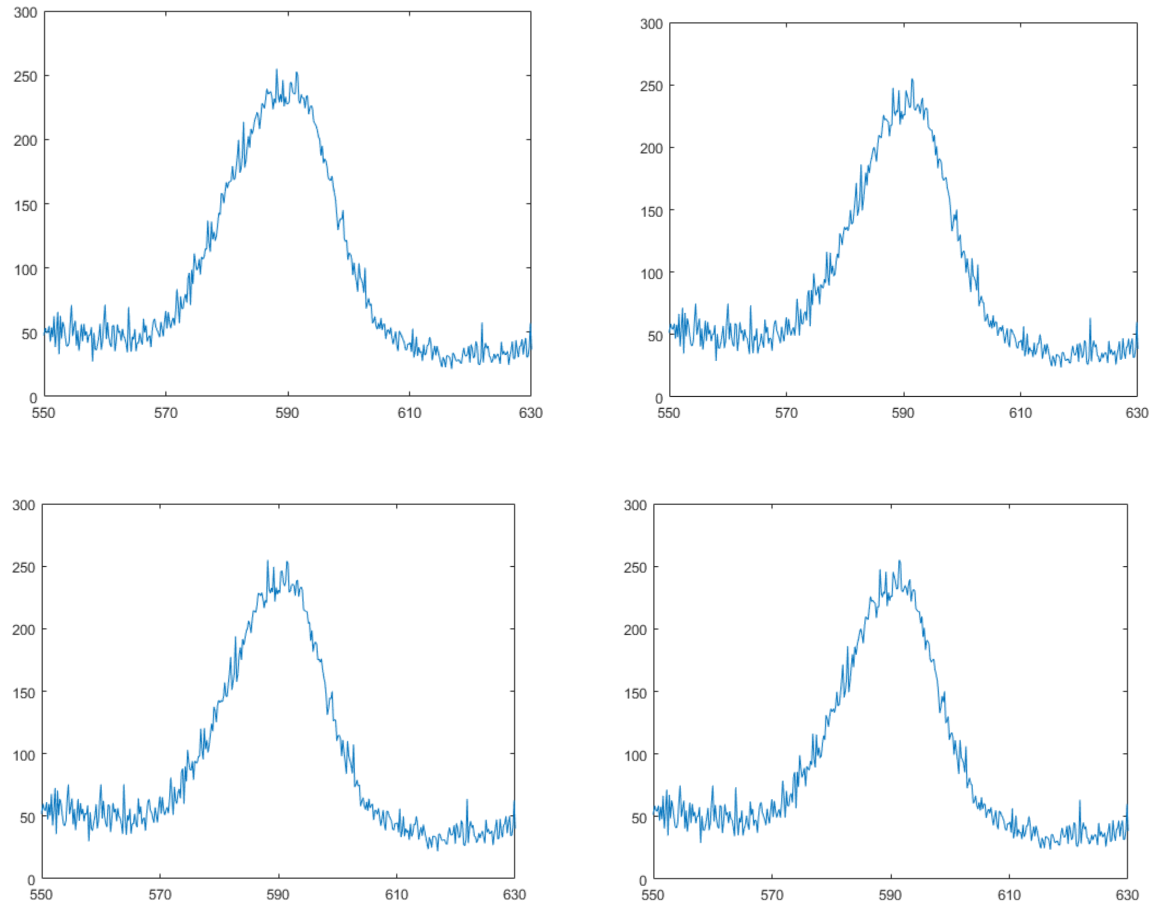
570
590
610
630




The average peak value executed from spectrometer is 589.815 so, the deviation is **0.185nm**

## 4.1.8 610nm peak

The initial design curve, the display image and the resulting curve of ten different measurements are:

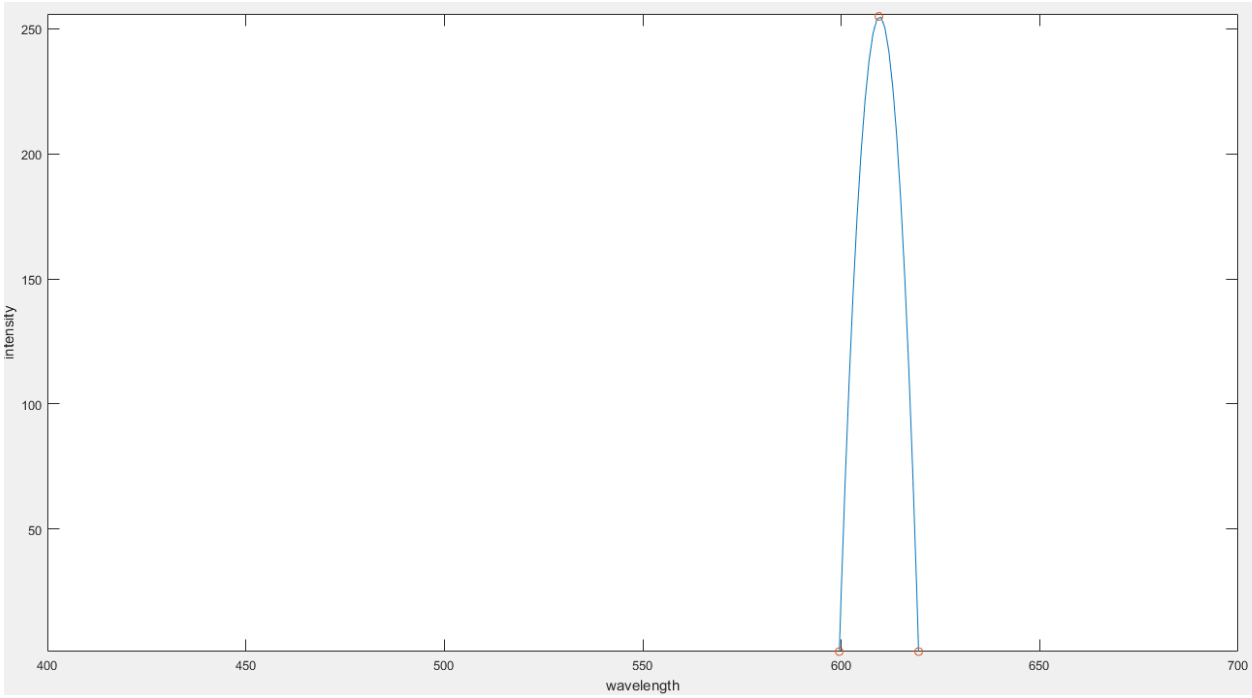



*Figure 4.1.8.1 – Initial Design of 610nm*

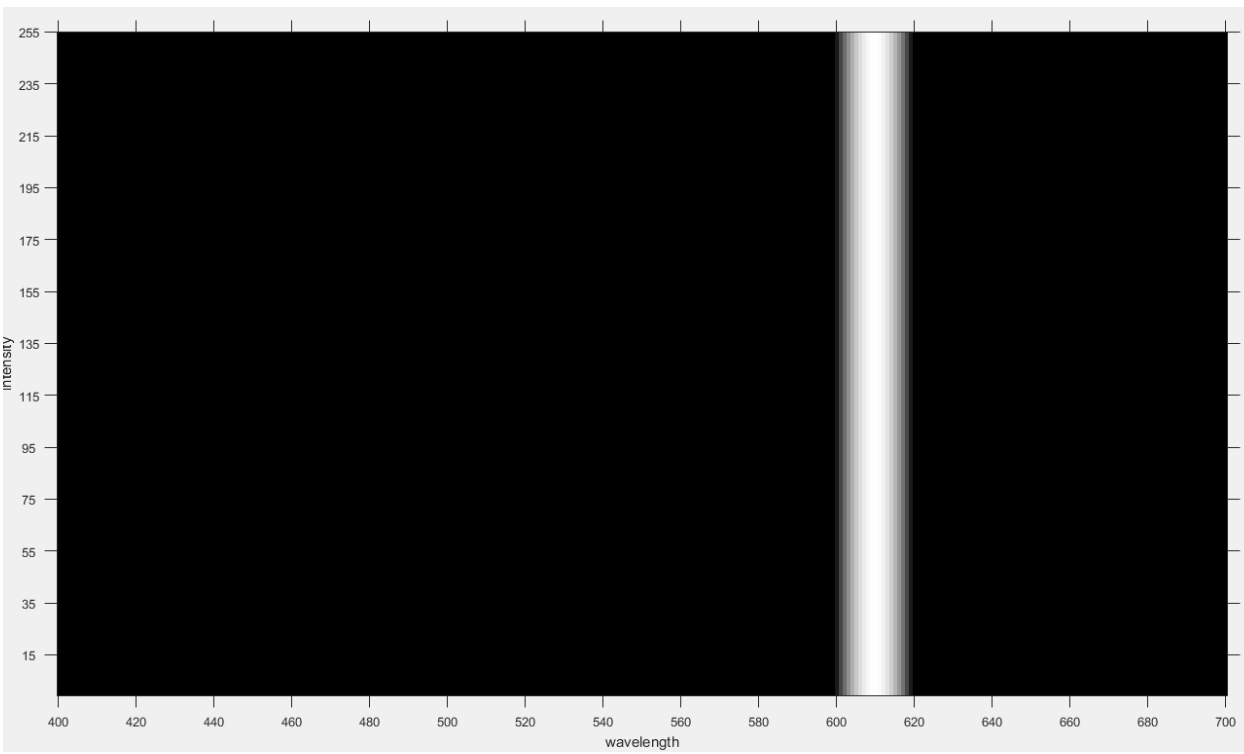
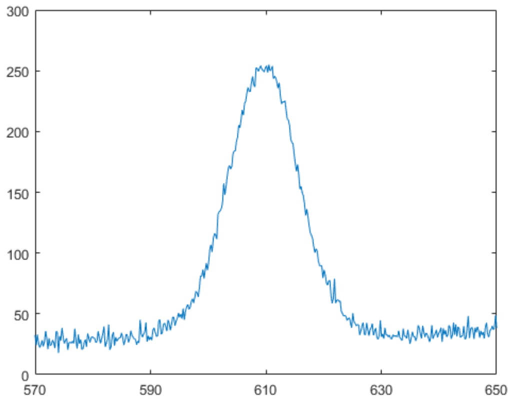



