

SIMULATING THE CHARGING OF AN ELECTRIC VEHICLE BY LASER

by

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## ABSTRACT

Laser power transfer (LPT) is a wireless power transfer technique which can be used for the charging of unmanned aerial vehicles (UAVs) and satellites. This research examines the potential of high-power laser transfer for the charging of electric vehicles (EVs). In this thesis, we describe the implementation of a MATLAB based circuit simulation of the charging of EVs by LPT. Existing wired and wireless charging methods have drawbacks, including short charging ranges and long charging times. Recent developments in photovoltaic (PV) cells and laser technology suggest that the transfer of power using light can overcome some of the issues associated with these other charging methods. This thesis describes the enabling technology required for LPT-EV charging and explains why a wavelength of 808nm is best suited for high power transfer. A specialized, highly efficient PV cell is described that can tolerate the required high-intensity laser beam. We also discuss some of the environmental factors affecting LPT-EV charging such as atmospheric attenuation and module temperature. A numerical method developed in MATLAB simulates the implementation of the laser, the PV cells. This study includes an examination of the effect of various input power levels and temperatures on the PV panel. In addition, a comparison of a uniform (or “top hat”) circular-beam and a Gaussian distribution is shown here to maximize the efficiency at the receiver. The research also examines the overall efficiency of the LPT for various input power-levels; it shows that using this technique with existing technology, a charging time of about 2 hours for a Tesla Model S or X can be achieved with an overall efficiency between 10% and 37%. The thesis also discusses the safety of LPT technology since it uses Class 4 lasers. Based on the performance of this model, some suggestions are made for future work.



## **LIST OF ABBREVIATIONS**

- AC – Alternating current
- AEL – Accessible emission limit
- ANSI-American national standards institute
- DC- Direct current
- EMI-Electromagnetic interference
- EV-Electric vehicle
- I-V-Current and voltage relationship
- LD-Laser diode
- LPT-Laser power transfer
- P-V-Power and voltage relationship
- SPL-Solar pumped laser
- UAV-unmanned aerial vehicle
- WiTricity-Wireless electricity
- WPIT-Wireless power and information transfer
- WPT-Wireless power transfer

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# 1 Introduction

Electric vehicles (EVs) are a less emissions-intensive alternative to conventional liquid fuel vehicles, especially when the electricity comes from clean energy sources. These days EVs are becoming increasingly popular around the world [1]. However, the uptake of EVs are limited by factors such as the lack of awareness, high initial cost, many hours of one time charge, it can go only 200-400kms, and lack of charging infrastructure [2, 3].

## 1.1 Overview of the types of EV's charging technique

This study examines EV charging methods. Broadly speaking there are two types of charging: wired (or plug-in) and wireless. Wired charging requires a cable to charge automobiles. At present, a variety of wired charging system exist, including Level-1 (Home charger), level 2 (home and public charger) charger, and the new Level 3 DC fast charger [4].

In plug in charging the grid will supply AC power through a cable to the car. This AC power is then filtered and rectified for power correction and that DC power again converted into the AC power by inverter. An on-board transformer will boost the voltage which will be rectified and filtered by the rectifier and filter respectively. At the end, this DC power will be ready to charge the battery pack [4]. Schematic diagram of Plug-in charger is shown in Figure 1.

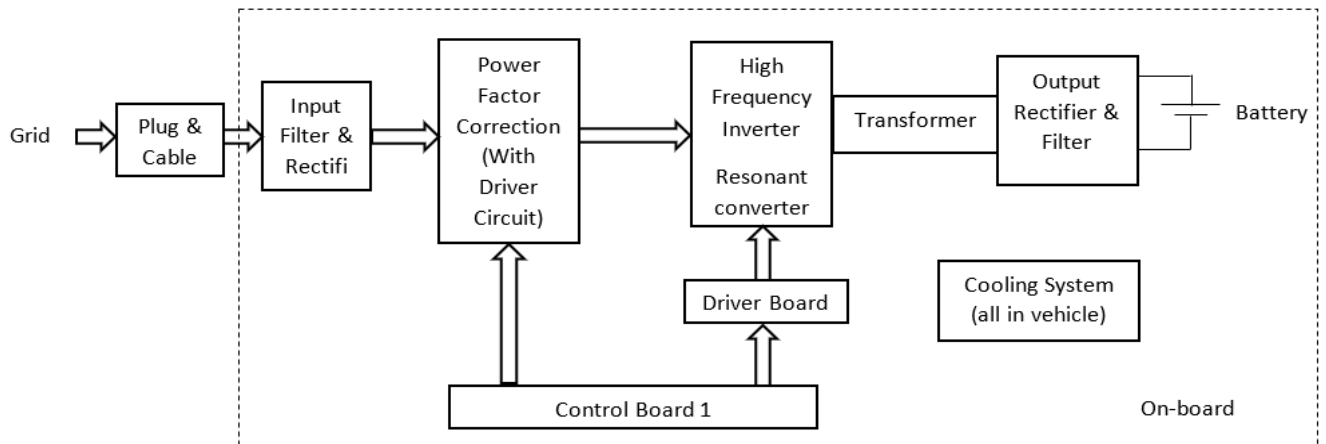


Figure 1: Schematic diagram of Plug-in charger [4]

There are three categories of Electric Vehicle Supply Equipment (Table 1) [5]:

*Level-1 charger:* Generally, all the EV are equipped with cord and they don't require any special outlet. This is a slowest charger of them. It has a power capacity of 1 kW. Using Level-1 charger overnight can provide up to 40 miles of range and 14 hours of charge which can give you 70 miles of range.

*Level-2 charger:* The car manufacture also provides Level-2 charger with 240 volts charging station. This charger can reduce the charging time in half but requires an installation of extra electrical circuit. It has power capacity range of 3-20 kW. It can provide 10 miles of charging in one hour and 8 hour or less charging time which can give you 80 miles of range.

*Level-3 DC fast chargers:* This is the fastest charger available in the market right now. It can charge the vehicle 4 to 6 times faster than the AC charger. It has a power capacity range from 50kW to 140kW. This charger can charge your vehicle in less than an hour, but it requires special charging outlet for EVs which is not available in every EV. In addition, the cost of the charger is high, so they are not widely available.

Table 1 Charger level [6]

Type of charger	Charger's capacity(kW)	Approximate charging time
Level-1 charger	1	200km ~20 hours
		400km ~43 hours
Level-2 charger	3 to 20	200km ~5 hours
		400km ~11 hours
Level-3 DC fast charger	50 to 140	80% of 200km ~30 minutes
		80% of 400km ~1 hour

The concept of wireless power transmission (WPT) is about 150 years old. Wireless charging is a method that does not require cables and fuel stations. There are two techniques of wireless charging: near and far-field. Near-field wireless charging can be further divided in three methods: magnetic coupling, magnetic resonance coupling and capacitive coupling [7]. Recent advanced in light amplification by stimulated emission of radiation (laser) and photovoltaic technology give us the opportunity to explore the new applications.

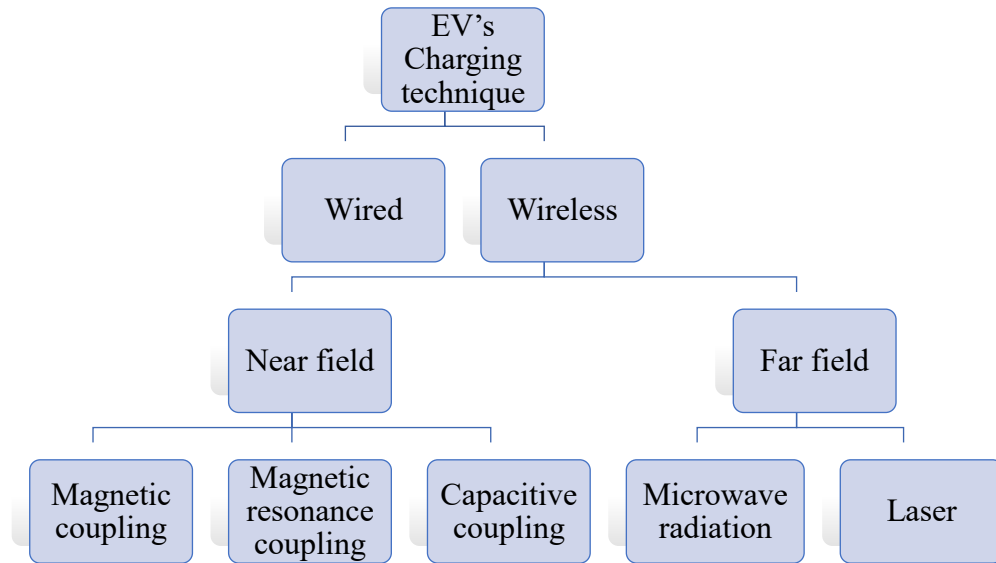


Figure 2: Classification of EV's charging technique

Table 2 History of wireless power transmission [7]

1880-1900s	<ul style="list-style-type: none"> <li>• H.R Hertz used an oscillator connected with induction coils to transmit high frequency power over a tiny gap (1891)</li> <li>• N. Tesla illuminated phosphorescent wirelessly. (1893)</li> <li>• N. Tesla patented the tesla coil. (1897)</li> <li>• N. Tesla transmitted microwave signals over about 48 kms. (1896)</li> <li>• N. Tesla light 200 bulbs and run an electric motor over 25 miles. (1899)</li> <li>• N. Tesla constructed the Wardencllyffe tower. (1901)</li> <li>• Marconi transmitted microwave signals across the Atlantic Ocean. (1901)</li> </ul>
1990-1970s	<ul style="list-style-type: none"> <li>• W.C. brown showed the first microwave wireless power transmission system (1963)</li> <li>• The concept of solar power satellite was introduced for wireless power transfer. (1968)</li> <li>• M.Cardullo patented the first modern RFID. (1971)</li> <li>• Don Otto designed inductively power trolley model. (1971)</li> <li>• Venus site of JPL's goldstone facility beamed 30kW over 1 mile at 84% RF-to-DC efficiency. (1975)</li> </ul>
1990-2010s	<ul style="list-style-type: none"> <li>• Inductive coupling-based wireless charger in a flat pad style was developed for consumer devices.</li> <li>• MIT scientist proposed WiTricity technology. (2007)</li> <li>• Cota system. (2008)</li> <li>• MIT scientist proposed to simultaneously transfer energy and information with RF signals. (2008)</li> <li>• PRIMOVE system. (2008)</li> <li>• Lockheed Martin and laser motive remotely charged UAV using laser to increase its flying time. (2012)</li> <li>• Apple, Samsung, AT &amp; T, Google, Nokia and LG to deliver their mobile phones with built-in wireless charging components (2014).</li> </ul>

## 1.2 History of wireless power transmission

WPT is different from the wireless communication system as wireless power transmission is the transmission of electrical power from one point to another through vacuum or an atmosphere without using wires or any substances. WPT is also known as ‘beamed power transmission’ [7]. WPT is different from the wireless communication system as in wireless

communication system requires only small amount of power to recover the signal while WPT transfer maximum amount of power to the receiver [8].

### 1.3 Existing work in wireless charging of electric vehicle

#### 1.3.1 Current technologies for EV in WPT

Figure 3 shows the near field WPT. In this method, first AC passes through the electromagnetic interference (EMI) and then boosted and rectified into DC power at nearly 1.0 power factor. The DC/DC buck converter then decreased the DC power for soft start/stop of the charger and continue tuning of the output. Here, the buck converter is optional and can be replaced by pre circuit charge and phase shift method which will slightly reduce the efficiency and cost. An inverter will convert the DC power into high frequency AC power which resonates in the primary compensation network and then primary coil. On the vehicle side, a secondary coil receives the AC power wirelessly because of the mutual inductance between two coils. The secondary compensation network needs to be tuned at the same frequency as the primary network to increase the efficiency. This high frequency AC power then rectified into the DC power then it passes through the filter network. It is available for charging the battery pack [9].

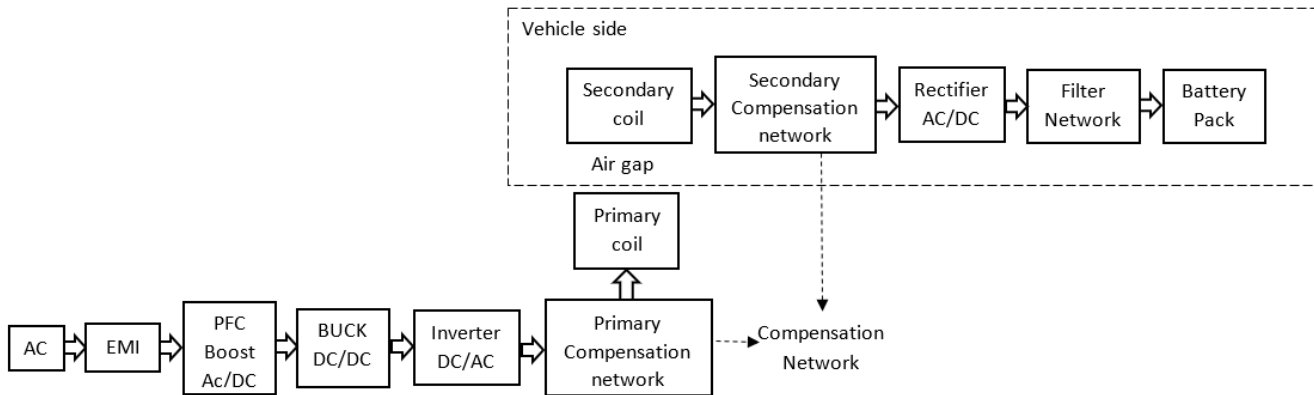


Figure 3: Near field WPT [9]

Magnetic coupling and magnetic resonance coupling work on the principle of electromagnetic induction while capacitive coupling transfer power through the electric field. The microwave radiation is far-field technique which work on the principle of

electromagnetic radiation [7]. The above-mentioned methods have drawbacks; for example, magnetic coupling, magnetic resonance coupling, and capacitive coupling have limited charging ranges and, complex implementation while microwave radiation has the disadvantage of low charging efficiency and is not safe when radio frequency density exposure is high [10].

#### **1.4 History of laser power transmission or LPT as a new approach**

To overcome these problems, we are proposing a wireless charging method using monochromatic or coherent light, that is, laser charging of electric vehicles. Research is currently being conducted in the wireless charging of UAVs (unmanned aerial vehicle) have successfully charged UAVs over long distances [11]. Lasers have the potential to deliver high power to the receiver making it an ideal source for the wireless power transmission. In 1970, lasers were proposed to provide thermal energy for the beamed energy propulsion spacecraft and 1990 the transfer electricity from one location another was suggested [12].

In this method, electricity will be transferred to the automobile in the form of light using a laser and converted back to electricity using photovoltaic (PV) cells.<sup>1</sup> In practice, it can be achieved by fitting a PV panel under the carriage of the car with a laser beam propagated through the air to the PV panel.<sup>2</sup> During the application of EV charging, the distance between the laser source and the PV panel is assumed to be not more than 2-3m. Figure 4 shows a block diagram of proposed technique. To successfully charge the EV using this procedure a vehicle can be in a stationary or mobile. Here, we will be examining a static method, where the car will be in stationary position in parking space.

The main problem with the laser power transfer is the efficiency of the laser (electricity to light) and PV cells (light to electricity). Current advancements in laser and PV cell technology allows the transfer power using these devices with greater efficiency and higher power transferring capability [12].

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<sup>1</sup> A photovoltaic cell is a semiconductor device usually made from silicon and gallium arsenide which can convert solar light into electricity

<sup>2</sup> PV panel is the frame where PV cells are connected in series and parallel to form a module



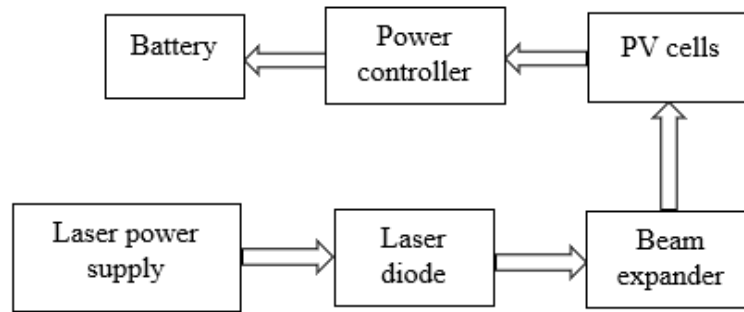


Figure 4: Proposed technique

### 1.5 Laser safety

Since the proposal deals high powered laser diode, safety needs to be addressed in this project. The top three issues associated with the high-powered laser is addressed below.

- Eye safety: Here, laser operates between 810nm-850nm wavelength which is near to infrared and invisible to the human eye. Therefore, direct viewing to the laser beam and exposure to reflections can cause retina damage.
- Skin burning: Direct exposure to beam or reflection exposure can be led to tissue burning.
- Fire: A high-power laser can ignite a fire easily when the laser beam comes into the contact with a flammable material.

In an implementation, laser warning signs must be provided near the area, avoid direct looking at the laser charging system during its operation, use personal protective equipment, use proper eye protection, PV cells surface should be 0% reflective, light curtains can be put around the PV panel to absorb the scattered light and protection. More details related to laser hazard for EV and its prevention is provided in Appendix A: Laser Hazards and safety evaluation).

### 1.6 Research objectives

The objective of this work is to find an alternative approach to charging electric vehicles by transferring high-intensity power with high efficiency in the minimum time by laser. The transmitter needs to supply adequate amount of power to the receiver efficiently. Also,

study the laser source's beam profile on the receiver to get the maximum output. The receiver needs to meet the thermal and electrical requirements of the system in order that various laser power level and temperature can be used to evaluate the performance of the laser-power converter.

The PV panel design is to be redesigned to achieve maximum efficiency. This can be done by studying optimal non-uniform illumination, and thermal effects at high intensities. We will also consider ways to improve the future performance of the design based on the data collected from the simulation model.