*Figure 4.1.8.2 – Displaying image of 610nm*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250
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590
610
630
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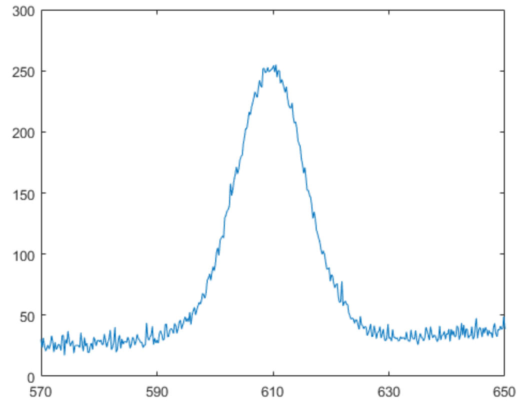
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200
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100
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0
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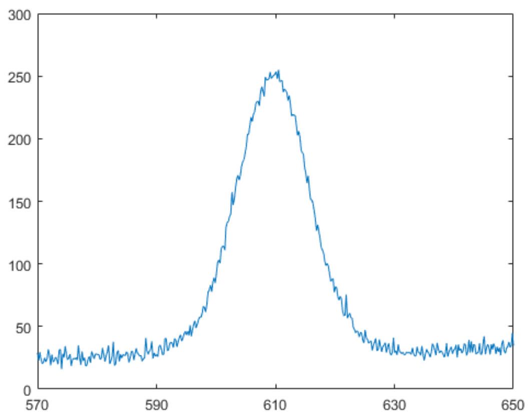
630
650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200
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100
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0
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590
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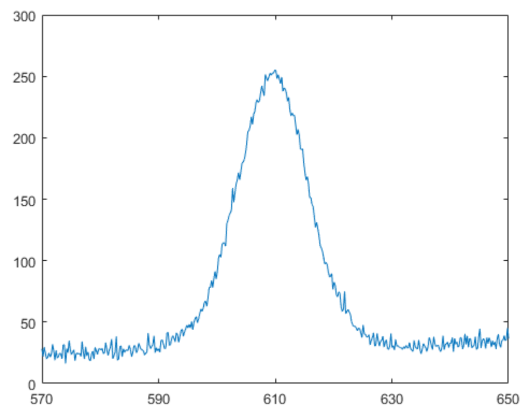
650


300
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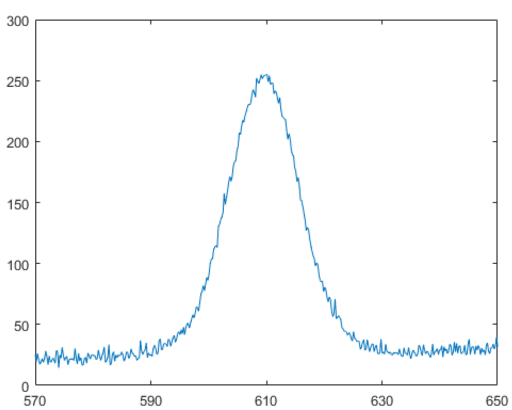
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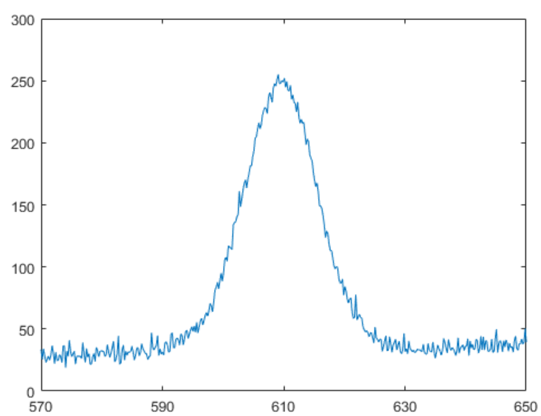
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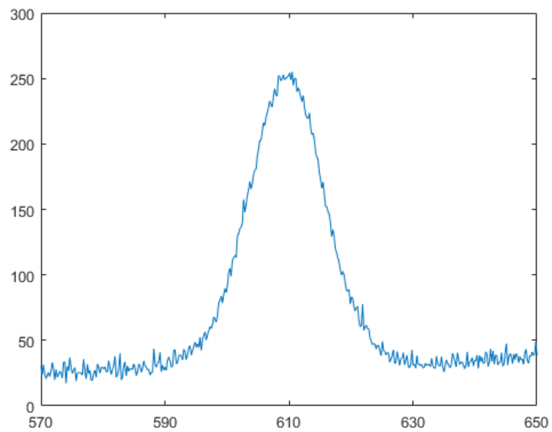
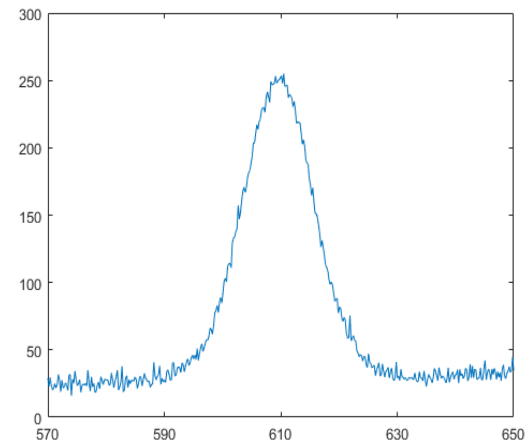
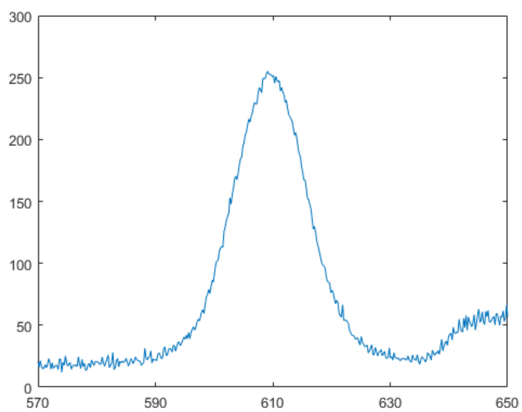
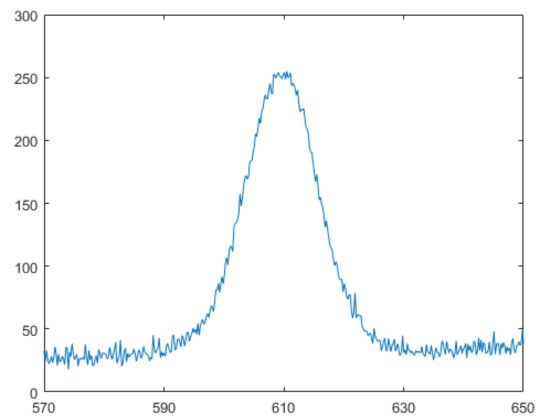



The average peak value executed from spectrometer is 609.91 so, the deviation is **0.09nm**

### 4.1.9 630nm peak

The initial design curve, the display image and the resulting curve of ten different measurements are:

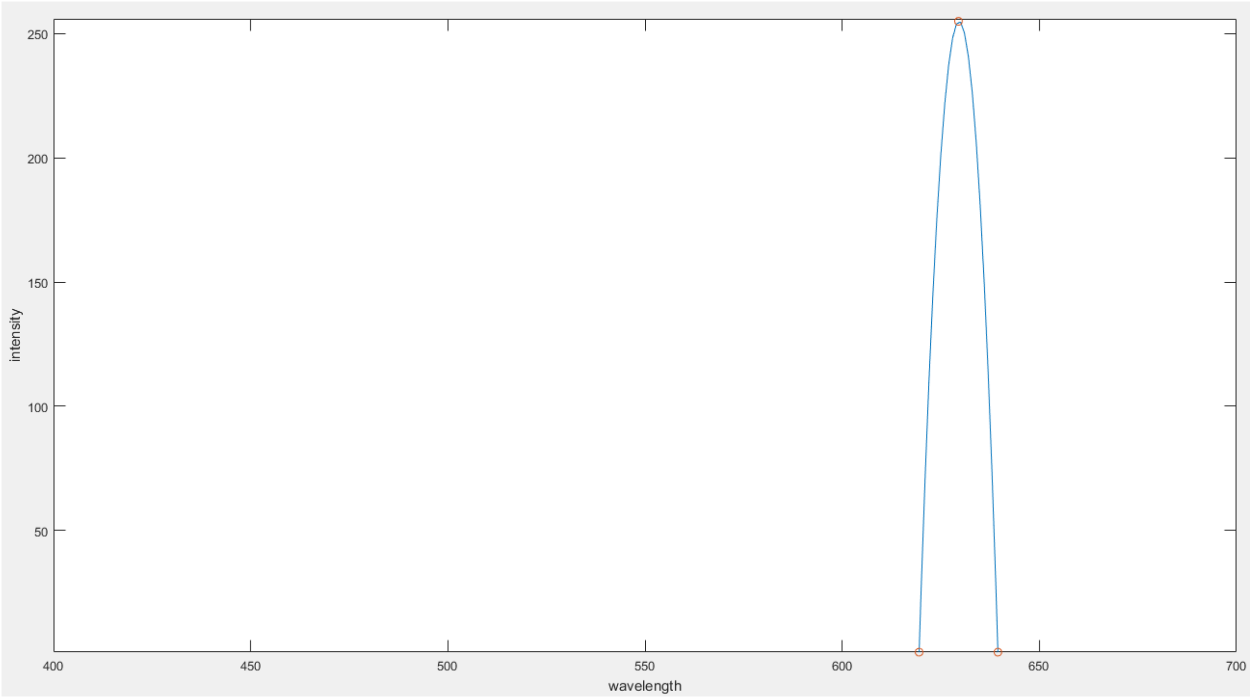



*Figure 4.1.9.1 – Initial Design of 630nm*

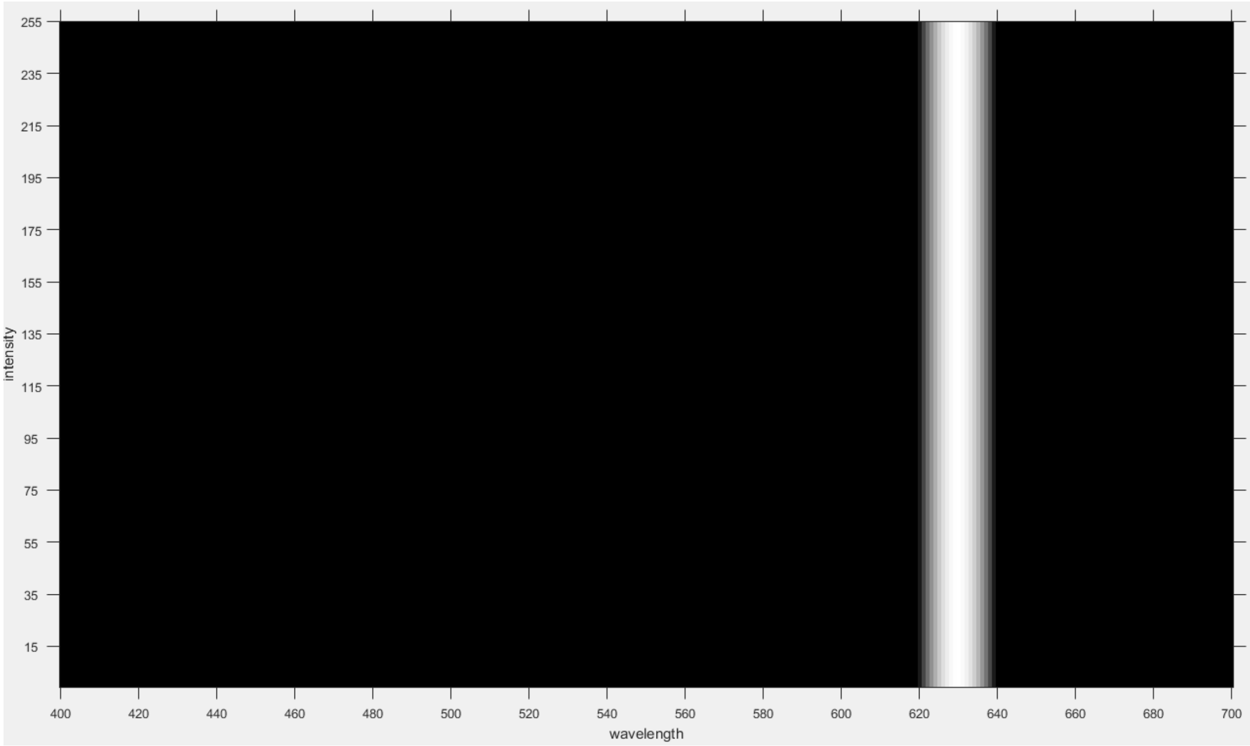
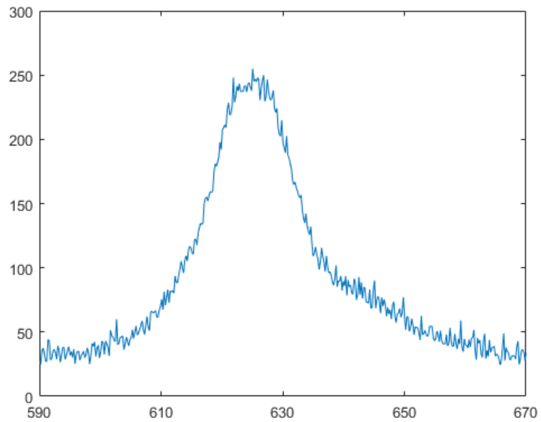