For the implementation of laser source and PV cells, project uses commercial laser and PV values from manufacturer's data sheets for the simulation of the system in MATLAB.

## 2 Background

This chapter examines the fundamentals of lasers and photovoltaic cells.

### 2.1 Laser

A generic laser structure consist a resonator (cavity), two mirrors for feedback, and a gain medium for amplification which is shown in Figure 5. A laser is basically an oscillator. To form an oscillator, we need an amplifier and feedback. Feedback is provided by two mirrors: one mirror is fully reflective while the other mirror allows some light to escape through the gain medium [13].

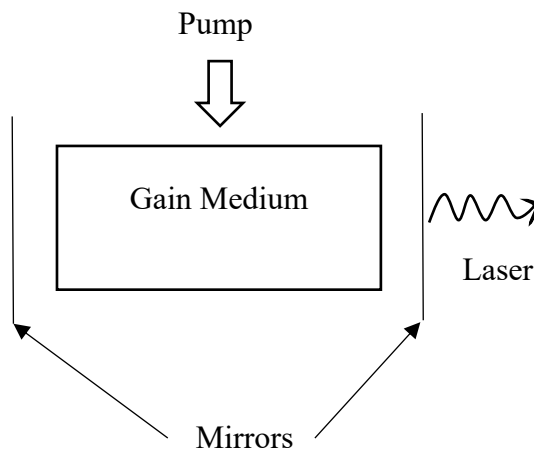


Figure 5: Basic laser structure [13]

For lasing action, population inversion is necessary.<sup>3</sup> For population inversion, external energy is required to pump the electrons from the valence band to the conduction band using a process is known as pumping [13]. The gain medium is typically create using a gas molecules and semiconductor laser use semiconductor as gain medium [13].

As mentioned earlier, electrons can be excited into the higher energy state by applying external energy. Eventually electrons will lose the energy by emitting photons. A population inversion is necessary for lasing action to take place. Population inversion

---

<sup>3</sup> In a material normally more atoms available in the lower energy state than in the higher energy state. However, when we pumped the energy to the material then the population inversion occurred where more atoms will be available in higher energy state than the lower energy [13].

means there are a greater number of photons available in higher energy state than the lower energy state. Transition of electron from the higher energy level to the lower energy level will generate light of photon which is amplified in cavity and creates a lasing action [13].

Now consider two level system with energy level E1 and E2 which contains N1 and N2 number of atoms per unit volume respectively. When the energy is applied to the medium the number of atoms absorbs the energy and go to the higher energy level (from E1 to E2) will be [13]

$$B_{12}N_1\rho(\nu_{21})$$

This process is known as absorption.

The number of atoms undergoing a stimulated emission from E2 to E1 will be [13]:<sup>4</sup>

$$B_{21}N_2\rho(\nu_{21})$$

The number atoms undergoing a spontaneous emission<sup>5</sup> from E2 to E1 will be [13]:

$$A_{21}N_2$$

Where,  $B_{12}$  Probability of absorption

$B_{21}$  Probability of stimulated emission

$A_{21}$  Probability of spontaneous emission

$\rho(\nu_{21})$  Density of photon with frequency  $\nu_{21}$

For two level system absorption, stimulated emission and spontaneous emission is shown in Figure 6 and probability of absorption, stimulated emission and spontaneous emission is shown in Figure 7.

---

<sup>4</sup> A suitable photon energy wave can stimulate photon emission with another photon. This process is known as stimulated emission. (This process is artificial)

<sup>5</sup> In a laser, after some time excited atom or ion decay into the lower level by releasing energy in the form of photon in a random spatial direction. This phenomenon is known as Spontaneous emission. (This process occurs naturally)

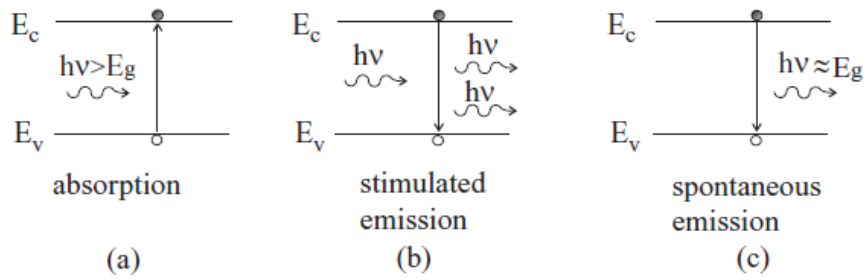


Figure 6: Transition in two level system

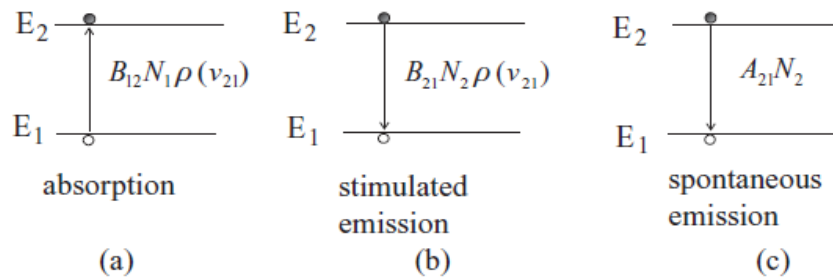


Figure 7: Transition in two level system

For lasing action, the amplification should be greater than the absorption. Therefore, the number of stimulated emissions should be greater than the absorption [13].

The change of occupancy of the higher energy level with a time is

$$\frac{dN_2}{dt} = -A_{21}N_2 - B_{21}N_2\rho(v_{21}) + B_{12}N_1\rho(v_{21})$$

There are three types laser system: two level, three level and four level. Three and four level system shown in Figure 8 and Figure 9 below.

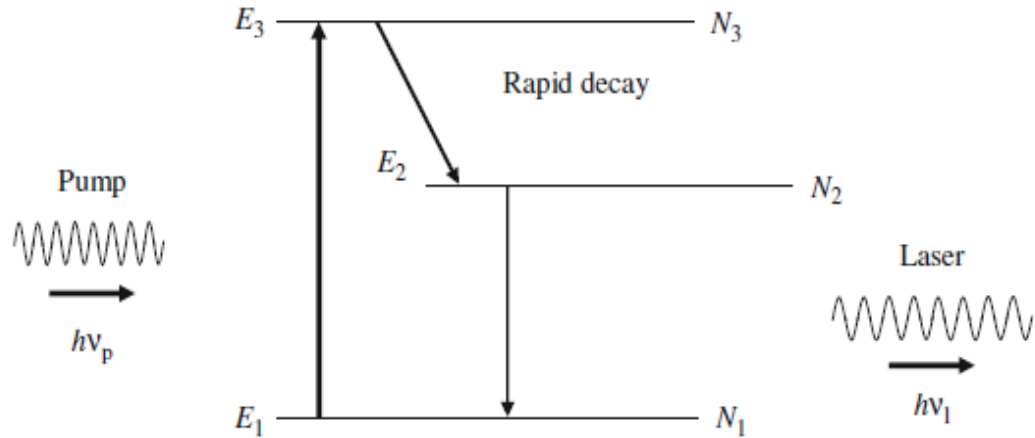


Figure 8: Transition in a three-level system [14]

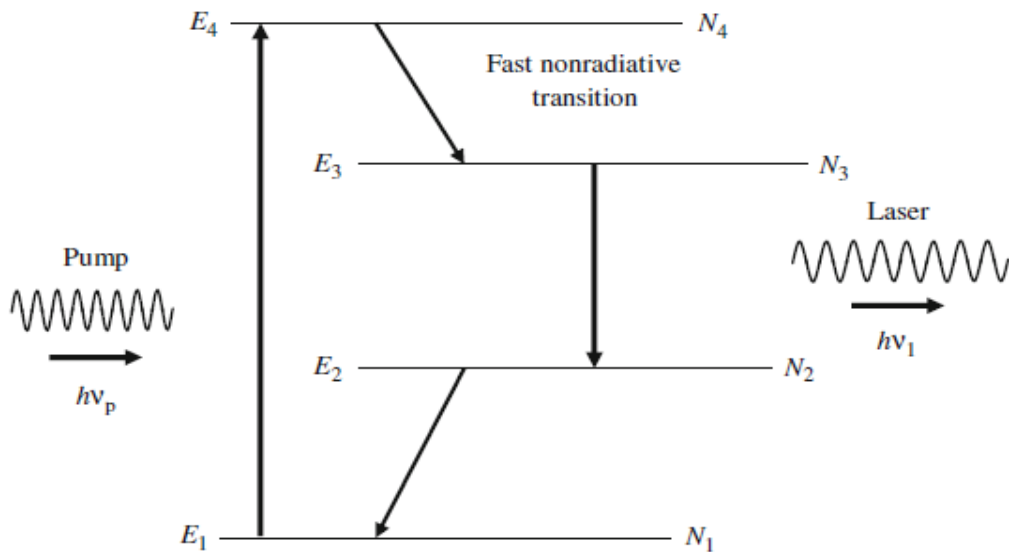


Figure 9: Transition in a four-level system [14]

In practice, two level systems are not useful as the probability of absorption and the probability of stimulated emission is same, so the lasing action would be very difficult. A three and four level system are efficient so it can be used practically [14].

### 2.1.1 Laser Diode

In laser diode the light emission is amplified by the stimulated emission. A basic laser diode structure is shown in Figure 10. In a stimulated emission a photon triggers radiative recombination of an electron and hole and creates a new photon with same energy and

phase. This is called the cloning of photon. A cloning of photon creates coherent laser beam [14].

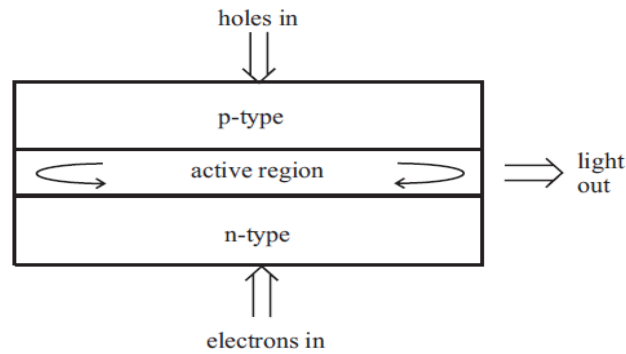


Figure 10: Semiconductor laser [14]

A laser diode is a p-n junction diode which operates into the active region of the diode, the electron-hole recombination in diode creates light emission. In laser diode the n-type don't have enough energy to pass the potential barrier. Same goes for the P-type. So, there is a need to apply forward voltage who can lower the potential barrier for p and n type which is described in Figure 11 [14].

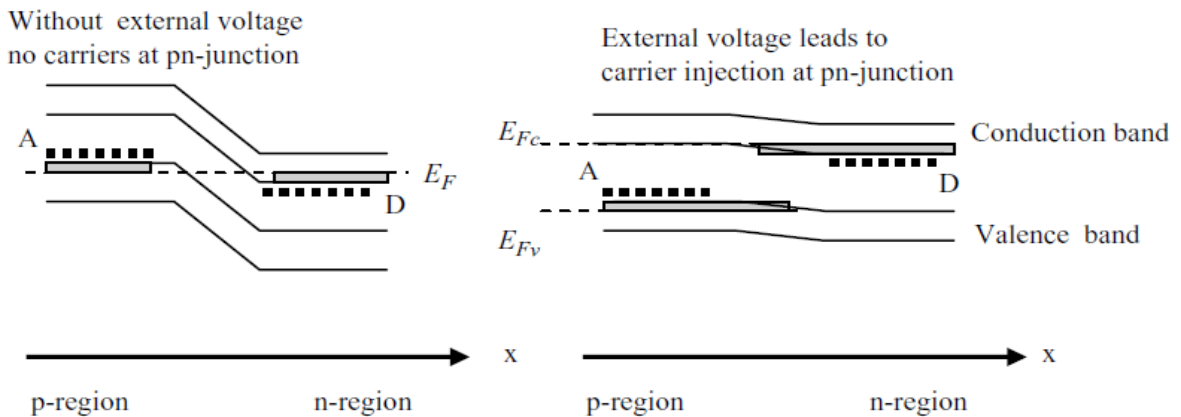


Figure 11: Operation in the semiconductor laser [15]

A semiconductor laser's wavelength is determined by the size of the band gap which means it depends on the material used in it. High power semiconductor laser generates 700nm to 1000nm of wavelength which is basically made of a GaAs and latticed matched with GaAs

material. Semiconductor laser contains quantum wells which allow a different material composition with GaAs with different lattice constant. Using different material one can altered the wavelength range from 700nm to 1100nm which shown in [15].

Table 3 Laser material and their wavelength [15]

Wavelength	QW-material	Lattice mismatch
780nm	GaAsP	0.8%
810nm	GaAsP	0.5%
810nm	AlInGaAs	1%
880nm	In <sub>0.08</sub> Ga <sub>0.92</sub> As	1%
940nm	In <sub>0.10</sub> Ga <sub>0.90</sub> As	1.2%
980nm	In <sub>0.12</sub> Ga <sub>0.88</sub> As	1.3%
1060nm	In <sub>0.15</sub> Ga <sub>0.85</sub> As	1.5%

The current at which the gain satisfy the lasing condition is known as the threshold current of laser  $I_{th}$ . The laser output power equation is [16]:

$$P_{out} = \zeta \frac{hv}{q} (I_t - I_{th})$$

Where,  $\zeta$  is modified coefficient (indicates that the only the generated photons can contribute to the output power.)

$h$  -Plank constant

$v$  -Laser frequency

$q$  -Electron charge

$I_{th}$  -Current threshold.

## 2.2 Photovoltaic Cells

Photovoltaic (PV) cells converts the solar energy into the electricity. This process is known as photovoltaic effect. Basically, the PV cell is made of a semiconductor material which converts incoming photons into electric current [17].



### 2.2.1 Layers of PV cell

PV cell made of two distinctive material which is responsible for generating electric current. On the other side of the layer is conducting material which collects the current. The conducting material covers the back side and shaded part of the PV cell as front area is needed for illumination. Another layer which is anti-reflective coating used on the front side. As PV cell's surface is naturally reflective and contribute to a significant amount of energy loss. Therefore, to harvest maximum energy anti-reflective coating is used on the front side [17]. A layers of PV cell is shown in Figure 12.

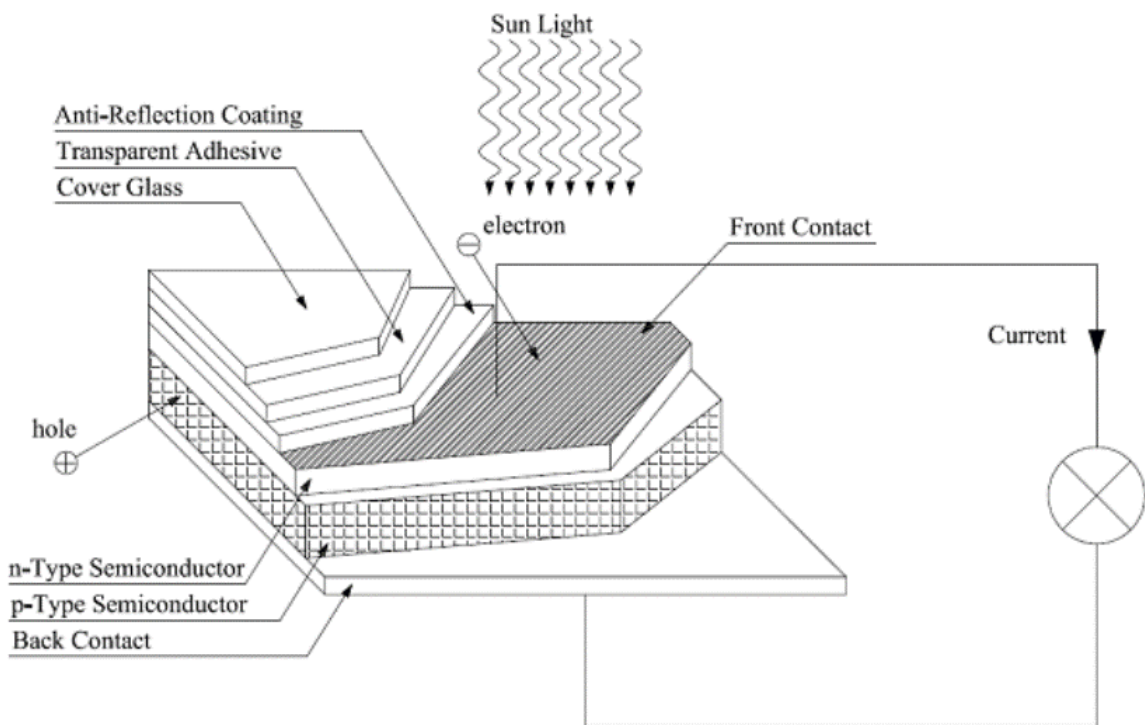


Figure 12: Layers in PV cell [18]

### 2.2.2 Photovoltaic effect

PV cells contains two different types material, n-type and p-type. Together this material forms a p-n junction. The n-type materials contain electrons and p-type contains holes. When we combine these two materials the electrons move to the p-type and holes moves to the opposite side and creates an electric field. This field cause the negatively charged particle to move in one direction and positively charged particle into the other direction.

Light contains a photon, when the suitable wavelength of light is applied to the PV cell the photon transferred their energy to electrons. These excited electrons then transition from the valence band to conduction band and moves freely through the materials. This flow of electrons creates an electric current [17]. Basic operation of PV cell is shown in Figure 13.