*Figure 4.1.9.2 – Displaying image of 630nm*


300
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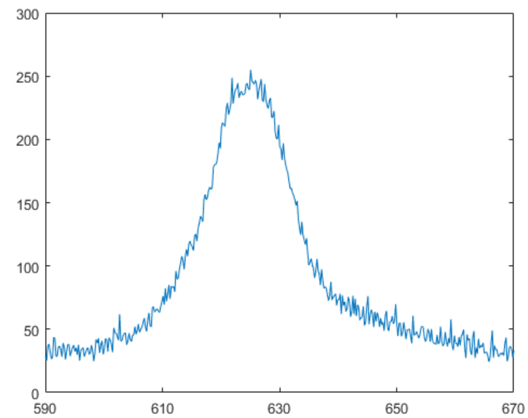
300
250
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50
0
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610
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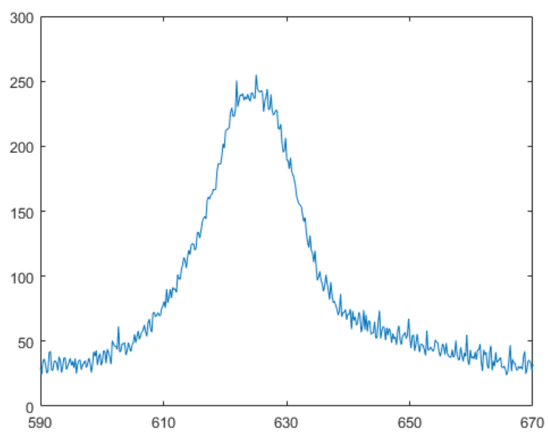
650
670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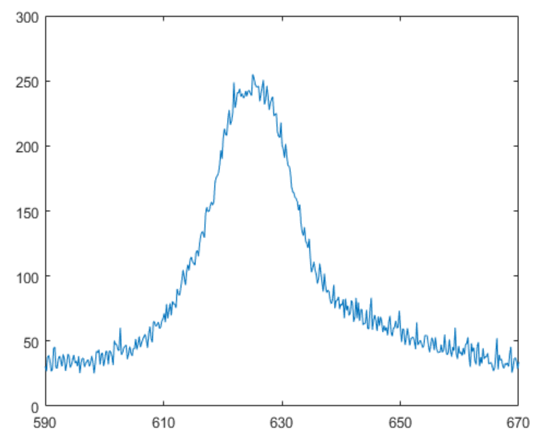
670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50
0
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610
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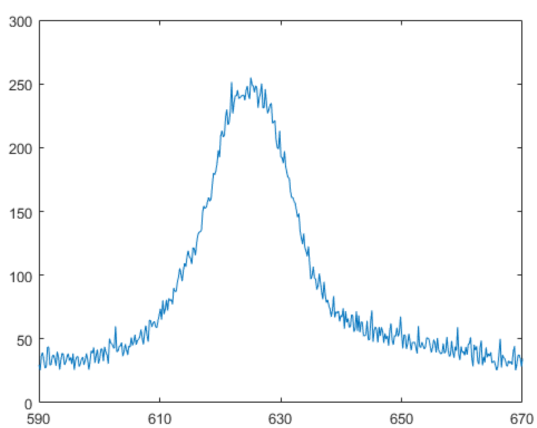
670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250
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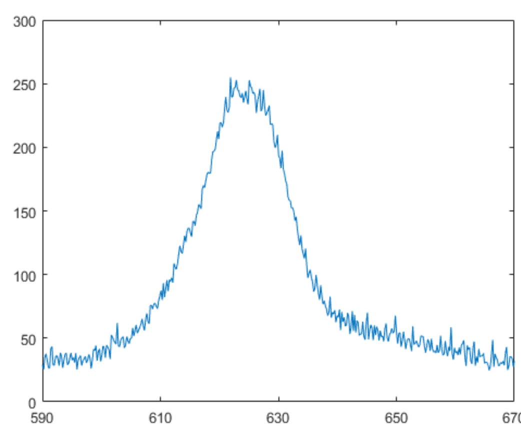
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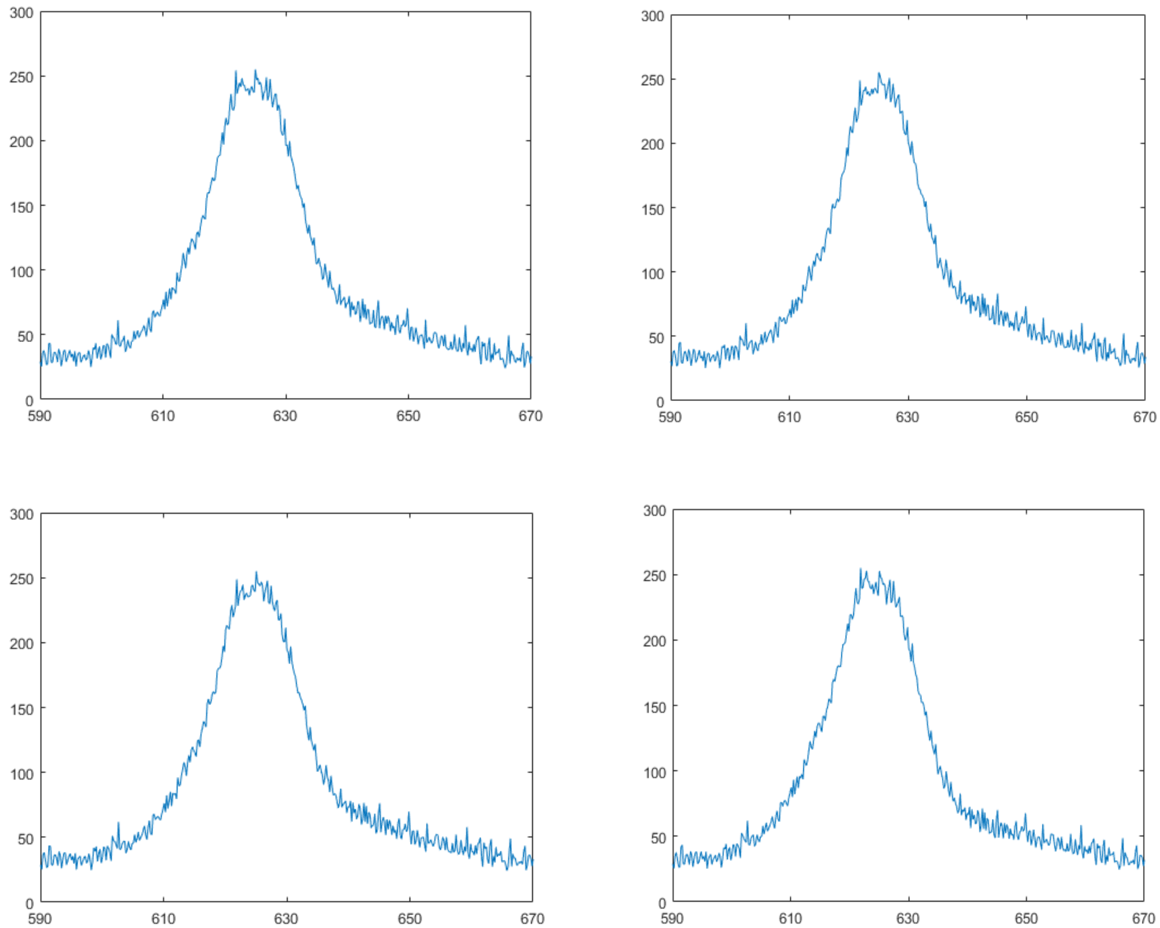
670




The average peak value executed from spectrometer is 624.85 so, the deviation is **5.15nm**

### 4.1.10 650nm peak

The initial design curve, the display image and the resulting curve of ten different measurements are:

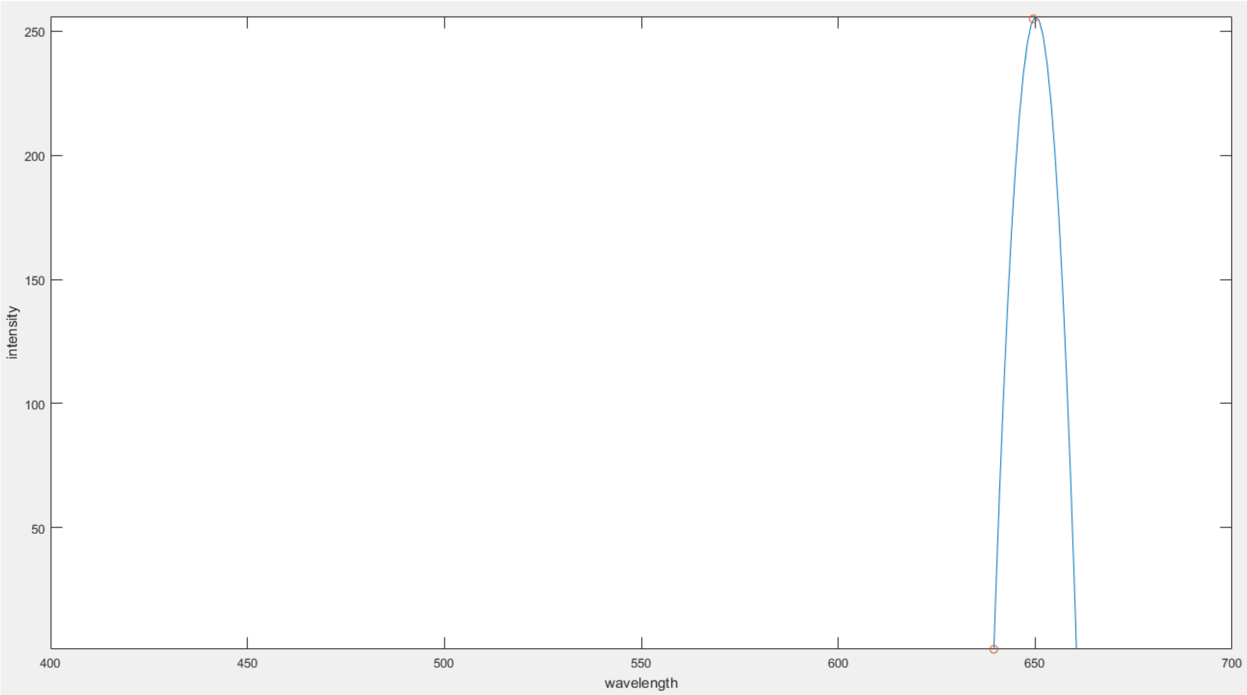



*Figure 4.1.10.1 – Initial Design of 650nm*

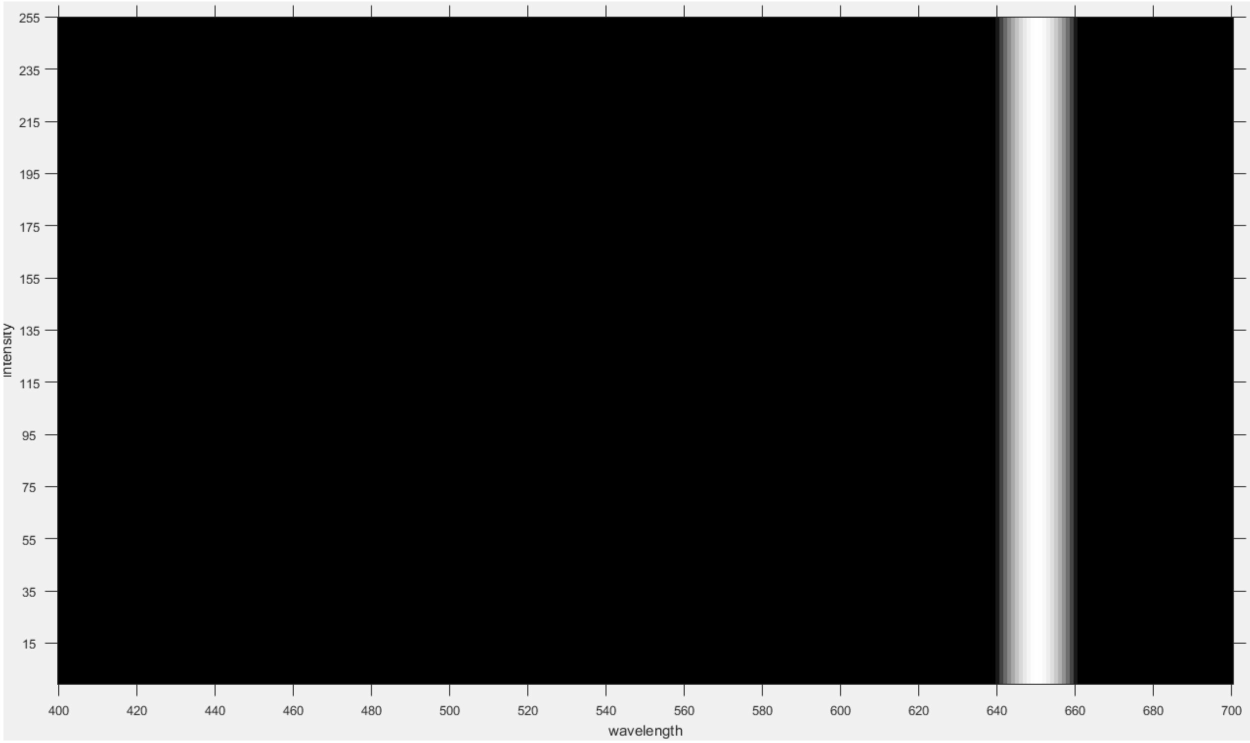
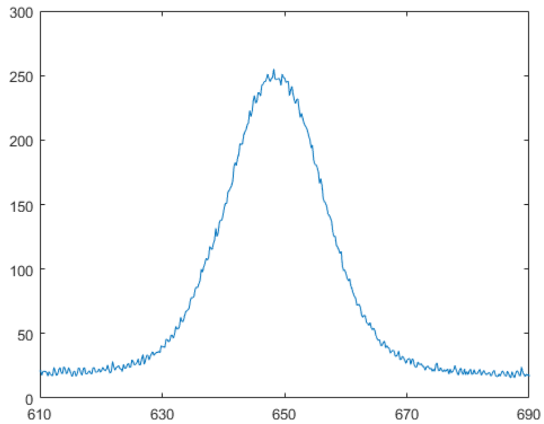



*Figure 4.1.10.2 – Displaying image of 650nm*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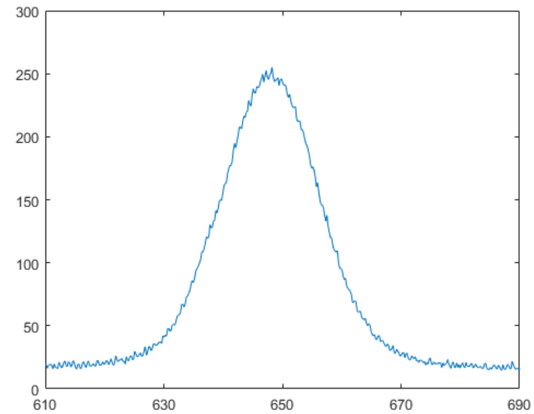
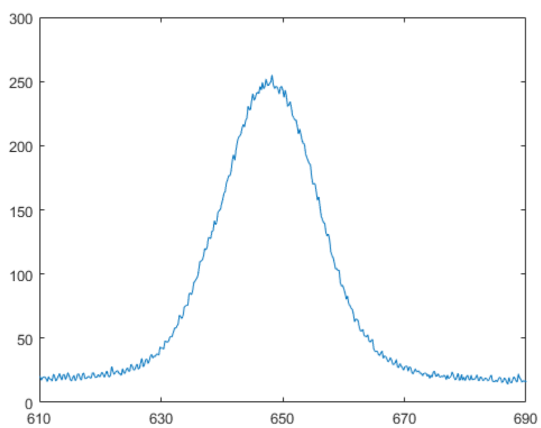
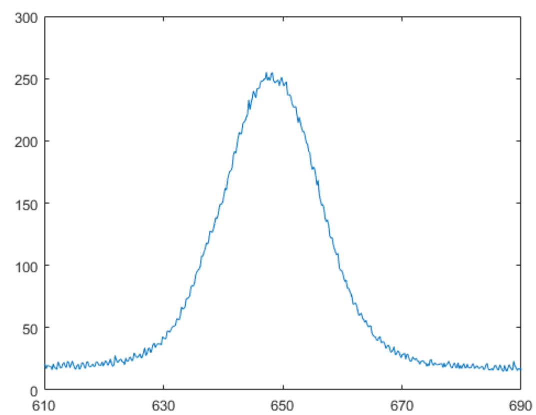
100
50
0
610
630
650
670
690


300
250
200
150
100
50
0
610
630
650
670
690


300
250
200
150
100
50
0
610
630
650
670
690


300
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100
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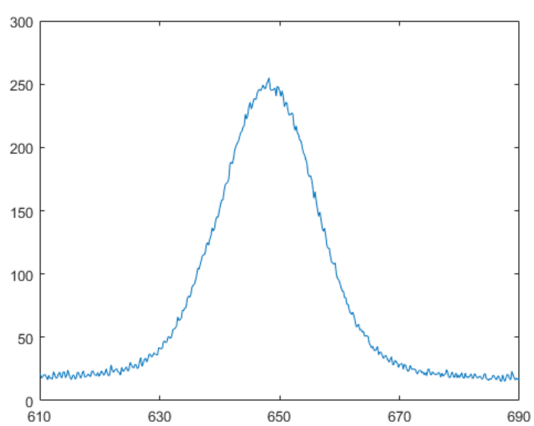
0
610
630
650
670
690


300
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200
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100
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0
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670
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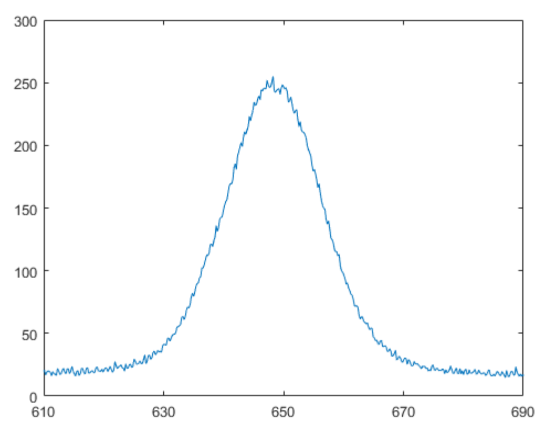
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670
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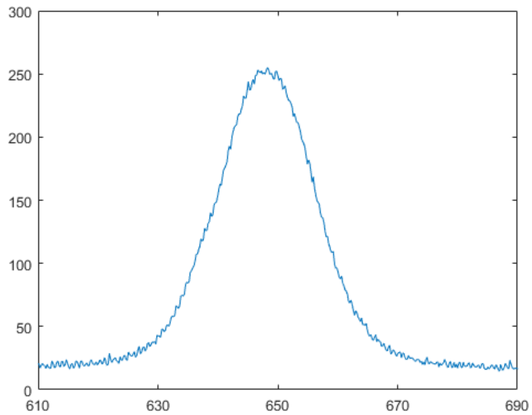