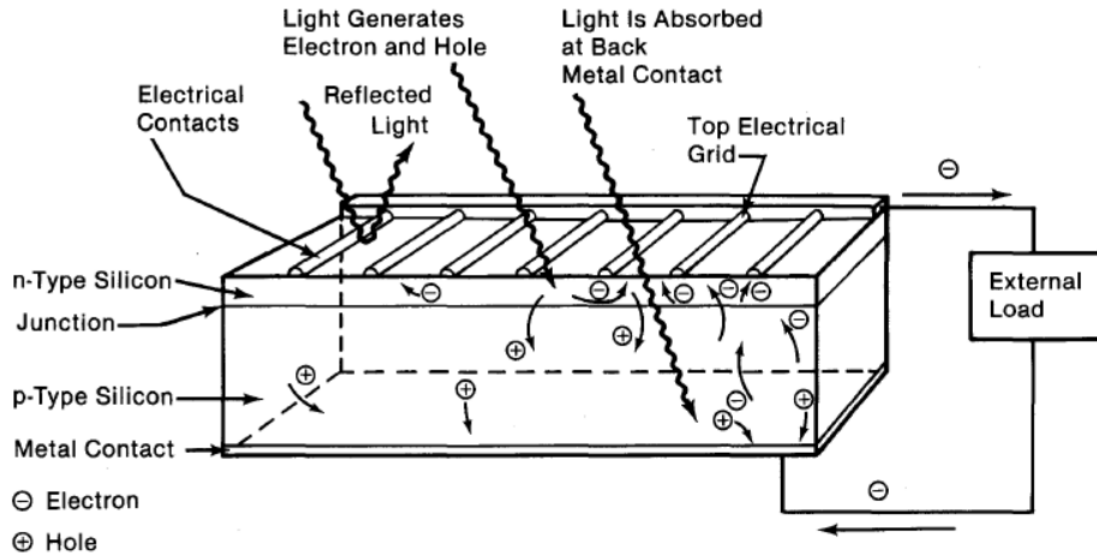


Figure 13: PV cell [19]

A PV cell's efficiency depends on its design and the material used. Every material required different band gap energy to put the electrons from the valence band into a conduction band. For example, Silicon required 1.12 eV to generate free electrons. If photon energy is less than the band gap energy, then photons get absorbed into the material. If photon energy is higher than the band gap energy, then it generates heat. Sunlight contains wide spectrum with different energy, as a result the efficiency of PV cell is not good [17].

PV cell can be made of different materials. The most common material Silicon (Si), but others include Gallium Arsenide (GaAs), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). Solar cells can be constructed using brittle crystalline (Si, GaAs) or as flexible thin-film cells (Si, CdTe, CIGS). The crystalline PV cell can be divided into monocrystalline PV cell and polycrystalline PV cell. In addition, PV cells can be further divided based on the junction: single and multi-junction [17].

## 2.2.3 Characteristics of PV cell

### 2.2.3.1 I-V characteristics

PV cell's I-V characteristics will give a detailed description of cell's ability and efficiency. It is the graphical representation of the electrical parameters of PV cell. It can be measured by applying constant light and temperature with variable resistive load from short circuit to open circuit [8].

### 2.2.3.2 Maximum power output

The product of voltage and current at any point on the curve describes the output power of the cell. The point on where we get maximum output is Pmax and Vmax and Imax are corresponding maximum voltage and current [8].

### 2.2.3.3 Fill Factor

The fill factor shows squareness of the curve. It is the ratio of the maximum voltage and current to the open circuit voltage and current [8].

$$\text{Fill factor} = \frac{V_m I_m}{V_{oc} I_{oc}} \%$$

### 2.2.3.4 Efficiency

PV efficiency is the ratio of the Converted energy to the incident energy on the cell [8].

$$\eta = \frac{\text{Converted energy}}{\text{Incident energy}} \%$$

### 3 Design and implementation

#### 3.1 Enabling Technologies

##### 3.1.1 Selection of wavelength

Atmospheric gases can absorb laser energy at a given wavelength, thereby reducing its efficiency. Therefore, it is necessary to find the range of wavelength which allows the free transmission in the atmosphere with minimal energy absorption. Atmospheric data transmission, shows that there is a range between 780nm to 1100nm which is ideal for wireless power transfer to get the required output power to the receiver end [12].

##### 3.1.2 Selection of Laser Source

There are various types of laser sources available, all of which have their own characteristics and capabilities. For LPT (Laser Power Transfer) the available laser technologies shown in Table 1. Output power of PV cells depends on the laser intensity ( $W/m^2$ ). Therefore, it is a necessary factor which can be obtained from the laser flux (see equation) [13].

Table 4 Available laser technology [7]

Laser type	Wavelength $\lambda$ (nm)	Efficiency $n$ (%)	Radiance ( $W/m^2$ -sr)
Diode laser 10 kW	850	50	$1 \times 10^{10}$
Thin disk laser 25 kW	1060	25	$2.4 \times 10^{15}$
Fiber laser 10 kW	1060	25	$4 \times 10^{13}$
Fiber laser 20kW	1060	25	$1.4 \times 10^{13}$

$$\phi = \frac{R * A * n_{trans}}{L^2}$$

Here,

$\phi$  = Laser flux

R= Radiance (Power per unit area per steradian) ( $W/m^2$  -sr)

A=Area of the beam source ( $m^2$ )

$L$ =Transmission distance (m)

$n_{trans}$ = laser transmission efficiency in atmosphere (%)

Solid state lasers such as a thin disk and fiber have the advantage of good beam quality and high-power transfer capabilities over long distance, but their efficiency is low [8]. On the other hand, high power diode lasers are not good for long range, but they are more efficient, compact and inexpensive. This project deals with short ranges.

For EV charging, the distance between the laser source and the PV panel is assumed to be less than 2-3 meters making a laser diode ideal for this application [12]. Since a laser produces a coherent beam there is a very low divergence over such a small distance. In case of laser beam divergence, it can be controlled by beam expander, a device containing beam expander optics which can control the beam divergence. Beam divergence can be measured only in the practical application as it requires to measure beam spot size and its height from the ground at the receiving and origin [12].

### **3.1.3 Selection of photovoltaic cell**

To generate an electricity from the PV, a photon's energy must be greater than the bandwidth of the PV material. There are many types of photovoltaic cells available in the market that can provide the good efficiency.

Spectral response of different PV material for a various wavelength can be seen in Figure 14, PV cells like Ga-As and Si can give the highest efficiency when it's illuminated by monochromatic light at wavelength between 800nm-950nm [12, 20].

The spectral response of Ga-As can give the highest efficiency between 810nm-850nm and for Si this range is 900nm-950nm. However, it appears from the Figure 14 that the atmospheric absorption is very high for the region of 900nm to 1000nm [12]. So, Si wouldn't be the best choice as a PV cell for this method, but for the wavelength 840nm-890nm disturbance is very less and Ga-As PV cell gives the highest output in this range. Spectral transmission data shows that there is another range available beyond 1000nm which have low disturbance and it will be useful for laser transmission, but the problem with this range is that the associated PV receiver with longer wavelength such as InGaAs,

InGaP, and CIS (copper indium selenide) have a low power withstand capacity [13]. Therefore, the optimized Ga-As cell has been chosen because it can withstand much higher power intensities, greater than 1000 sun [21]. There are list of available PV materials and their efficiency associated with their laser intensity is shown in the Table 5 [13].

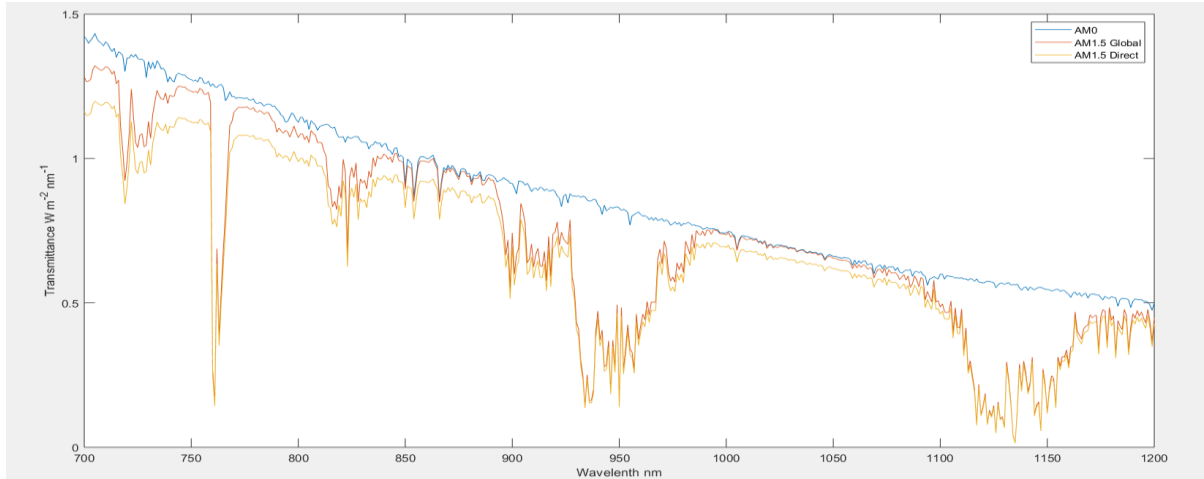


Figure 14: Atmospheric transmission spectrum [21]

From Table 5 we can see that Ga-AS can give the highest efficiency with a high laser intensity. As the laser intensity increases efficiency decreases gradually. The other noticeable fact is that other PV cells can't operate an intensity as high as that of Ga-As.

Table 5 Various PV cell's efficiency for laser illumination [13]

PV material	Ga-As		Si		InGaAs / InP	InGaP	CIS
Wavelength(nm)	810		950		>1000		
$n_{trans}$ (%)	53.4	60	27.7	28	40.6	40	19.7
Laser intensity (kW/m <sup>2</sup> )	430	110	10	110	2.37	2.6	10

To charge high-powered batteries associated with electric vehicles, we need a high-power laser diode and efficient PV cells that can withstand high intensity power. The available types of laser matched with their PV cells shown in Table 6 [13].

Another factor which needs to be considered is to decide a PV cell with how many junctions will be required for this operation. There are two types of PV cell junction: single and multi-junction. A single junction PV cell responds to only on specific wavelength range, while multi junction PV cell comprise more than one junction; these junctions responds on a specific range of wavelength [22]. Here, a single junction PV cell is used rather than multi junction since multi junction cells cannot be illuminated fully using a single laser wavelength. For efficient operation of multi junction cells all the junctions need to illuminate by source light. In multi junction cells, if one of the junctions was not illuminated, most likely it will not provide output. Therefore, the single junction PV cell chosen over multi junction cell [20].

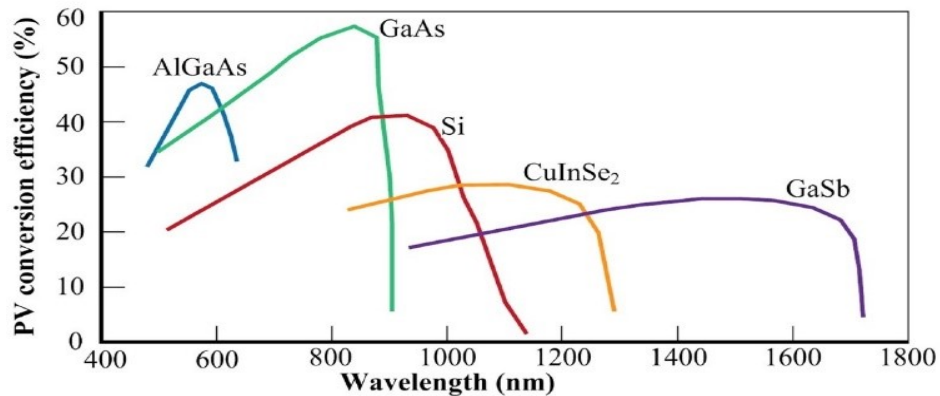


Figure 15: PV materials and their response for various wavelength [13]

Furthermore, PV cells used in LPT technology are optimized Ga-As with low antireflection coating from 0% to less than 2% at 810nm wavelength [12, 21].

Table 6 PV cell's matched with their laser source [13]

Laser type	Wavelength (nm)	Laser efficiency (%)	Types of PV cell	PV cell efficiency (%)	Possible transmission distance
Diode laser (10kW)	850	50	Ga-As	>50	<10km
Fiber laser (20kW)	1060	25	CIS	17	<100km

### 3.2 Atmospheric attenuation for laser transmission

When a laser beam pass through the air the power loss occurs during transmission which is known as laser power transmission attenuation. The attenuation depends on the air quality of the atmosphere [16].

However, in this case distance (the distance between receiver and transmitter is 1m) is short therefore the power attenuation is very less. (a negligible)

For long distance the laser attenuation can be calculated using below equation (For simplicity laser diameter is assumed as a constant).

Laser transmission efficiency  $n_{lt}$  can be given by using this equation [16],

$$n_{lt} = \frac{P_r}{P_l} = e^{-\alpha d}$$

Laser transmission efficiency over the distance is given in Figure 16.

Where,  $P_r$  is the received laser power at the PV cells.

$P_l$  is the transmitted laser power from the source.

$\alpha$  is the laser attenuation

$d$  is the distance.

$\alpha$  can be described as [16],

$$\alpha = \frac{\sigma}{k} \left( \frac{\lambda}{x} \right)^{-\rho}$$

Where,  $\sigma$  and  $x$  are two constants, there values are given in Table 7

$k$  is the visibility and  $\lambda$  is the wavelength

$\rho$  is the size distribution of scattering particle and it's depends on the visibility.



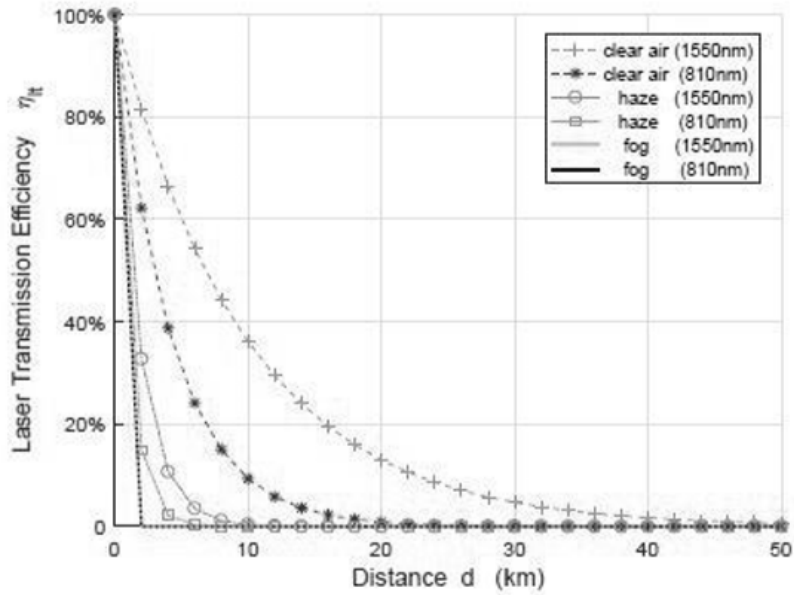


Figure 16: Laser transmission efficiency vs distance [17]

Laser power transmission efficiency decreases exponentially with increases in distance  $d$ . Also, for same laser wavelength when visibility  $k$  decreases laser power attenuation increases. It is seen that the laser attenuation for short wavelength (810nm) is more than the longer wavelength (1550nm) in clear air and haze. However, in fog the laser power attenuation is same for both wavelength which shows that the attenuation doesn't depends on wavelength for fog like harsh weather condition. The Laser power attenuation coefficient depends on various weather condition like clear air, haze and fog [16]. Laser transmission parameters for various condition is shown in Table 7.

Table 7 Laser transmission parameter [16]

Parameter	Clear air	Haze	Fog
$\sigma$	-	3.92	-
$x$	-	550nm	-
$k$	10 km	3 km	0.4 km
$\rho$	1.3	$0.16 k + 0.34$	0

The Table 8 shows the attenuation for various weather condition and two different wavelengths [23].

Table 8 Transmission attenuation for various weather condition [23]

Visibility (km)	dB/km (785nm)	dB/km (1550nm)	Weather
0.05	340	340	Fog
0.2	85	85	
0.5	34	34	
1	14	10	
2	7	4	Haze
4	3	2	
10	1	0.4	Clear Air
23	0.5	0.2	

### 3.3 Laser and PV implementation

A simulative method is used to determine the output of this project. In this chapter semiconductor laser is implemented using MATLAB and the PV cell is implemented in MATLAB Simulink environment.

#### 3.3.1 Laser Implementation

Basic laser implementation can be described by this flow chart. In this operation a certain amount of current is applied to the laser module which excites the carrier from lower level into higher level. As explained earlier, if these excited carriers go to the lower state then they emit photons. Here, these photons are generated by two process stimulated emission and spontaneous emission which creates laser beam. During this process laser loses some amount of power in the cavity and this loss is known as cavity loss [24].

A single laser diode is implemented here. Actual required data for this experimental data is obtained from the DILAS laser and the data sheet is given in Table 9 [25, 26] The figure represents the actual output power the laser diode. Here, only single laser diode is implemented therefore to get the required power. This laser diode can be used in multiple bars. For example, 8 to 16 bars. So, the generated power is multiplied by the number of bars. The details are given in Table 9.

Table 9 Optical and electrical parameters from the data sheet [26]

Parameters	Value	Units
Center Wavelength range	808	Nm
Center Wavelength range tolerance	$\pm 3$	Nm
Bar to Bar spacing	400	$\mu\text{m}$
QCW Output per bar	200	W
QCW output power (Total)	3200	W
Operating current(I)	200	A
Threshold current ( $I_{th}$ )	30	A
Recommended operating temperature	25	$^{\circ}\text{C}$
Operating temperature range	20-35	$^{\circ}\text{C}$
Divergence	3.4	mrad
Wavelength temperature coefficient	0.27	nm / $^{\circ}\text{C}$
Power conversion efficiency	55	%
Laser beam size at aperture	10.8	mm

A required parameter for the implementation of laser in MATLAB is obtained from the Table 10 below. First, laser volume and time span required to achieve the relaxation time are initialized. A semiconductor diode laser is simulated therefore the simulation time span is taken 2.5 ns [24].

These equations are used for implementation of carrier density, photon density and output power [27].

Carrier density,

$$\frac{dN}{dt} = \frac{I}{e} - \frac{N}{t_e} - \left( \frac{\gamma c g_0 \left( \frac{N}{V - N_0} \right)}{u_g} \right) s$$

Photon density,

$$\frac{ds}{dt} = \left( \frac{\gamma c g_0 \left( \frac{N}{V - N_0} \right)}{u_g} \right) s - \frac{s}{t_p} + \frac{\beta B N^2}{V}$$

Output power,

$$P = \frac{\gamma c (am) S}{2\lambda}$$

Here,  $\left( \frac{\gamma c g_0 \left( \frac{N}{V - N_0} \right)}{u_g} \right) s$  is a stimulated emission and absorption.

$\frac{N}{t_e}$  is a recombination of carrier.

$\frac{I}{e}$  is an operating current.

$\frac{\beta B N^2}{V}$  is a spontaneous emission.

$\frac{s}{t_p}$  is a cavity loss.

Then these differential equations can be solved by the ODE45 solver in MATLAB [28]. An operating current of 200 A is used for this test. Other required parameters for the laser operation are obtained from the Table 9. A solver solves these differential equations and provides the output for carrier density, photon density with respect to time and output power using the following steps:

1. Obtain laser volume and time span values from Table 10.
2. Call ODE45 solver with rate equations and laser parameter to get carrier density, photon density and power output.
3. Display the results.

The graph for the carrier density and photon density and output power is shown in section 4.1.

Table 10 Laser parameters [26]

Parameter	Symbol	Typical values	Unit
Carrier density output	N	$2.75 \times 10^{11}$	$\text{m}^{-3}$
Photon density output	S	$4.8 \times 10^9$	$\text{m}^{-3}$
Electron charge	Q	$1.602 \times 10^{19}$	C
Thickness of active region of laser	D	0.1	$\mu\text{m}$
Width of laser stripe	W	10	$\mu\text{m}$
Length of laser cavity	L	500	$\mu\text{m}$
Radioactive recombination factor	B	$10 \times 10^{-16}$	$\text{m}^3/\text{s}$
Carrier lifetime	$\tau_n$	$2.2 \times 10^{-9}$	s
Photon lifetime	$\tau_p$	$3 \times 10^{-12}$	s
Speed of light	C	$3 \times 10^8$	m/s
Plank constant	H	$6.626 \times 10^{-34}$	Js
Resonator loss	am	$45 \times 10^2$	$\text{m}^{-1}$
Group refractive index	$u_g$	4	
Gain coefficient	G	0.44	
Beta	$\beta$	$1 \times 10^{-3}$	
Lasing Wavelength	$\lambda$	810	nm
Lasing frequency	$\nu$	$3.7 \times 10^{14}$	Hz
Time span	t	2.5	ns
Carrier density at transparency	$N_0$	$1 \times 10^{24}$	$\text{m}^{-3}$

### 3.3.2 PV cell implementation

As mentioned above, to generate electricity from the PV cell, the photon energy must be greater than the band gap energy of the material. A wavelength is inversely proportional to the bandgap energy of the material. The wavelength of a PV material can be found using equation [29]. This technique is associated with high temperature therefore, the temperature effect on the band gap of that material. The band gap of the material depends on the temperature and it can be found using Varshni's equation [29]:

$$\lambda = \frac{1240}{E_g}$$
$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta}$$

For a Ga-As,

$\lambda$  = Wavelength of the material = 810nm

$E_g(T)$  = Band gap energy at particular temperature (eV)

$E_g(0)$  = Band gap energy at room temperature (298K) = 1.527 eV

Coefficient  $\alpha = 5.5$  and  $\beta = 225$

Generally, a PV cell is made to respond efficiently to sunlight, but the monochromatic light has single wavelength therefore there is a need to use specialized PV cell to respond on the specific wavelength. Shan and Qi described optimized Ga-As required for laser power beaming [21]. This single junction optimized Ga-As PV converter contains n-GaAs substrate ( $5 \times 10^{18} \text{ cm}^{-3}$ , 350  $\mu\text{m}$ ), n-GaAs buffer ( $5 \times 10^{18} \text{ cm}^{-3}$ , 1.0  $\mu\text{m}$ ), n-AlGaAs BSF (Back Surface Field) ( $5 \times 10^{18} \text{ cm}^{-3}$ , 0.05  $\mu\text{m}$ ), n-GaAs base ( $1 \times 10^{17} \text{ cm}^{-3}$ , 3.5  $\mu\text{m}$ ), p-GaAs emitter ( $2 \times 10^{18} \text{ cm}^{-3}$ , 0.5  $\mu\text{m}$ ), p-GaInP window ( $5 \times 10^{18} \text{ cm}^{-3}$ , 0.05  $\mu\text{m}$ ) and p++-GaAs cap layer ( $5 \times 10^{19} \text{ cm}^{-3}$ , 0.5  $\mu\text{m}$ ) [21]. This is dimension for the smaller size PV cell but according to manufacturer it can be available in required size upon request.

Furthermore, this cell is coated with the antireflective material  $\text{TiO}_2$  (61nm) and  $\text{SiO}_2$  (94nm) [21]. This model provides 0% reflectance with double layer of coating on the surface this is good for the safety of human and surrounded equipment. This Ga-As cell

has a photosensitive surface area of  $10 \times 10\text{mm}^2$  [21]. Apart from this cell, a larger size PV cell compatible with laser power can also be provided by the Spectro lab and Boeing PV cell.

A simulation of Ga-As single junction PV cell can be formed using these equations. The PV output current can be described using equation where,  $I_{ph}$  is light source current,  $I_s$  is reverse saturation current,  $R_s$  is series resistance,  $R_{sh}$  is shunt resistance,  $k$  Boltzmann constant,  $q$  carrier charge,  $T$  temperature,  $E_g$  band gap energy of the PV cell and  $n$  ideality factor. Ideality factor, series resistance and shunt resistance value obtained from this paper [30].

A detailed description of the parameters used for a simulation of the PV cell is given in Table 11. An interactive method is chosen over the other method because the numerical data to be entered easily and provides the ideal condition for the test environment. Below equations are being used to get the output current ( $I$ ), reverse saturation current ( $I_s$ ) and photovoltaic current respectively. Simulation for this block is given in Figure 17 below.

A data required for this simulation is obtained from this paper [21]. As there is no practical data available for the PV cell the average PV cell size is used for the calculation which is  $25\text{ cm}^2$ . The total area required for the PV panel is  $1.5 \times 10^4\text{ cm}^2$  which is explained in detail in 4.3.1.

Output current,

$$I = I_{ph} - I_0 \left( \exp \frac{q(v + IR_s)}{nKT} - 1 \right) - \frac{v + IR_s}{R_{sh}}$$

Diode current,

$$I_d = I_0 \left( \exp \frac{qv_d}{nKT} - 1 \right)$$

Reverse saturation current,

$$I_s = \frac{I_{ph} - I - (v + IR_s)/R_{sh}}{\exp(q(v + IR_s)/(nKT)) - 1}$$

Reverse saturation current is function of temperature in this test it is simulated using this equation,

$$I_s = I_s \left( \frac{T}{T_n} \right)^3 \exp \left( \frac{T}{T_n} - 1 \right) \frac{E_g}{N \cdot v_t}$$

Photovoltaic current,

$$I_{ph} = I_{sc} + k_i(T - 298) \frac{G}{1000}$$

Table 11 PV cell parameters [21]

Symbol	Parameters	Value
I <sub>ph</sub>	The photocurrent (For practical condition I <sub>ph</sub> ≈ I <sub>sc</sub> )	1.1
I <sub>o</sub>	The reverse saturation current	9.8x10 <sup>-18</sup>
n	The identity factor of diode	1.13
K	Boltzmann constant (J/K)	1.380x10 <sup>-23</sup>
Q	Charge of electron(C)	1.602x10 <sup>-19</sup>
T	p-n junction temperature (in ideal condition it is 25 °C)	25 °C
K <sub>i</sub>	Short circuit current/temperature coefficient	0.000025
G	Actual irradiation (W/cm <sup>2</sup> ) (50 kW/m <sup>2</sup> )	50000
G <sub>stc</sub>	Nominal irradiation (W/m <sup>2</sup> )	1000
N <sub>s</sub>	No of cells connected in series	70
N <sub>p</sub>	No of cells connected in parallel	70
E <sub>g</sub>	Band gap energy	1.4
I <sub>sc</sub>	Short circuit current	1.1
FF	Fill Factor	0.84 or 0.88
R <sub>s</sub>	Series resistance	16 Ω
R <sub>p</sub>	Parallel Resistance	497 Ω



This is the basic simulation model created for studying the Ga-As PV converter. By changing the band gap energy for different material this can be used for other materials as well. The advantage of this model is that to achieve desired voltage we can vary the number of cells connected in series. On the other hand, to achieve the desired current we can vary the number cells connected in parallel. This simulation is implanted in MATLAB Simulink but to get the desired graph it is transferred to the MATLAB workspace. The building blocks contain the PV cell's equation and their value is obtained from Table 11.

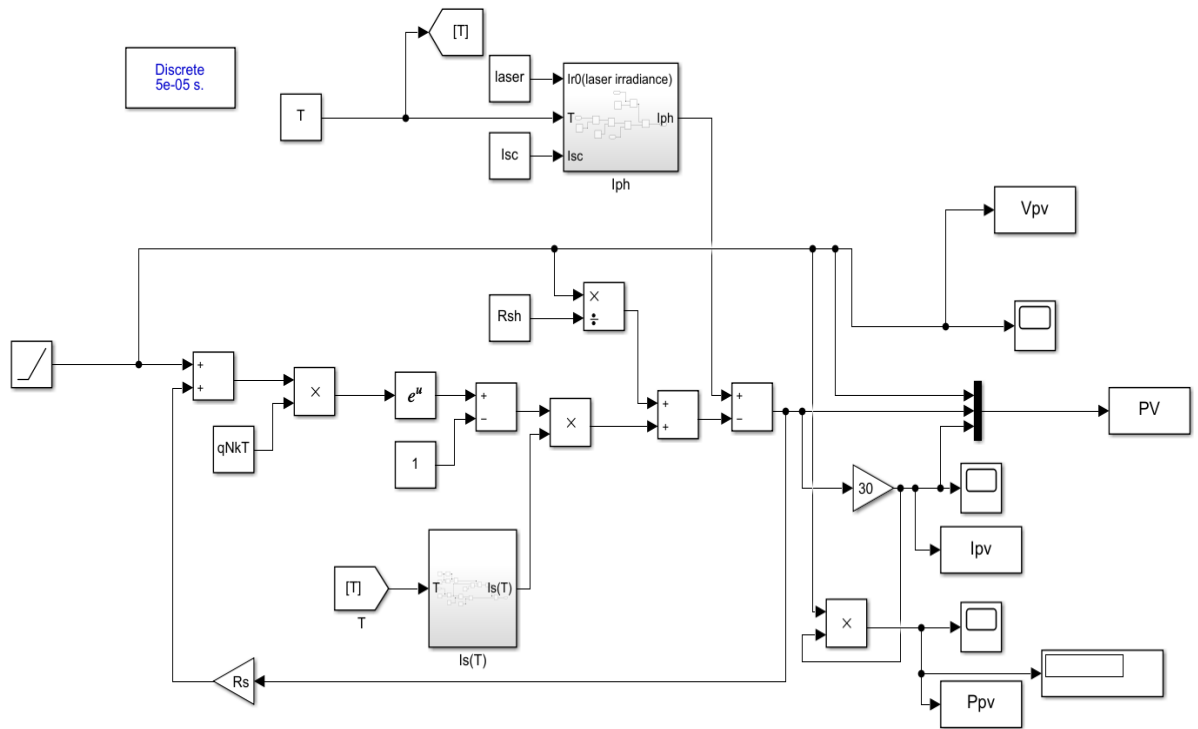


Figure 17: PV cell

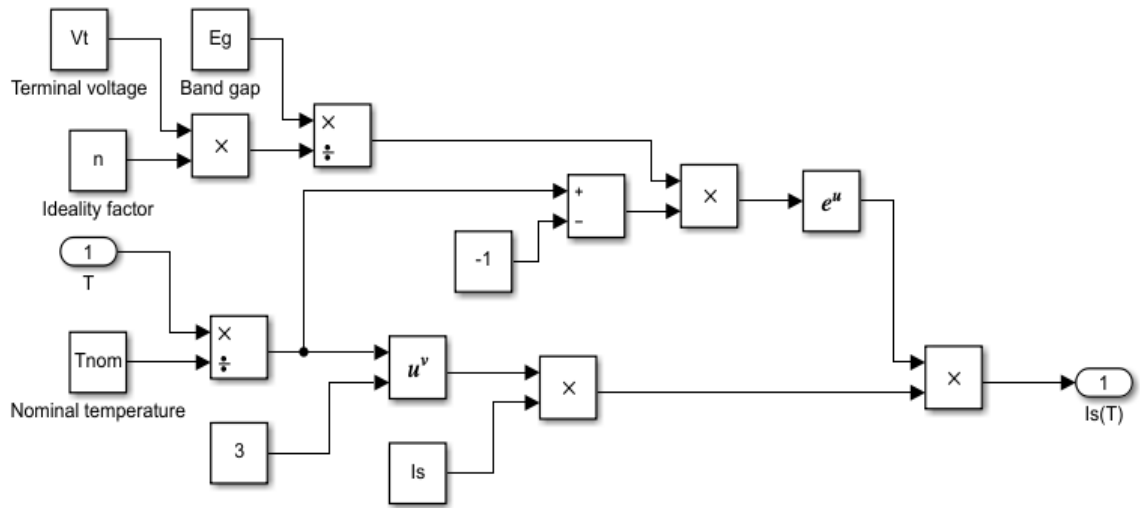


Figure 18: Reverse saturation current

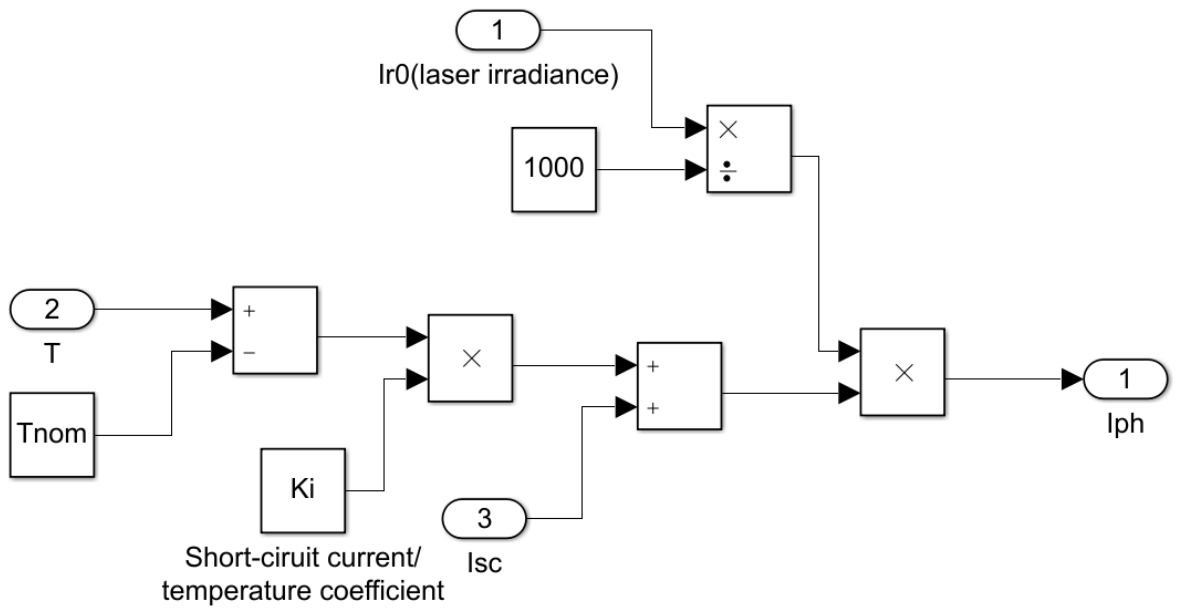


Figure 19: Laser generated photon current

## 4 Results and Discussion

The semiconductor lasers used in this thesis are class 4 laser which is dangerous for the human skin and eye. Therefore, during a practical implementation, particular care must be taken to prevent direct viewing of laser during its operation. More details are provided in Appendix A: Laser Hazards and safety evaluation.

### 4.1 Laser output

Figure 20 shows the carrier density in a laser cavity. As current is injected, the carrier is pumped into the higher state which can be seen in the Figure 20. Here we created volume of laser to see its effect on the final output.

Figure 21 describes the photon density in laser cavity which is responsible for the coherent beam and optical power. Figure 22 show the optical output power. In Figure 21 and Figure 22 it creates spikes at the start. These spikes are created because of the pumping process which was initiated by injecting a current. After the spike laser goes into the relaxation time and achieve the steady state. In steady state the photon density is  $4.8 \times 10^9$ , and the output optical power is 200W. This output data is only for one bar of laser. One laser module contains 16 bar which will gives the output 3.2kW [26]. Here, we are connecting 24 modules of laser source which give the laser power of 77kW.

From the results it is clear that if we apply more current to the module, we will get higher output but in practical condition output is dependent on the laser's material. Here we need to generate an 810nm wavelength of optical power therefore the data sheet we used for implementation of laser is (GaAsP or AlInGaAs laser) for 810nm wavelength [25].