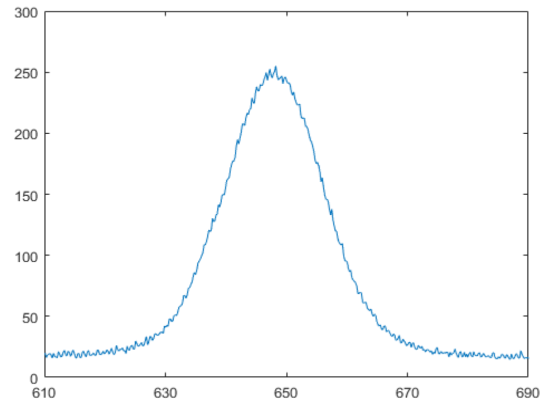


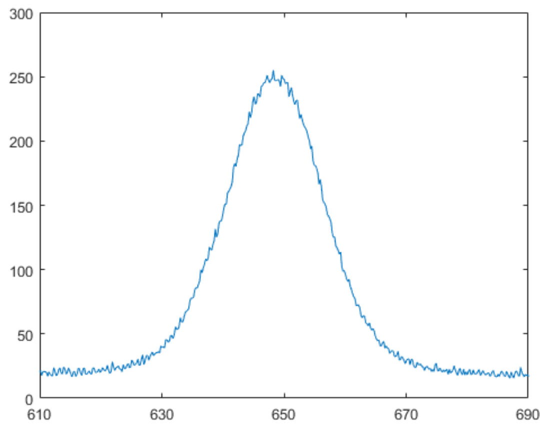


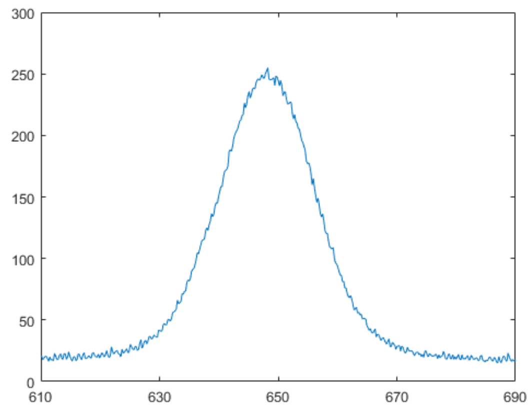


The average peak value executed from spectrometer is 647.76 so, the deviation is **2.4nm**

## 4.2 Accuracy test

As a way to test out Light Source's accuracy, it projected an image with two different spectrum peaks and we take the spectrum curves using the spectrometer. In the figure below compared spectrums are presented:

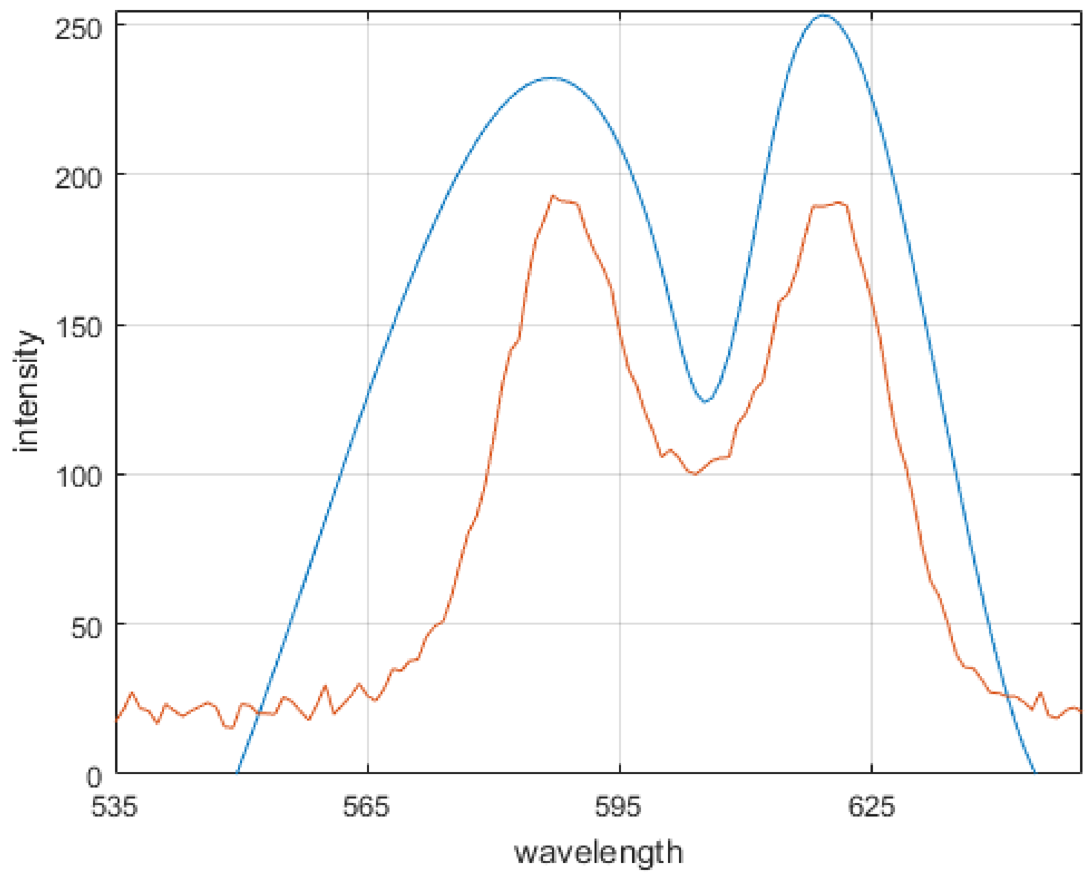


*Figure 4.2.1 – Accuracy test*

As we can observe from the above figure, the spectrum that we projected and the spectrum that we measured with the spectrometer are enough equal and this makes the system quite stable.

## 4.3 Flattened halogen

In this section the goal was to flatten the halogen source. Firstly, we took the spectrum of the halogen lamp and then we created the reverse spectrum of this beginning of and we projected it to the filter glasses. In this way, we measured again the projected spectrum and the result was a flattened source. In figure 4.3.1 Is depicted the spectrum of the halogen lamp, in figure 4.3.2 the reverse spectrum of the halogen lamp which is projected and in figure 4.3.3 the flattened spectrum.