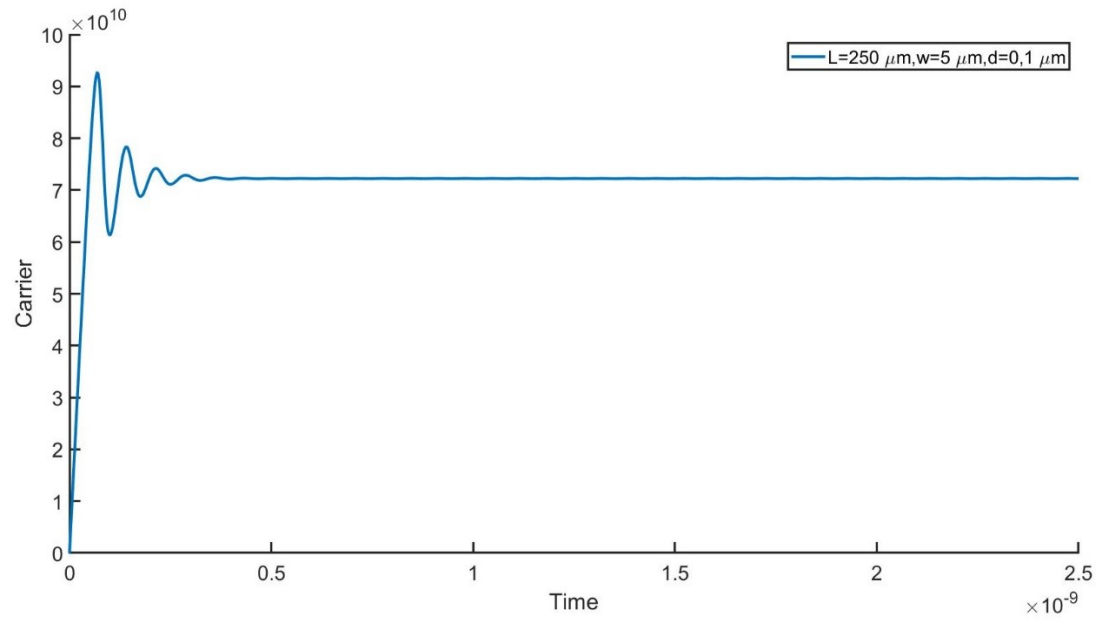


Figure 20: Carrier density

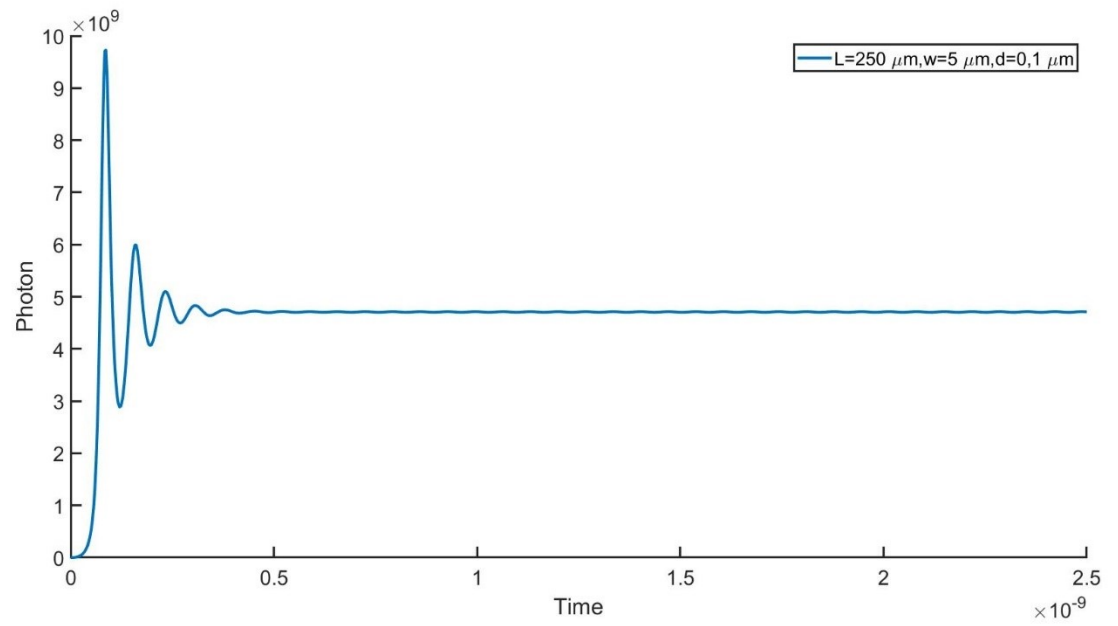


Figure 21: Photon density

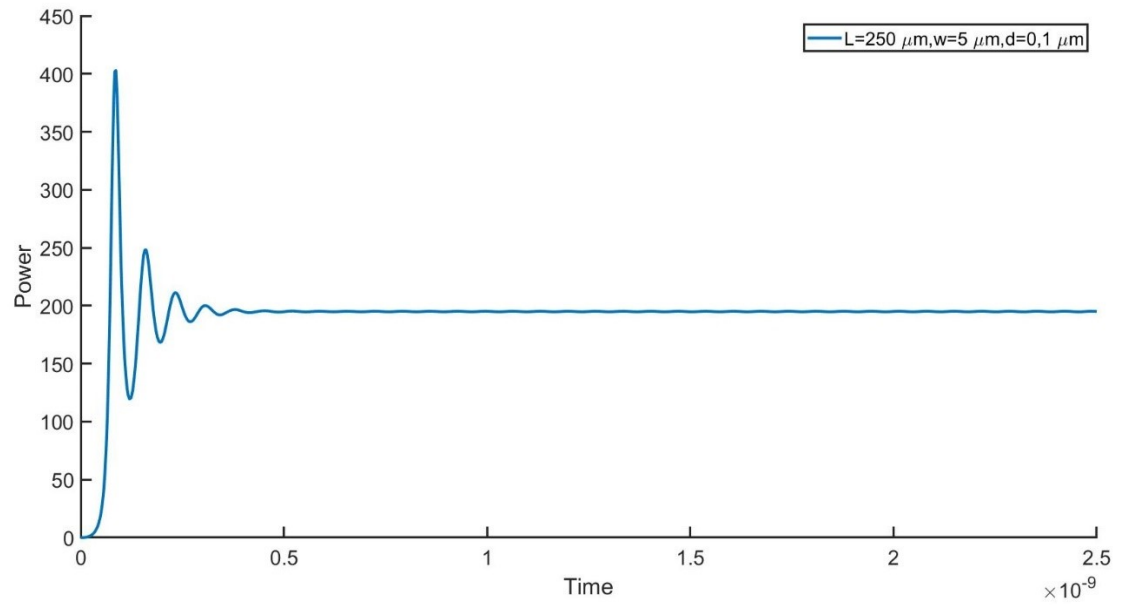


Figure 22: Laser output

#### 4.1.1 Beam distribution

At the receiver end, the arrangement of the PV cells is important to achieve maximum efficiency. As mentioned above, when the number of PV cells connected in series and parallel makes a PV panel. To achieve the maximum efficiency, we connected a greater number of cells in parallel than series. (If more cells are connected in series than in parallel, then the least illumination area will produce less current which will decrease the overall current value in panel [8]). Therefore, we considered connecting more cell in parallel than in series. For this calculation we considered a  $1 \times 1.5 \text{ m}^2$  panel area, less than the area of an average car's undercarriage. MATLAB laser toolbox is the software that provides the analysis and visualization of laser beam properties [31]. It is used here to study the laser beam properties, power intensity and beam profile on the receiver. Using MATLAB laser toolbox, we simulated the laser beam distribution on the PV panel [31]. Here, the beam area is assumed to be the circular.

In a practical setting it can be different and varies according to the manufacturer. A laser can give a uniform illumination and non-uniform illumination according to the beam distribution of that laser source. Laser have different beam distribution but the most

common are top-hat and gauss which is shown in the figures below. Top hat beam can give uniform illumination while gauss beam can give a non-uniform illumination.

#### 4.1.1.1 Top hat Distribution

The aim of this simulation is to reduce the energy waste and improve the PV cells arrangement to achieve high efficiency with minimum PV cells. The simulation provides the power density distribution on the PV panel as well as the cross-sectional distribution of the beam. As shown in Figure 23, a top hat circular beam on the panel covers the panel area edge to edge. If a uniform circular illumination is used, then the corner PV cells are useless and can be removed. Figure 23 represent the power density on the PV panel. The power density for this simulation is  $50.02 \text{ kW/m}^2$  ( $5 \text{ W/cm}^2$ ). Some researchers found that the radial arrangement of PV cells can give a better output than a square arrangement in the case of circular beam shape [8].

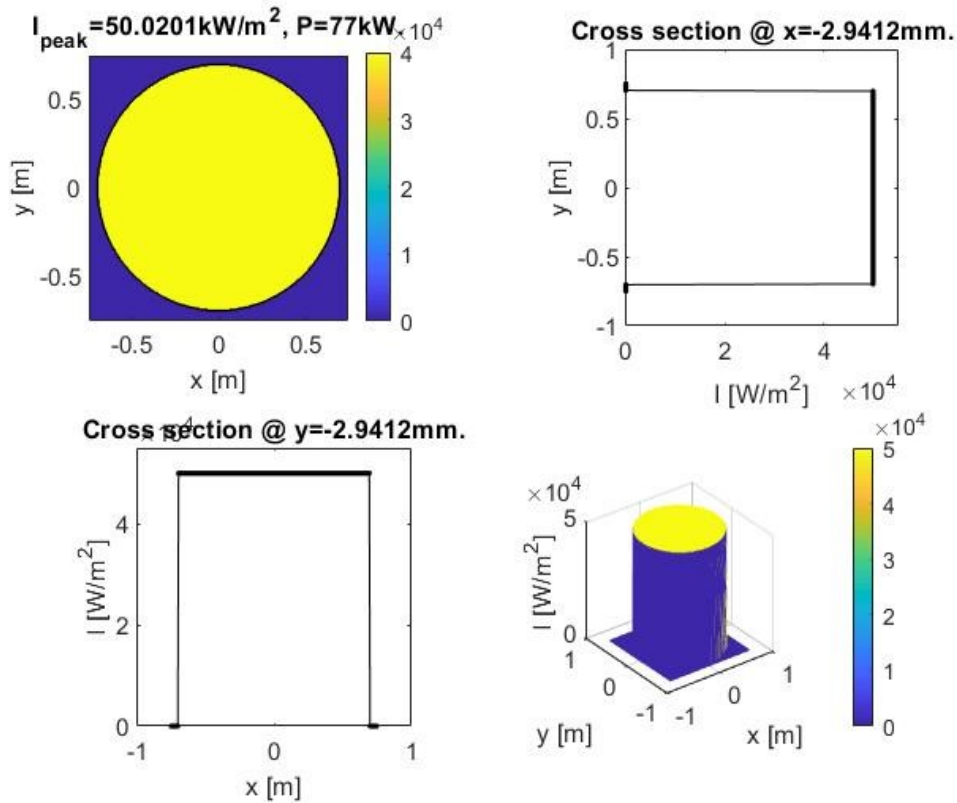


Figure 23: Top hat distribution

In another approach, we increased the beam area (Figure 24). As can be seen, some energy is being wasted on the edge of the PV panel so the total applied energy on the receiver is reduced. The power density on the panel is  $33.923 \text{ kW/m}^2$  for a laser power of  $77 \text{ kW}$ . Therefore, for a top hat beam the PV panel can be designed based on the laser beam shape. So, if we use square shape beam then square shape PV panel can give high efficiency.

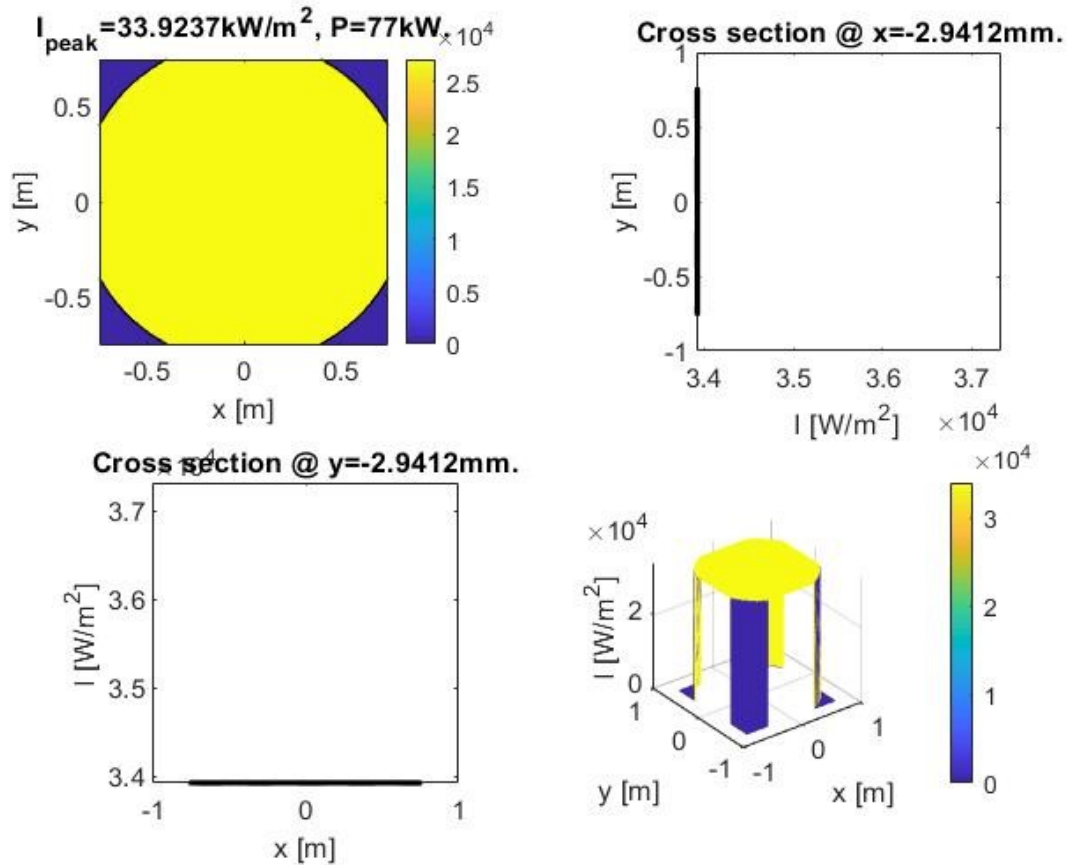


Figure 24: Top hat outside area

#### 4.1.1.2 Gaussian distribution

Gaussian beam distribution gives a non-uniform illumination on the PV panel, with the maximum power at the center of the PV panel (center of the beam), gradually decreasing as the distance from the center increases. In Figure 25, the PV cells in the yellow area will receive maximum power; decreasing towards the edge of the panel. The power at the edge

is only half the power at the center or one third of the maximum, thereby reducing the power received.

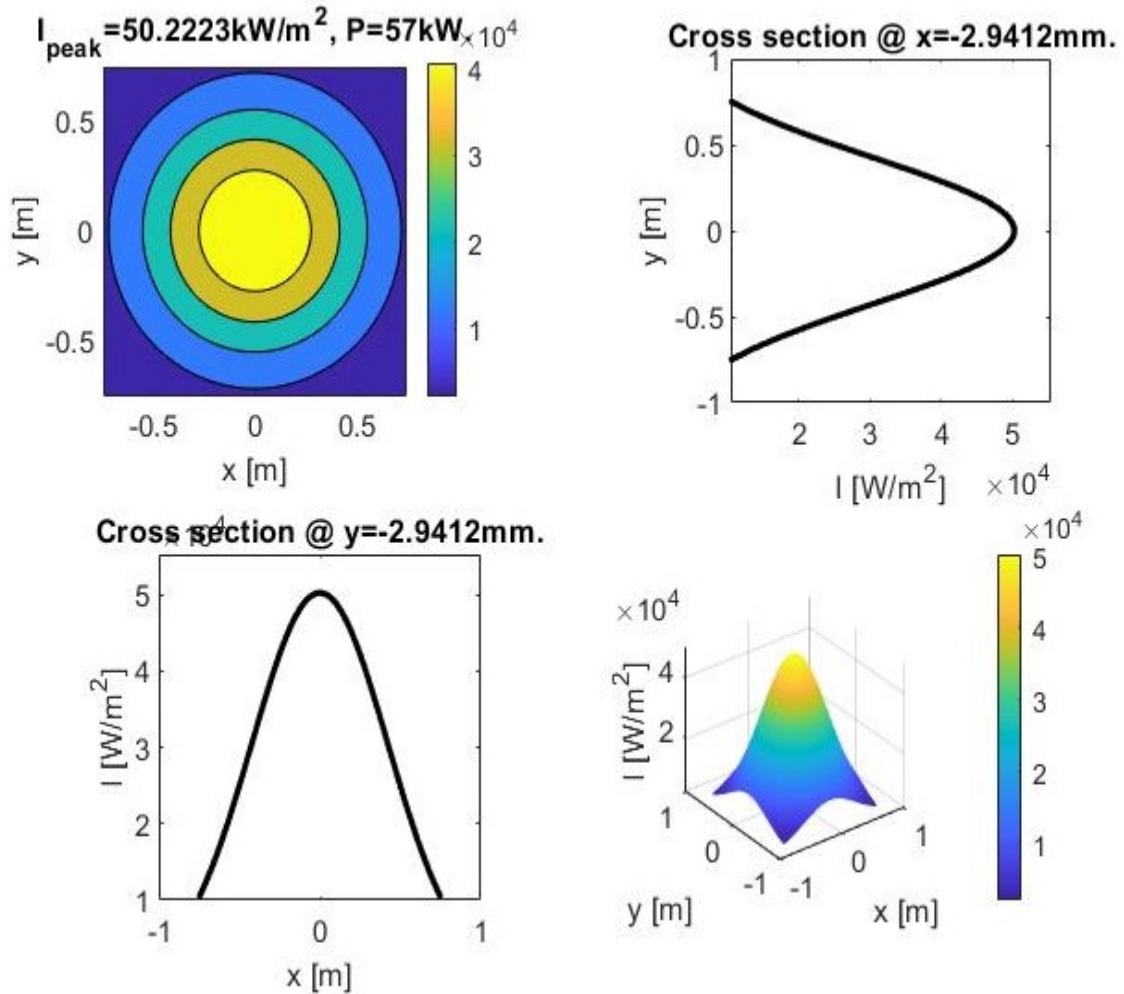


Figure 25: Gaussian distribution

Another approach is to apply a higher power density at the center and get the required power density at the edge, as shown in the Figure 26. However, this has one drawback, if the power density at the center is higher than its acceptable limit (It varies with manufacturer. In this case, it is  $5 \text{ kW/m}^2$ ), then it will increase the overall temperature of the PV panel and reduce the PV panel efficiency.



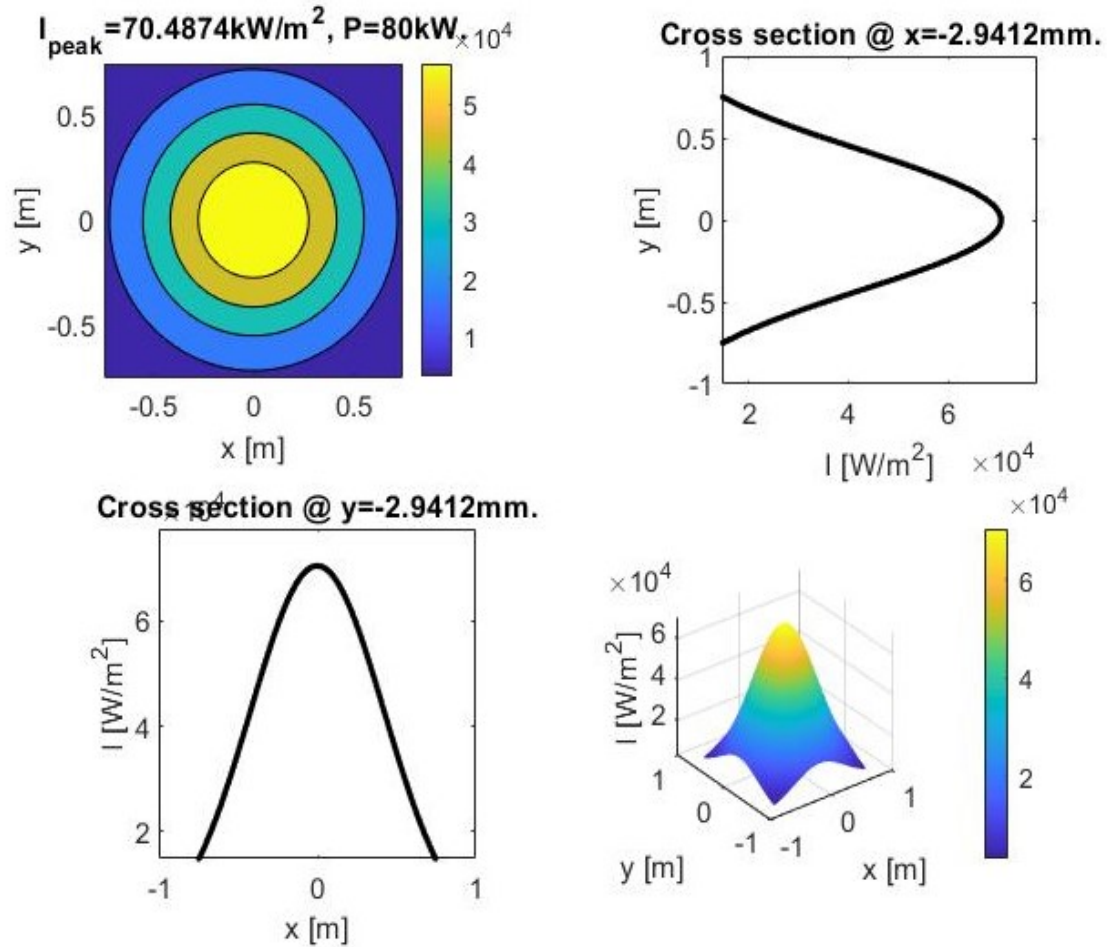


Figure 26: Gaussian high power at the center

These simulations show that the Gauss beam distribution can lead to power loss and create hot spot in some areas. Hot spots can be avoided using a bi-pass diode and there are various methods available to reduce power loss.

Modified PV receiver geometries and array configuration are the least complex and cost-efficient method to reduce power loss, but their efficiency is poor. In a modified PV receiver geometry, a radial orientation of array is proposed [8]. In this orientation, the PV cells are arranged in radial geometry which reflects the Gaussian distribution of the laser beam. In this configuration, a greater number of cells are attached in parallel than the series to reduce the losses [12]. Another complex method is to use a power electronic equalizer which can harvest high energy; however, this is an expensive solution [12].

From these two simulations we can conclude that the top hat distribution can give a uniform illumination so there is minimal loss due to the divergence of the beam which is neglected here because the distance between transmitter and receiver is one meter. On the other hand, Gaussian distribution provides non-uniform illumination and is subject to power losses. To reduce these losses requires different methods which can reduce the efficiency and increase the cost. The above simulations indicate that the top hat beam distribution can give higher efficiency than the Gaussian beam distribution.

## **4.2 PV cell output**

The simulation results provide the PV and IV curves for various input power and temperature. For this simulation, a 77 kW laser irradiance is used as input supply. In practical condition a high amplitude 808nm optical laser power available from DILAS [25, 26, 32].

All the tests shown here are performed under standard test condition. In the first test we applied the different optical power levels to check the effect on efficiency. Figure 27 describes the P-V characteristics for four different input optical powers 77 kW, 60 kW, 50 kW and 40 kW. In this experiment 30 rows of PV cell connected in parallel where each row contain 20 series connected PV cells. More detail can be found in section 4.3.

The results show that for a higher input power we can get a high output power and efficiency. Figure 28 shows the I-V characteristics for the PV cells. A current value decreases as the input power decreases. Until certain limit we can increase the input optical power after that it only creates heat which can decrease the efficiency. These specialized cells can handle much higher power than expected but their limit is  $5\text{W}/\text{cm}^2$  beyond this

limit the efficiency will decrease [21]. Also, when we decrease the input power the efficiency decreases slowly which can be seen in the following graphs and Table 12.

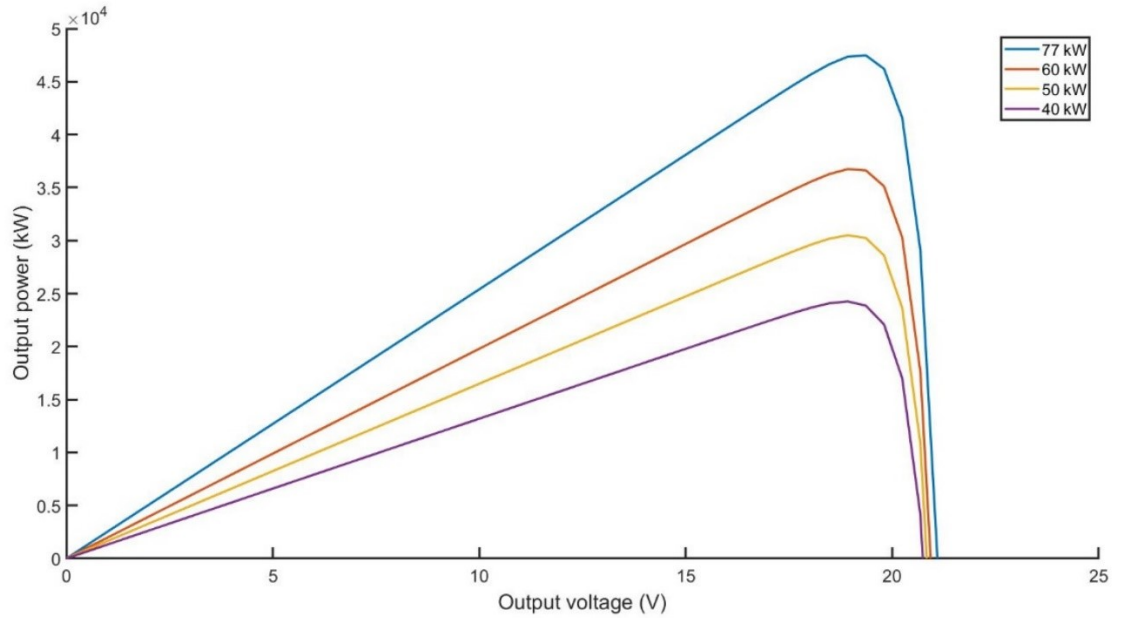


Figure 27: PV curve for various input power

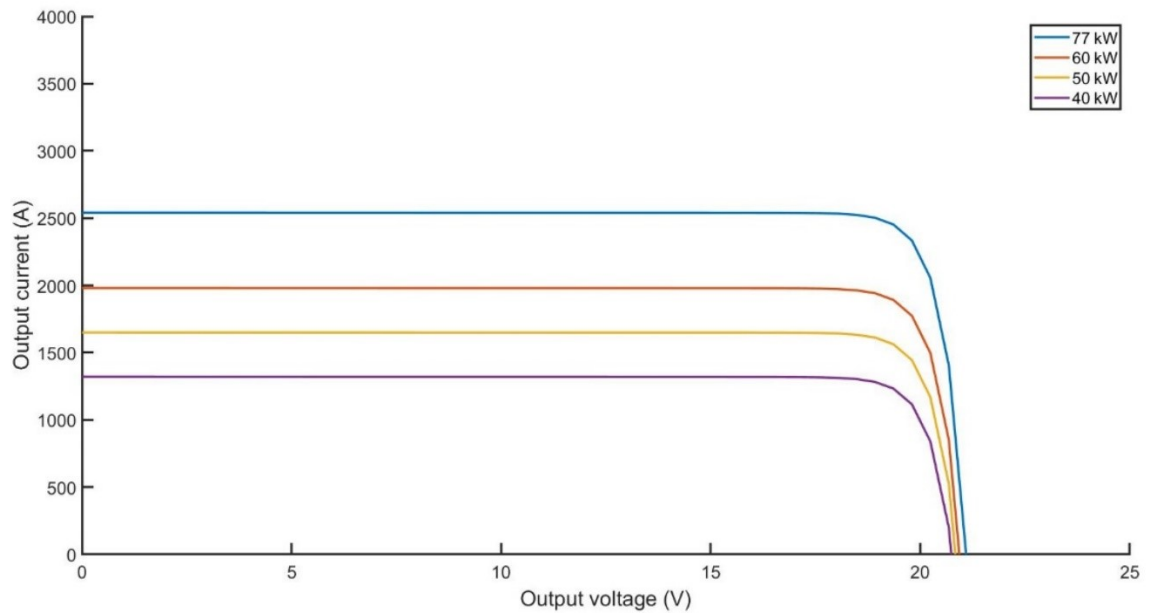


Figure 28: I-V curves for various input power

The output values of the power, voltage, current, and efficiency are given in Table 12.

Table 12 Output values for different optical power

Input power (kW)	Output power (kW)	Output voltage (V)	Output current (A)	Efficiency (%)
77	47.5	19.4	2452	61.7
60	36.7	18.9	1941	61.2
50	30.5	18.9	1612	61.0
40	24.3	18.9	1282	60.6

In second test, a various temperature applied to the PV cell to check its behavior when exposed to higher temperatures. Figure 29 shows the I-V characteristics and Figure 30 gives P-V characteristics for various temperatures. Tests performed for 0°C, 25°C, 50°C, and 75°C with 77kW input power. In practical condition, when a PV cell is exposed to laser optical power, a temperature can quickly rise. Therefore, cooling process is required to keep the temperature of PV cell under its operational limits.

Test results shows that when this converter is exposed to the higher temperature then the output current decreases, but the output voltage increases. A result shows that for 0°C we got a highest efficiency which is difficult to maintain during practical condition. As temperature rose up the output power and efficiency gradually reduce.

The output value of power, voltage, current, and efficiency are given in Table 13.

Table 13 Output values for different temperature

Temperatures (°C)	Output power (kW)	Output voltage (V)	Output current (A)	Efficiency (%)
0	47.6	17.6	2713	61.8
25	47.5	19.4	2452	61.7
50	46.7	20.6	2260	60.6
75	45.0	22.0	2045	58.4

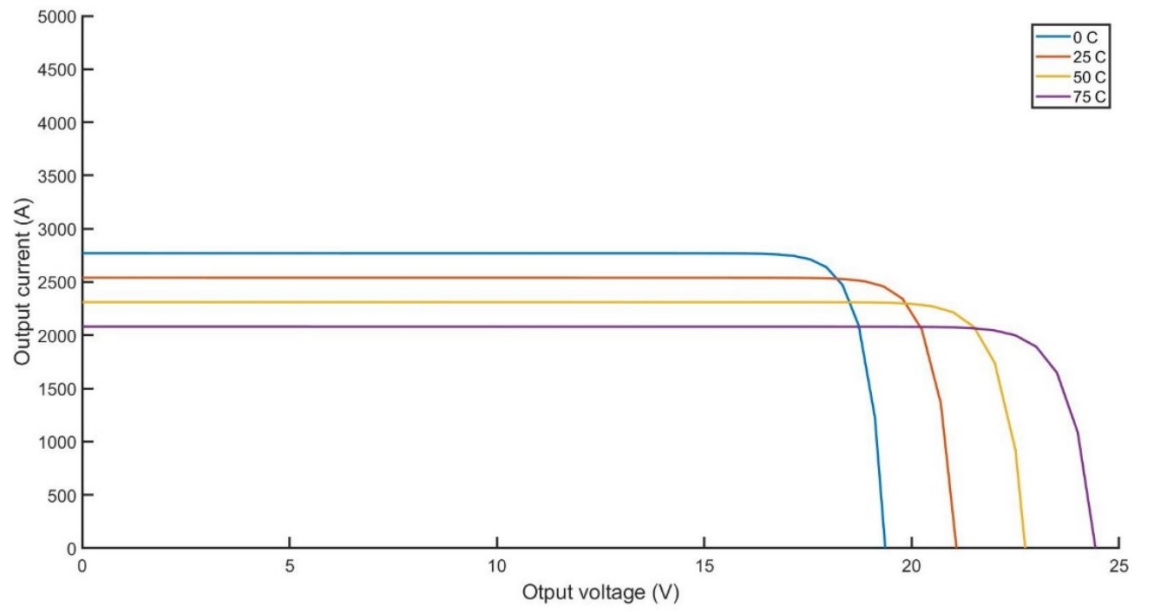


Figure 29: I-V curves for various temperature

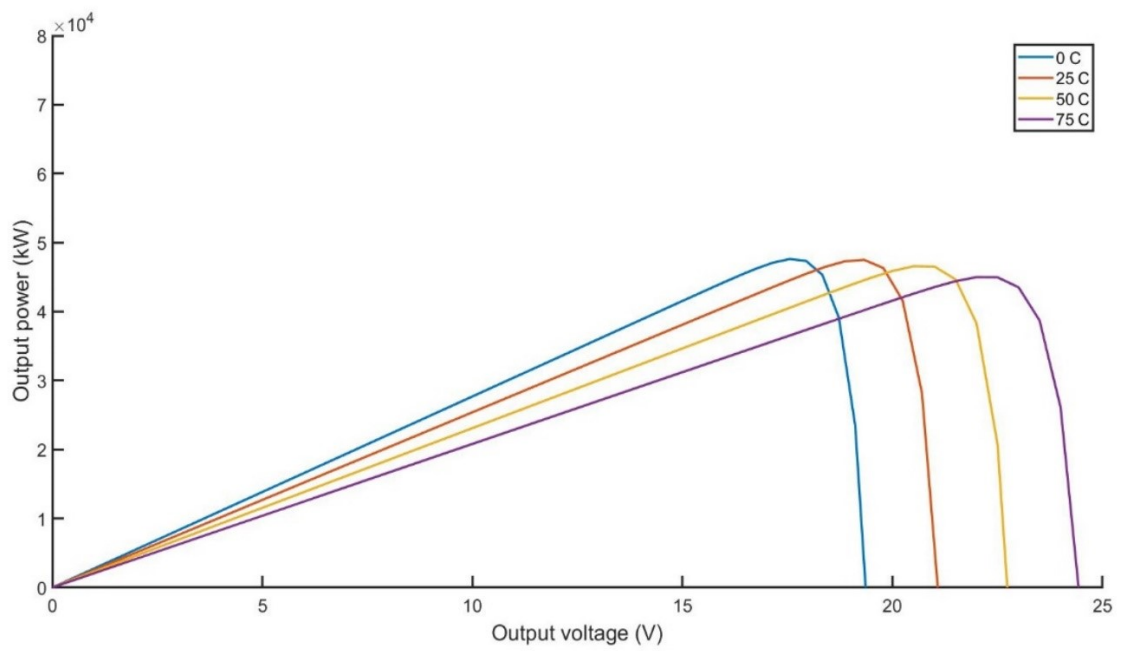


Figure 30: P-V curves for various temperature

From these tests we have seen that the input optical power and temperatures can affect the performance of PV converter. If we supply an adequate amount of optical power and maintain an acceptable temperature, we can achieve high efficiency. In the standard test condition and assuming no optical power losses on the PV receiver, we achieved 61.65% efficiency, which is an acceptable result with current technologies. In practical applications, the optical power loss on the surface of PV cell and high temperatures can reduce the efficiency.

In the third test, 200 cells are connected in series to achieve a higher output voltage. Here, 200 cells are connected in 3 parallel rows. As the number of cells in parallel are reduced, the output current is reduced as well, as shown in Table 14. Figure 31 and Figure 32 shows the P-V and I-V curves for various power level.