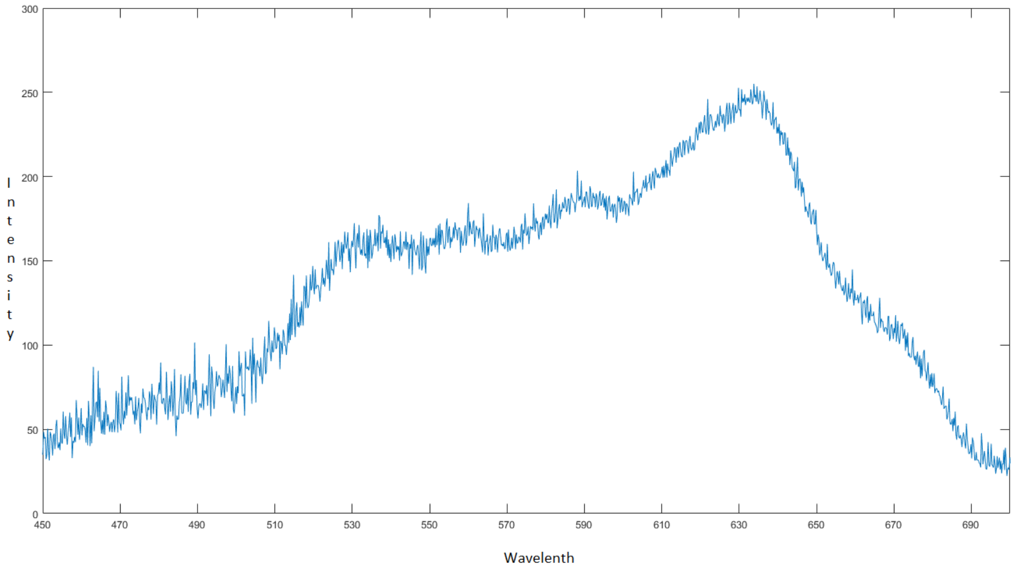


*Figure 4.3.1 – Spectrum of halogen lamp*

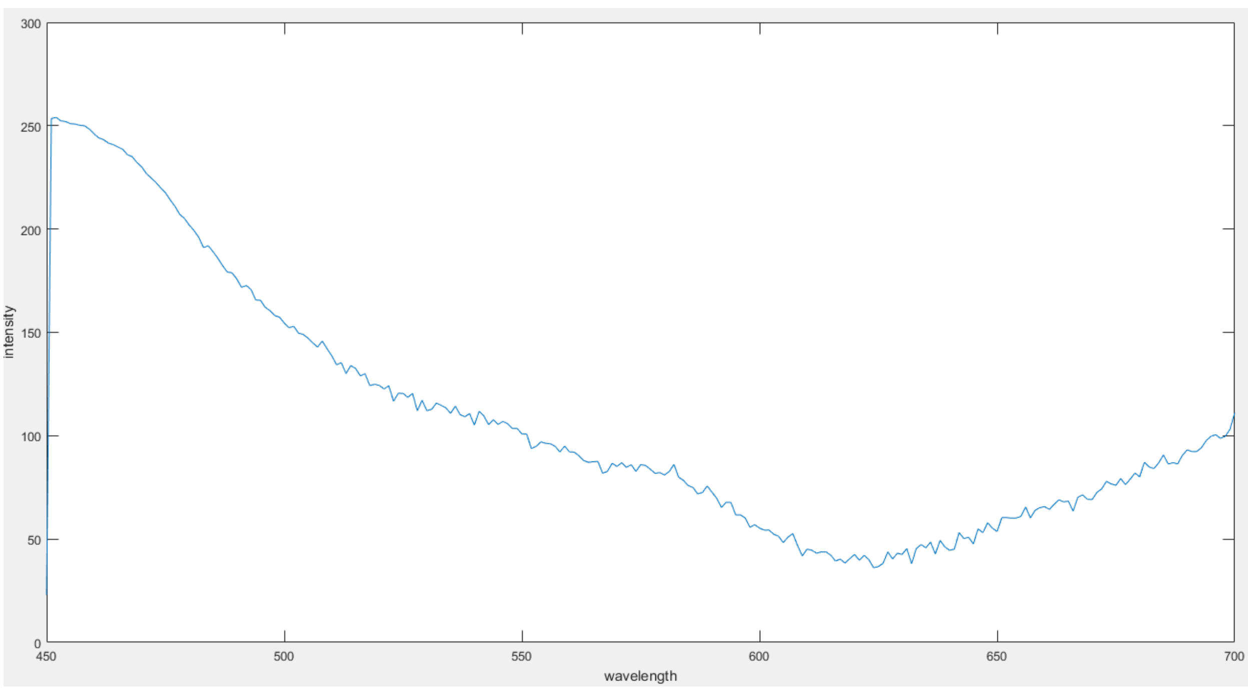


*Figure 4.3.2 – Reverse Spectrum*

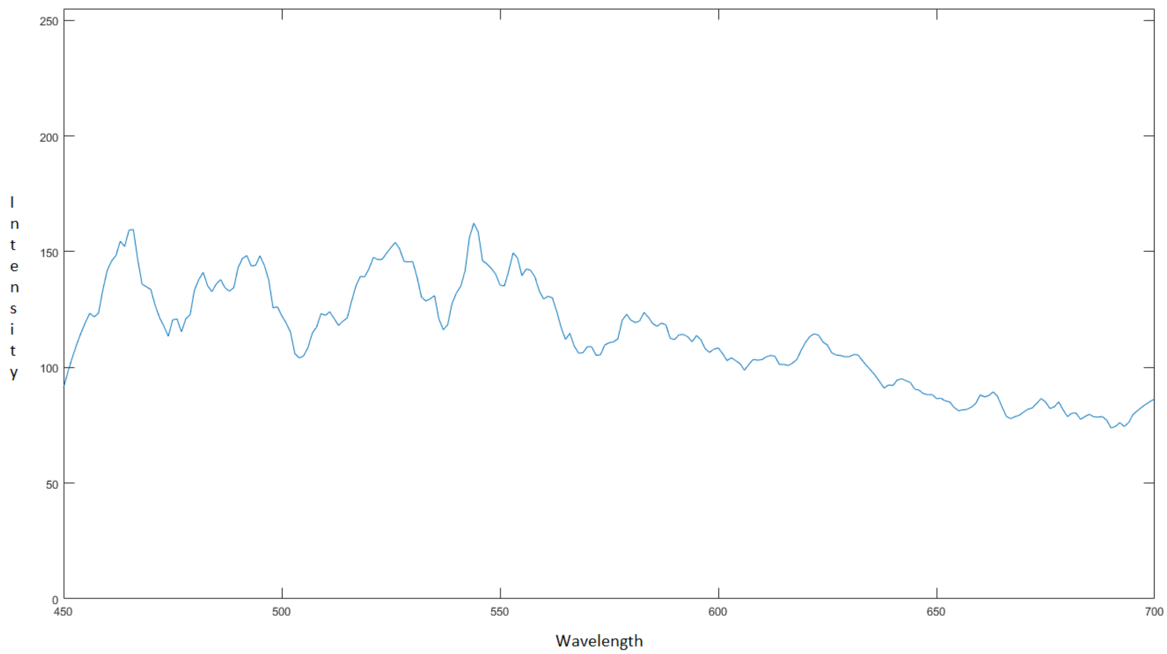


*Figure 4.3.3 Flattened spectrum*

The final flattened spectrum that we measured with the spectrometer has some uneven curves at the beginning and this is due to the big integration we've given to get the result. However, it is observed that the light source has been flattened satisfactorily.

## 4.4 Projection of Chlorophyll and Skin

In this section we projected a spectrum of the chlorophyll and a spectrum of one human skin. In the next figures, the projection spectrum of chlorophyll, the projection image and the chromatic result of this, are depicted.

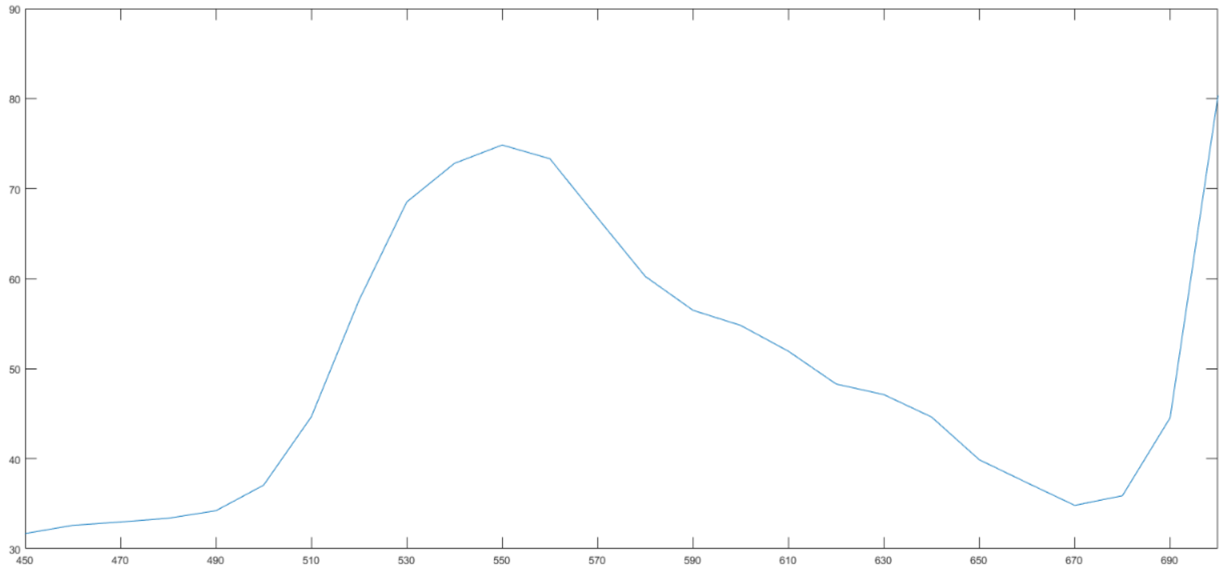


*Figure 4.4.1 – Spectrum of Chlorophyll*

**Figure 4.4.2 – Projection image of chlorophyll** *Figure 4.4.3 – Chromatic result of chlorophyll*

The final projected color is identical to the color of the chlorophyll.

Now in the next figures, the spectrum of a human skin, the projection image and the chromatic result of this, are depicted.