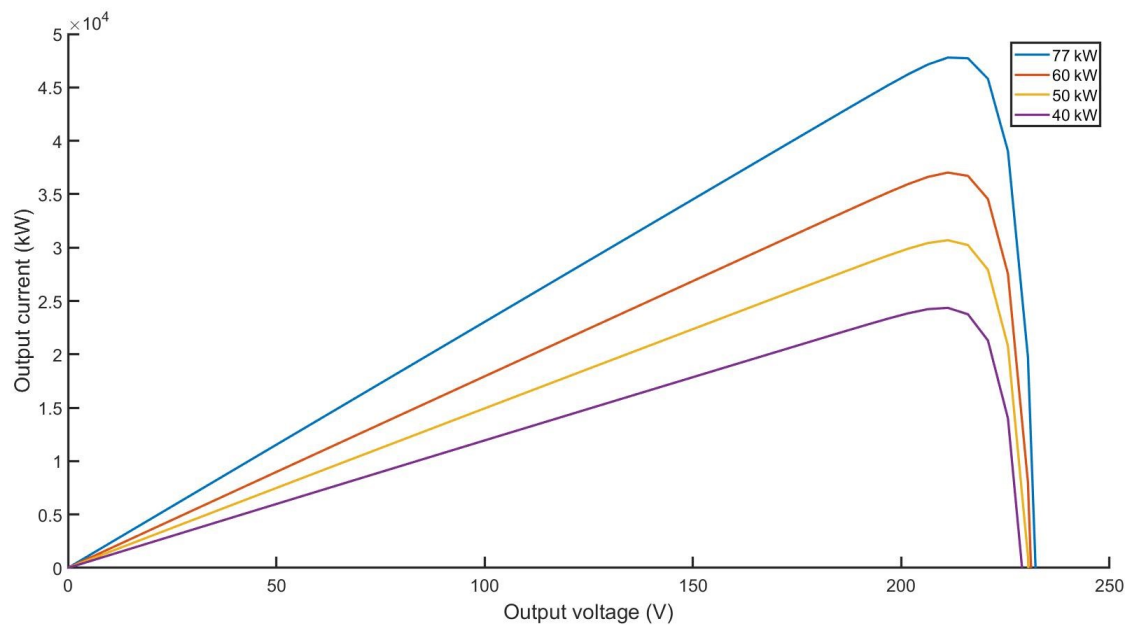


Figure 31: P-V curves for various power

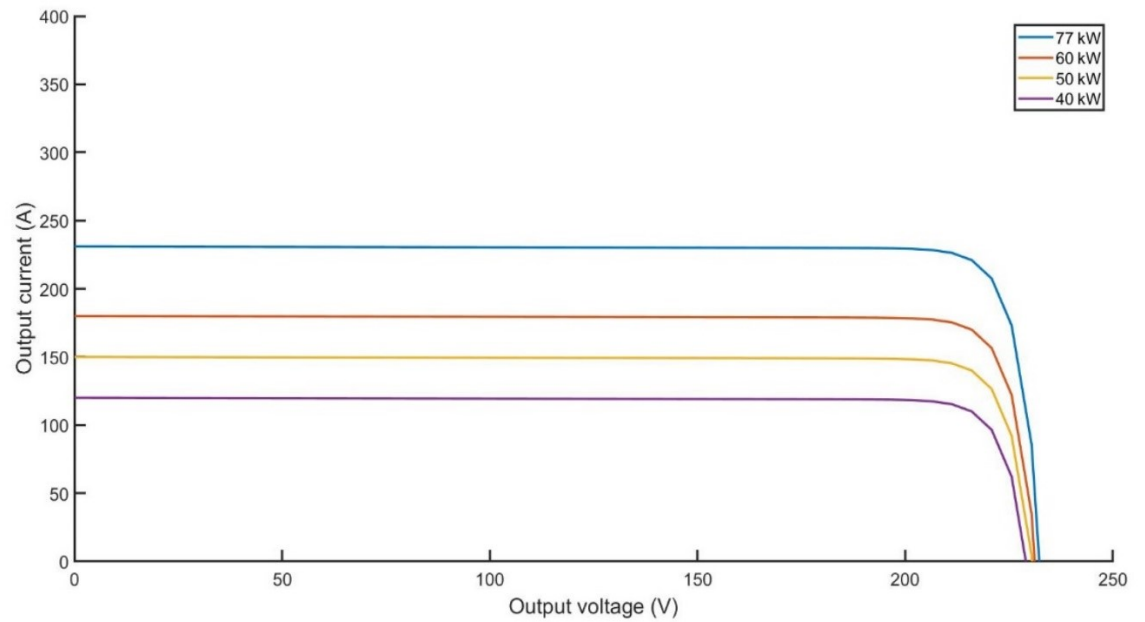


Figure 32: I-V curves for various power

Table 14 Output values for various power

Input power (kW)	Output power (kW)	Output voltage (V)	Output current (A)	Efficiency (%)
77	47.8	210.1	226.8	62.0
60	37.0	211.2	175.3	61.7
50	30.7	211.2	145.3	61.4
40	24.4	211.2	115.3	60.9

Figure 33 and Figure 34 shows the P-V and I-V characteristics for various temperatures. It shows that higher temperatures have greater effect on efficiency and decrease gradually as the voltage decreases. As we increase the temperature, the output current decrease. In both the cases, when we increase the input power, efficiency increases, when we increase the temperature, efficiency decreases.

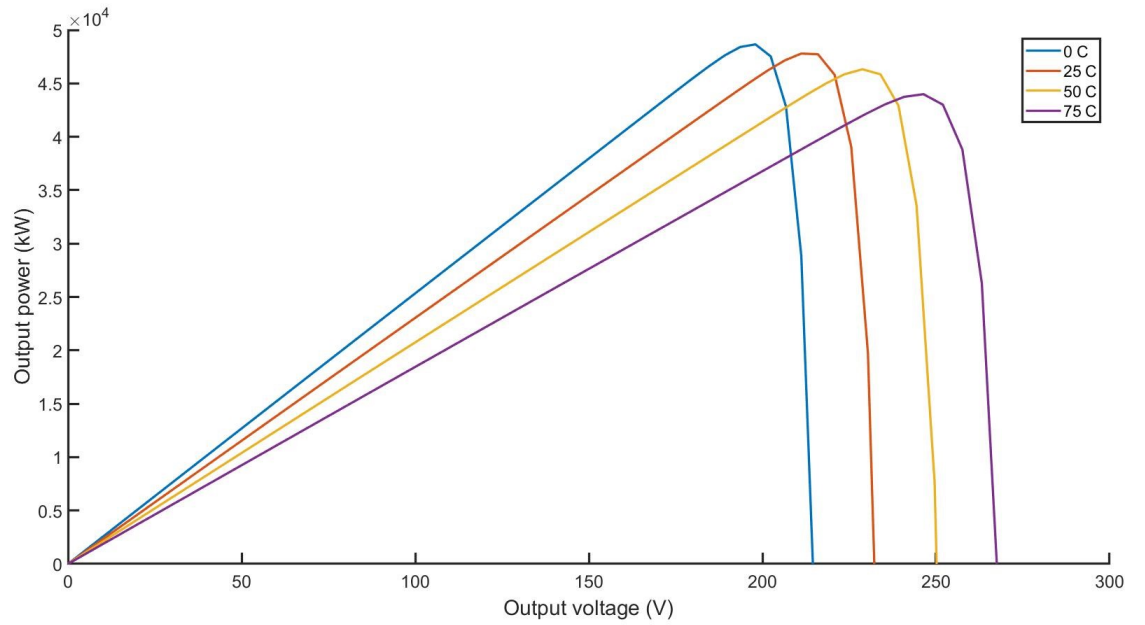


Figure 33: P-V curves for various temperature

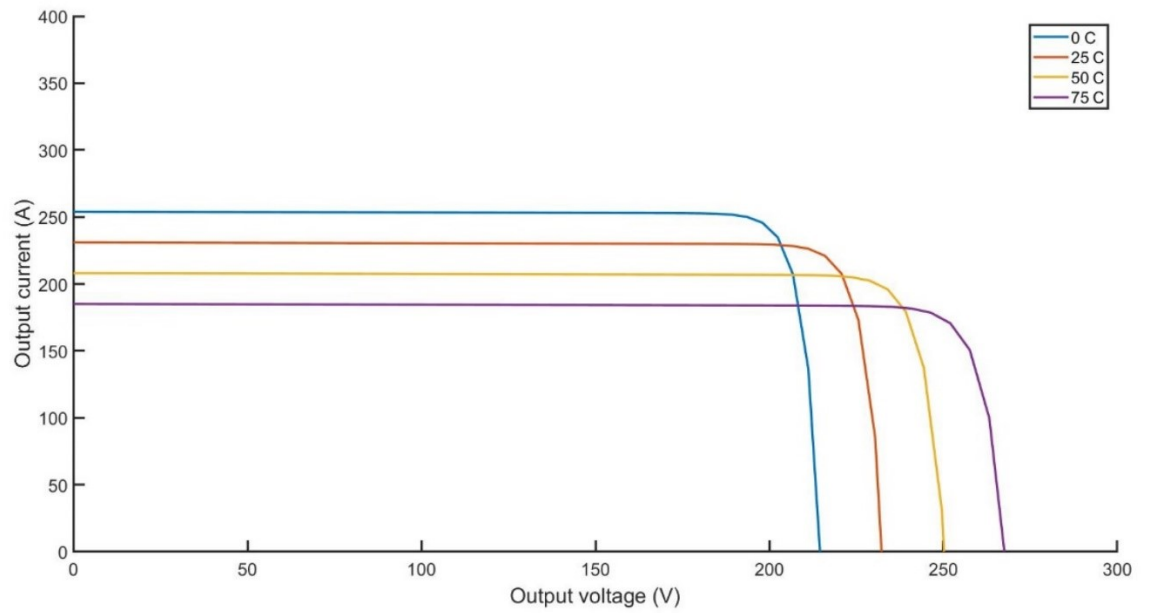


Figure 34: I-V curve for various temperature



Table 15 Output values for various temperature

Temperatures (°C)	Output power (kW)	Output voltage (V)	Output current (A)	Efficiency (%)
0	48.7	198.0	245.5	63.2
25	47.8	210.1	226.8	62.1
50	46.3	228.8	202.5	60.2
75	44.0	246.4	178.5	57.1

From the laser data sheet, the laser efficiency is 50% [26]. According to data sheet laser gives 50% efficiency therefor to get the power output of 77kW the supply power will be 154kW. We supply 77kW of laser power to the PV panel where PV panel convert into the 47.47kW output power with efficiency of 61.65% where we connected a greater number of cells in parallel and 47.79 kW output power with efficiency of 62.0% where we connected more numbers of cell in series.

In this research, the electricity to laser conversion can achieve efficiencies of 50%. The current generation of PV cells can get up to 62.0% efficiency using monochromatic coherent light. Since, the lithium-ion battery can give the 99% of efficiency for charging and discharging, this technique has an overall efficiency of 31.03% because of the number of energy conversions.

### 4.3 Mathematical calculations for the implementation of the PV cell and laser

#### 4.3.1 PV cell

PV cells size vary for different manufacturer and they allow custom size according to the requirements. For ideal condition the average size of PV cell is taken here which is 25 cm<sup>2</sup> Car's undercarriage area also varies according to the manufacturer. Therefore, the smallest area is taken into account where PV panel can fit to the smallest car. The dimension of the various car can be found here [33]. So, the PV panel below the undercarriage of the car is 100 x 150 cm<sup>2</sup> = 15000 cm<sup>2</sup>, which is shown in Figure 35.

Since one PV cell has an area of  $25\text{cm}^2$ , the required number of PV cells is  $\frac{15000}{25} = 600$  which can be connected in series and parallel. For high current, a greater number of cells are connected in parallel than the series which can produce high current therefore 20 cells can be connected in series and 30 cells can be connected in parallel. PV panel size and number cells required for it can be reduce or increase according to power requirements of the EV.

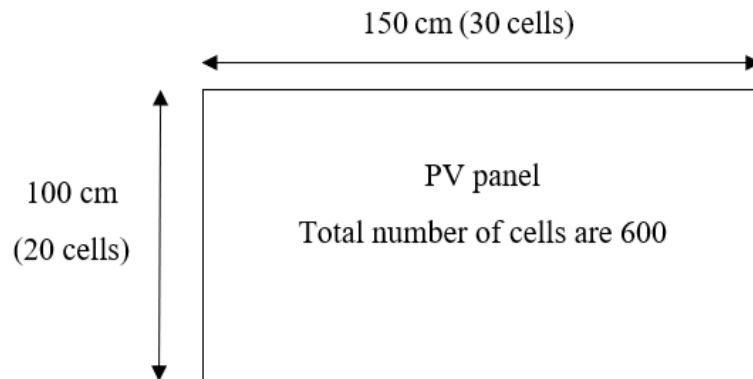


Figure 35: Required number of PV cell for PV panel area

In a practical condition undercarriage area of the car can be used to place a PV panel.

#### 4.3.2 Laser

From the data sheet description of the 808nm laser diode stack<sup>6</sup> [25], laser divergence is 8mrad or less. This means that over a distance of 1m, divergence will be about 8mm. Laser dimension can be obtained from Figure 36.

One laser module provides 3.2kW laser power with laser beam diameter at its aperture is 11.9 mm and laser power intensity is  $287.72\text{ W/cm}^2$  (Laser power density calculator is used here to calculate the power density [34]), which can reduce the efficiency or destroy the PV cell in long term therefore the laser beam intensity should be within a limit of PV cell [34]. As explained earlier, PV cells give a maximum efficiency on  $5\text{W/cm}^2$  [21], meaning that the laser beam must be expanded, which can lower its power density. A laser expander

<sup>6</sup> Laser diode stack- Here 2-16 bars of laser arranged on a single module, such as the one shown in Figure 36.

can be used to expand the laser beam. For the purpose of these calculations, laser expander related losses are neglected.

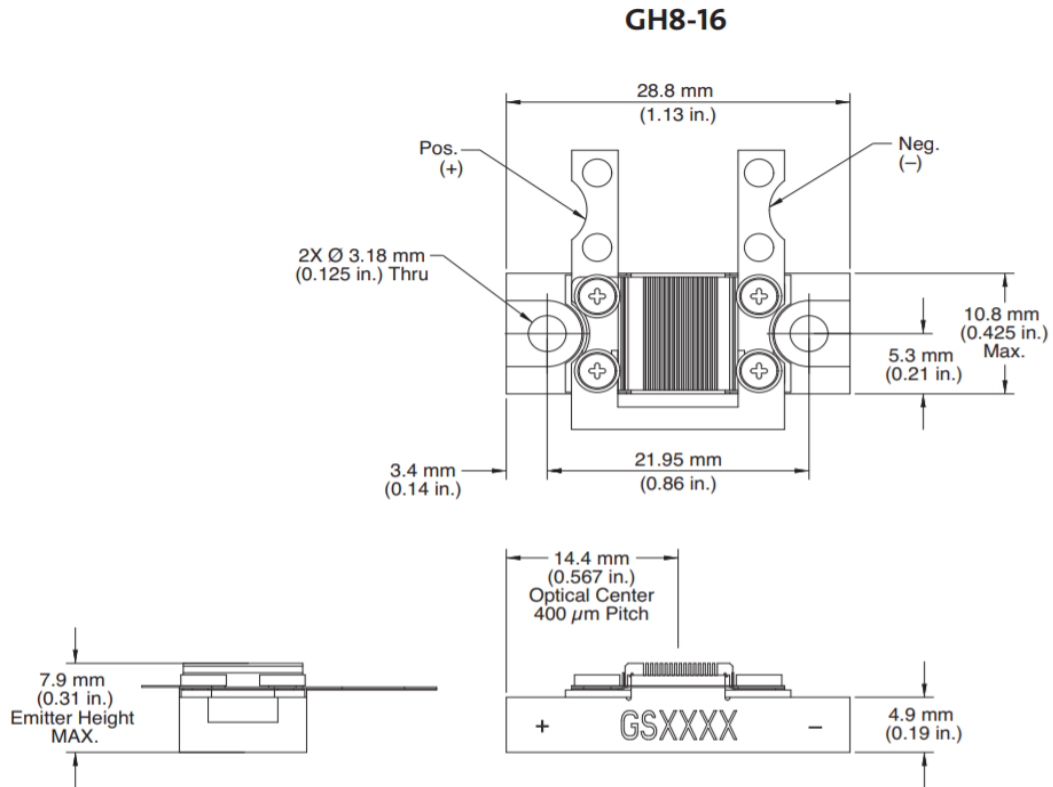


Figure 36: Laser package dimensions [26]

Laser power density calculator shows that, to get a power density of  $5 \text{ W/cm}^2$ , laser beam diameter must be expanded to 285.5 mm (28.55 cm) [34]. For this diameter, the laser spot area will be  $639.55 \text{ cm}^2$ . So, one laser module with 3.2 kW power can give a power density of  $5 \text{ W/cm}^2$  on area of  $639.55 \text{ cm}^2$ . The PV module area is  $15000 \text{ cm}^2$  (from section 4.3.1), therefore, the required number of laser module for this operation is  $\frac{15000}{639.55} = 23.44 \approx 24$  lasers sources.

Data obtained from the laser toolbox shows that to get the power density of  $5 \text{ W/cm}^2$  on the PV panel area requires 77 kW of power which is shown in Figure 37 [31]. One laser module can supply 3.2kW power. So, we require  $\frac{77}{3.2} = 24.006 \approx 24$  lasers sources. In both the case we require 24 laser modules which shows that we chose right number of laser module for the required laser beam area and PV panel area.

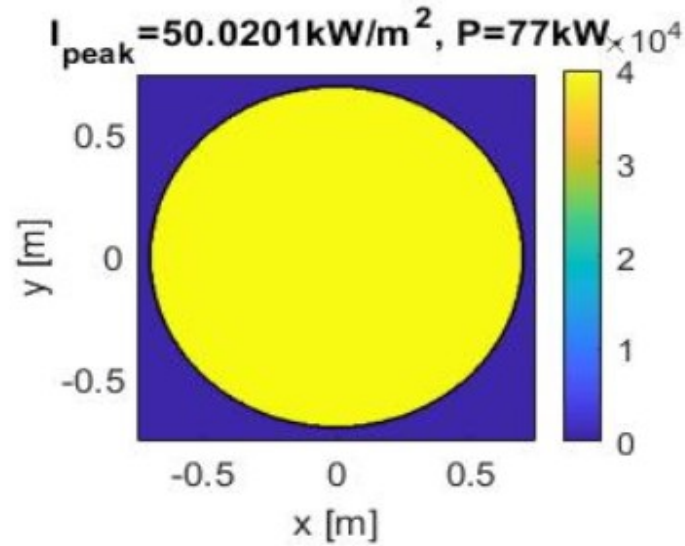


Figure 37: Required laser power to achieve a power density of  $5 \text{ W/cm}^2$

#### 4.4 EV battery charging

Electric vehicles typically use a lithium-ion rechargeable battery [35]. Lithium-ion batteries are favored over other batteries because of their high specific energy (140 Wh/kg) and energy density. In addition, it has a low self-discharge rate (5% per month [35]) compared to the other batteries. Lithium-ion battery have some drawbacks like overcharging and overheating but that is being by researcher; for example, special cooling technology can be used to prevent overheating and charge controllers can prevent overcharging [35].