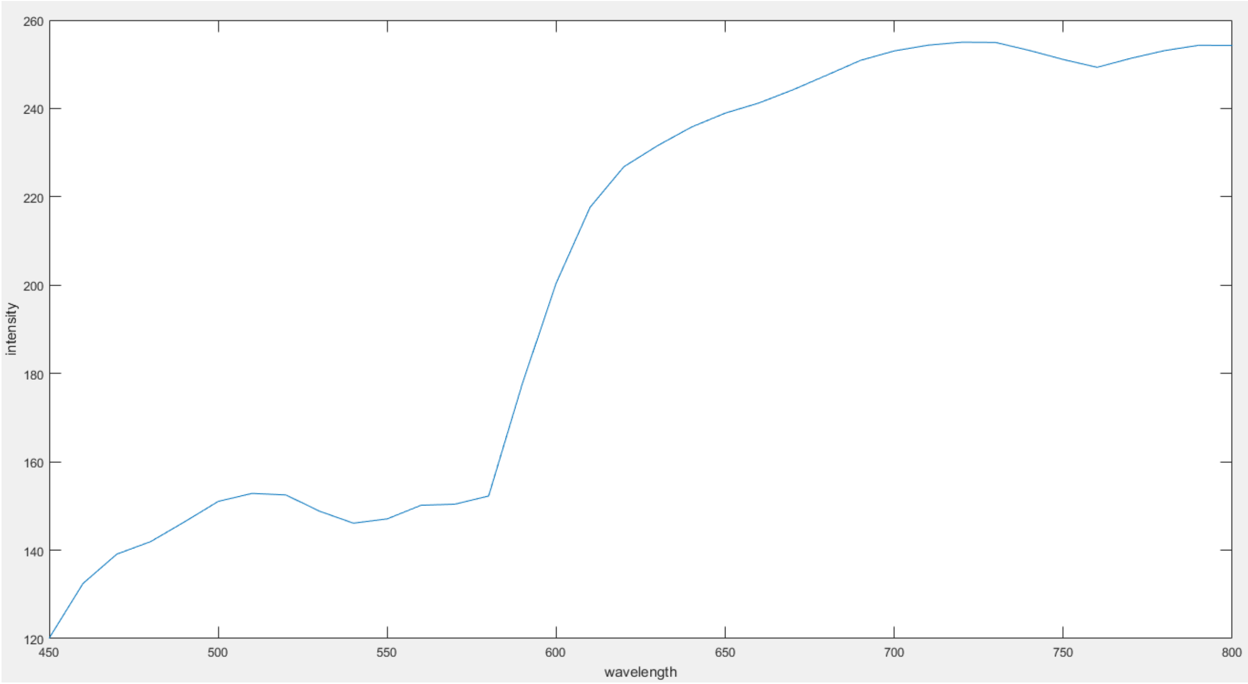


*Figure 4.4.4 – Skin spectrum*

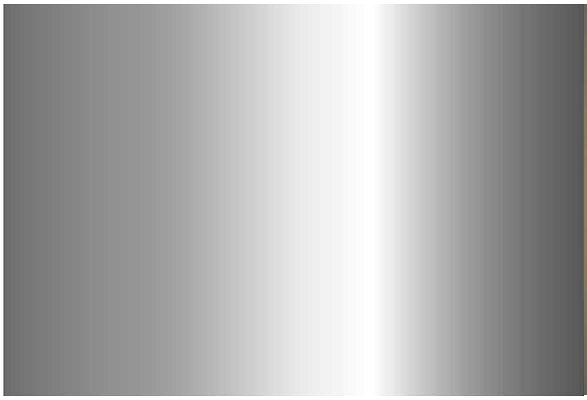

*Figure 4.4.5 – Projected image of one skin*

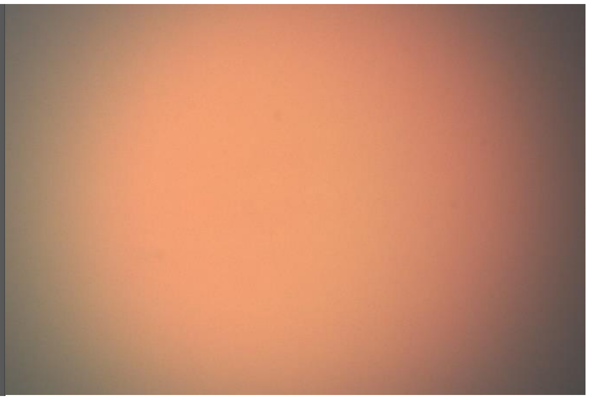

Figure 4.4.6 – Chromatic result of skin

The final projected color is identical to the color of the human skin.

## 4.5 Metameric colors

In colorimetry, metamerism is a perceived matching of the colors under of one lamp, with different spectrum. These colors are called metameric. In this section we created two metameric colors. The spectrums of the colors are depicted in figure 4.5.1. Then we projected these colors and we take the results. As we can see in figure 4.5.2 and 4.5.3 the two colors are enough equal.

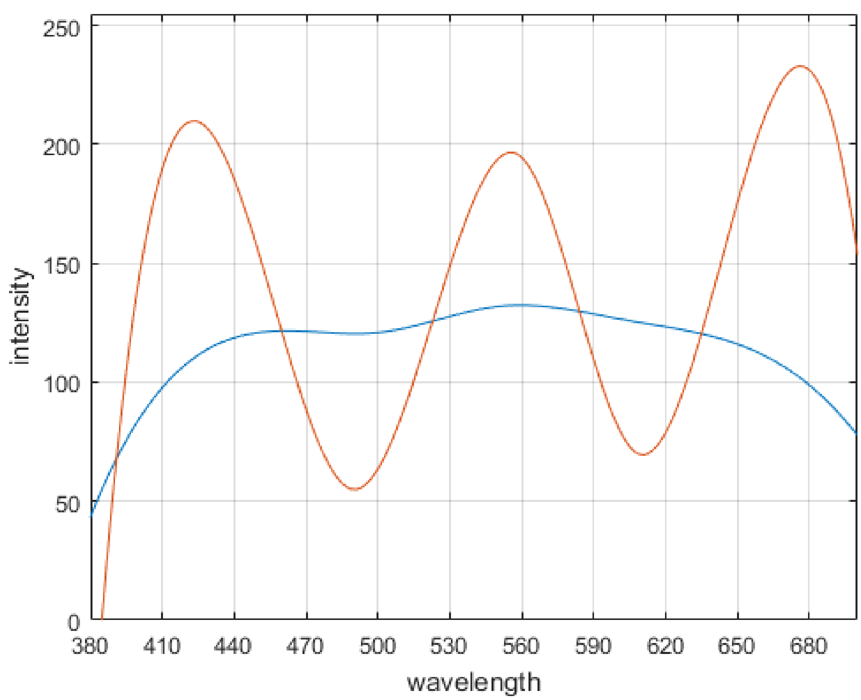


*Figure 4.5.1 – Spectrums of two colors*

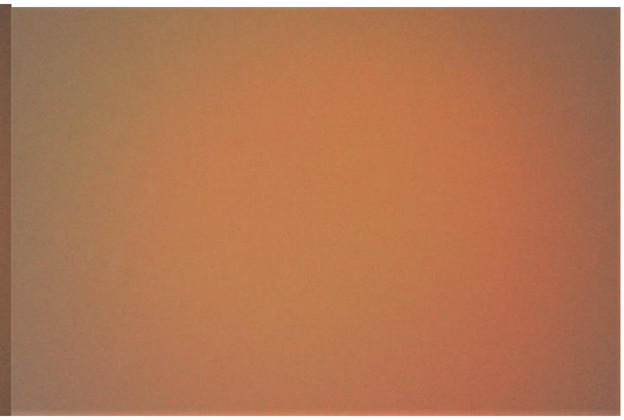

Figure 4.5.2 – Color 1

Figure 4.5.3 – Color 2

We can notice that the two colors look very similar to each other.

# CHAPTER 5
# FUTURE WORK AND CONCLUSIONS

In this diploma thesis a Spatial light modulator based light source with controlled spectral emission is presented. Firstly, we use a DLP for projection and a halogen lamp as light engine. Black and white image is sending to DLP using MATLAB and is created according to the design of the spectrum chosen by the user. More specifically, the user draws the spectrum that he wants and the Light Source is able to project the designed spectrum.

Second, this image is projected directly onto the linear filters and behind its light passes according to the intensity of the white color of the image in the corresponding spectrum. Behind the filters there are the optical fibers which transmit and display the color created in the output.

Our configuration is a cost-effective approach in hardware and software demanding areas of biomedicine. The device can cover a wide spectral range and is able of emitting whatever spectrum the user wants, unlike other configurations which are able to emit only peaks 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.

The intended applications of the light source span a wide range of disciplines including but not limited as an achromatopsia tester, vision sensitivity tester, calibrator for optical instruments and for Metameric color reproduction and study etc.

A future work, there are a lot of improvements to made hardware and software-wise. An example is the software can be wrote in C, C++ to become quicker. Also, an improvement on the power throughput would be the replacement of the halogen lamp with more powerful and efficient lamp and be able to cover broader spectral range (UV to near infrared).

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