There are various types of electric vehicles are available in the market; for example, Tesla's Model S and X. Both vehicles have 100kWh capacity batteries which contains 6 group of 86 cells in 16 modules for a total of 8256 cells, where each module provides 25 volts. The total voltage of battery is 400V [36], giving it a 250Ah rating. The 140kW Tesla Level-3 DC fast charger supplies 300A at 400-480V, allowing it to charge the vehicle fully in  $\frac{250Ah}{300A} = 0.83 \approx 49.8$  minutes [37].

Since the battery is rated at 400V, if more current is supplied it can be charged faster. Experiments results show that we can adjust the charging current and voltage by increasing

the PV cells connected in parallel and series. Connect more cells in series increase the voltage and connect more cells in parallel increase the output current.

In this case, we go the high current value but not the voltage which can affect the charging time. The below calculation shows that what if we get this much high current at 400V, we can reduce the charging time greatly. The experimental results show that we got 2452A current at maximum power point (MPP) value.<sup>7</sup> To charge the whole battery would require  $\frac{250 \text{ Ah}}{2452 \text{ A}} = 0.101 \approx 6.1$  minutes approximately for 400 V. The only problem with high current is that it creates heating problems in the battery which can reduce the battery life and ignites easily.

In the first test, a more cell connected in parallel to get high current where we got a current value of 2452A with 19.36 V which gives 5165.28Ah rating. To charge battery would require  $\frac{5165.28 \text{ Ah}}{2452 \text{ A}} = 2$  hours and 6 minutes (Battery charging related losses are neglected here which is very low <3%). In the second test, a more cell connected in series to get the higher voltage where we got a current value 226.8 A with 210.12 V which gives 475.91 Ah rating. To charge battery would require  $\frac{475.91 \text{ Ah}}{226.8 \text{ A}} = 2$  hours and 5.4 minutes. So, in both the test it takes same time but in second test we can reduce the current value. By doing so we can prevent the heating problem and increase the battery life.

This time can be reduced by increasing the PV panel area and input laser power where we can increase the number PV cells which can increase the voltage and current. Although this wireless power transfer using laser is faster than any other wireless power transferred method. WiTricity has developed wireless charging pad for EVs. It used magnetic resonance to charge EV. It has capacity to transfer 11kW within couple of hours but to charge 100kWh battery it's going to take whole day [38]. This shows that wireless charging by laser is faster than other wireless charging methods.

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<sup>7</sup> MPP- The point on P-V curve has the highest value of voltage and current or highest voltage is known as maximum power point [51].

#### 4.5 EV charging setup

Figure 38 shows the assumed relationship between the vehicle, PV, and laser. The PV panel is mounted to the undercarriage of the car and the laser is in an opening in the floor. To charge, the vehicle drives over the opening to align the laser and PV.

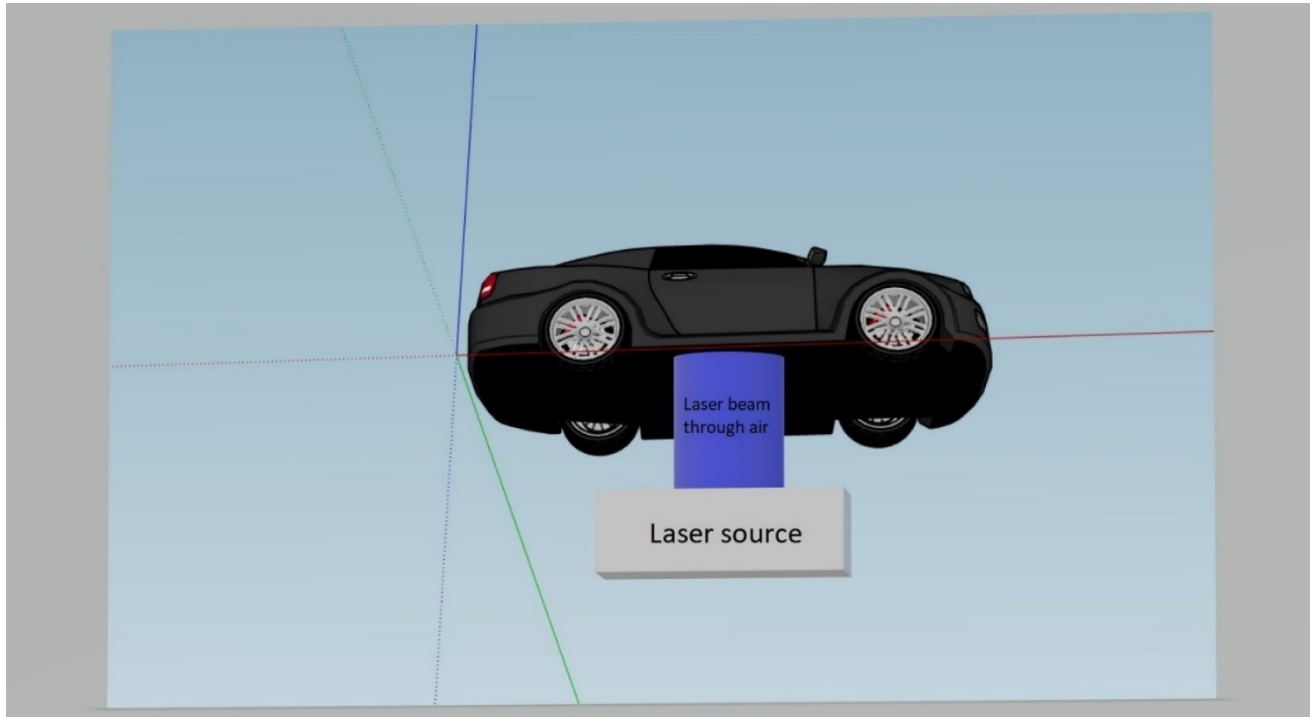


Figure 38: Laser source and PV panel on the car

A possible implementation of the proposed technique is shown in Figure 39, where the laser is powered by the electrical system and supplies optical power to the PV panel through the laser expander, which maintains the power density of the laser beam within the limits of the panel and increases the overall area of the beam. The PV panel converts optical power into electrical power for charging the battery. The PV panel is mounted on the undercarriage of the car, meaning it needs to be protected when not being charged; for example, by fitting an electrically driven sliding-door to the undercarriage which opens when charging. The high-power laser beam operates into the infrared region of the spectrum, which is invisible to human eye, therefore a low-power visible laser beam can be mounted on the corner of the PV panel for safe operation.

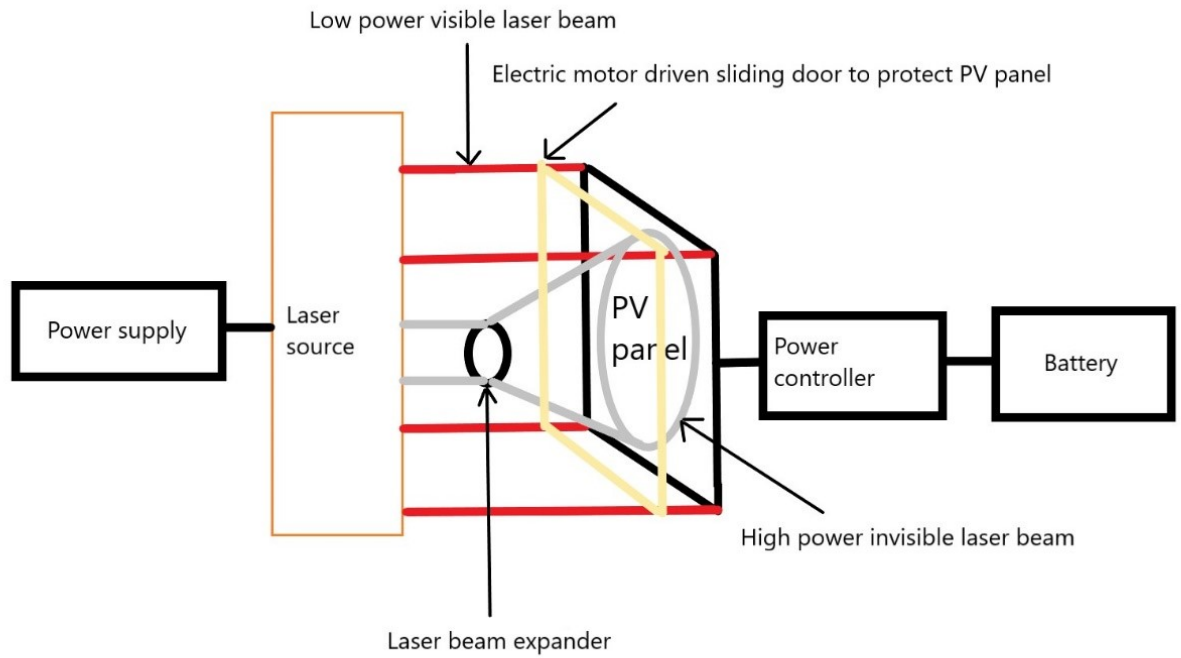


Figure 39: Basic implementation of proposed technique

## 5 Concluding Remarks

This research proposed a method for the transfer of high intensity energy by light for the purpose of charging electric vehicles. We began by reviewing the enabling technology required for laser charging, notably lasers and PV cells.

Since the vehicle being charged is assumed to be stationary in a charging station, the distances between the laser transmitter and the PV receiver will be no more than one meter. In this case, the atmospheric attenuation for laser power beaming is negligible. Research shows that the 808nm wavelength is best suitable for high power transfer in combination with a Ga-As PV cell. Although other wavelengths can be used, they are unable deliver high efficiency compared to the 808nm wavelength.

We compared the “top hat” and Gaussian laser distributions, where top-hat distribution provides uniform illumination and Gaussian distribution provides non-uniform illumination. A non-uniform illumination creates hot spot and uneven power distribution on PV panel which means all the PV cells will not get equal amount of illumination which can leads to decrease the efficiency compared to the top hat distribution which provides uniform illumination.

I-V and P-V characteristics shows the behavior of the cell for high powered input. The output power decreases as input power decrease also it decreases when cell temperature increases. Here, we calculated a time required to charge the battery. During the two test it shows that it requires 2 hours and 6 minutes to charge 100kWh battery compared to the other wireless method like magnetic resonance, wireless laser charging is fast. This time can be improved by increasing the input power and PV panel area which can increase the output voltage. If we increase the output voltage to 400V with this method, then it can charge the 100kWh battery in 6.1 minutes which will be faster than wired charging (using Level-3 dc fast charger) methods.

The simulations achieved 62.0% efficiency for laser power converter; the overall efficiency is 31.0%. Therefore, it appears to be a room to improve the efficiency of this method. If this can be done, it could be commercially viable. Results shows that by using specialized



PV cell we can convert the high intensity of laser into electricity and can useful for EV charging. Since wireless power transfer is a relatively new technology, it holds a lot of potential for other application such as satellite charging, simultaneously transfer power and information as well as efficiency improvement in PV cells.

## **5.1 Future work**

### **5.1.1 Efficiency improvement**

The overall efficiency that can be obtained from this technique is between 10% and 37%. To make laser charging potentially commercial acceptable, we need to improve the efficiency. As the technology is improving research will improve the efficiency of this component. Currently, most of the researchers are trying to improve the efficiency of solar cell therefore, there is need to improve the efficiency of PV cell which is specifically used for LPT. There is also a need to improve the efficiency of the laser diode. If this is possible, improvements to the efficiency of these two components to a greater percentage than this method can be used for commercial purposes [12].

### **5.1.2 Safety**

The most efficient LPT technology these days is operated into the infrared region which can cause eye damage in case of faulty system. As the proposed system works on high power density which is always a threat to the human eye and skin. In faulty condition slight reflection from the PV cell can be dangerous. Therefore, we need to find an eye-safe technology which usually operates at longer wavelength. Longer wavelength beam can be less destructive compared to the beam operates in the infrared region. There are other Laser diodes available that can operate at longer wavelengths, but they are not suitable for high power application, are inefficient and expensive such as InGaAs, InGaP and CIS. As technology is improving, we will able to find efficient longer wavelength LPT technology [12].

### **5.1.3 Wireless power and information transfer (WPIT)**

This technology can also be used for the simultaneous transfer of power and information. In this technique, a PV cell can receive the information in conjunction with the power

beam. Currently, there is no work available that can show that this technique can efficiently transfer both information and high photon energy beam to the receiver [12].

#### **5.1.4 Direct use of light to convert into electricity**

In LPT, electricity is converted into the light and light is converted back into the electricity leading to conversion losses occurs, limiting the overall efficiency of the system. As technology improves, it may not be necessary to have two types of conversion, directly using light converted into the electricity using solar pumped laser (SPL).<sup>8</sup> Currently SPL technology is not efficient as needed for high-power applications, but in future if efficiency is improved, it could be a use for high-power EV charging [39].

#### **5.1.5 Possibility of dynamic charging**

In the future it may be possible that using this technique automobiles can be charged while in motion. Specially designed infrastructure to enable dynamic charging will be required.

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<sup>8</sup> Solar Pumped laser- A device which concentrates solar light on crystalline material to create a laser beam [38]. A solar pumped laser uses solar radiation for pumping laser medium and generates laser beam [50].

## **Appendix A: Laser Hazards and safety evaluation**

As we are talking about high powered 10kW laser diode, safety needs to be addressed in this project. According to Canadian standards, the lasers used in this thesis are high-power and fall into the Class 4 category, which is dangerous for eyes and skin [40]. Special care should be taken when using this type of laser, like sensors and interlock safety.

### **Some source of laser hazard**

- Accidental eye exposure during alignment
- Misaligned laser beam
- Lack of eye protection
- Equipment malfunction
- Improper handling of input voltage
- Use of unknown equipment [18].

There are mainly two types hazards:

- 1) Laser beam hazards: It occurs due to the direct exposure of laser beam to a body which can cause eye and skin burns [41].
- 2) Non beam hazards: It occurs because of the laser equipment or the hazardous substance released from the laser equipment [18].

### **Hazard evaluation**

#### **1) Beam Hazard**

Eye Hazard: Eye hazard is common injury during the laser beam operation. The high laser beam with power greater than the 0.5W can damage your eye easily. laser operates between 810nm-850nm wavelength which is near to infrared and invisible to the human eye. Therefore, direct viewing to the laser beam and exposure to reflections can cause retina damage [20]. In addition, the infrared absorption in the cornea can damage corneal and loss of vision [41].

Skin Hazard and protective clothing: Direct exposure to beam or reflection exposure can be led to tissue burning. Therefore, Protective clothing cap, mask and gloves required to work near the laser [20].

## **2) Non-Beam Hazard**

Source of fire hazards from lasers: A high-power laser can ignite a fire easily when the laser beam comes into the contact with a flammable material [20].

Electric hazards: EV's charging using laser associated with high voltage and current. Therefore, there is high risk related if unauthorized person does maintenance work. Therefore, Electric equipment should be properly grounded and make sure that there is no electromagnetic interference between laser and electric equipment.

To avoid any kind of laser hazard, a proper training will be provided to the laser handler and laser safety officer must examine the system before its operation. In addition,

- Use proper eye wear protective equipment [41].
- Use eye wear equipment which is recommended by the manufacturer [41].
- Consult American national standards institute (ANSI) standard Z87.1 for selecting a proper eye wear [41].

## **Laser handling for EV charging**

- 1) Laser warning signs provide near the area.
- 2) Avoid direct looking at the laser charging system during its operation.
- 3) PV cells surface should be 0% reflective.
- 4) Avoid flammable compound in the undercarriage area of the car.
- 5) Curtains around the PV panel to absorb the scattered light and protection for the external beings (animals).
- 6) Proper cooling, and Ventilation provided to the laser source [41].

## **Engineering controls**

- Local exhaust ventilation.

- Lock and key to prevent unauthorized activation of laser.
- Elimination of reflective surfaces from the room.
- Window covers to absorb the scattered laser beam [41].

### **Personal protection while working near laser system**

A person should wear appropriate eye protection, adequate respirators, and protective clothing and gloves [41].

As we are just simulating a laser so the above precautions don't apply here but if you use a practical system then a practitioner must follow the necessary steps to avoid any kind of incidents.

### **Classification of laser based on the output power**

Based on the output power and the wavelength the laser is classified into four main categories [42].

#### 1) Class-1

Class-1 laser is safe for normal use under all conditions. This means it is under MPE and you can view it directly.

#### 2) Class-1M

It is safe for all conditions except it passes through magnifying or telescopic lenses. Its beams are usually divergent in nature except it passes through the magnifying lens. The laser is classified as 1M when the power passing through the naked eye is less than AEL<sup>9</sup> of class 1 but when it passes through the magnifying lens then its AEL is higher than the class 1.

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<sup>9</sup> AEL (Accessible emission limit) is the product of maximum permissible exposure limit (MPE) as given in the standard and the area of the limiting aperture [41].

### 3) Class 2

For continuous wave and power less than 1mW and emission time less than 0.25s will consider as class2 laser. It considered as a safe as long emission time is less than 0.25s

### 4) Class 3R

This type of laser emits visible wavelength of light. It has output 5 times AEL of class1. It is considered to be safe as long as it handled carefully [42].

### 5) Class3B

It is hazardous to eye but the reflection from paper or matte surface is not considered as hazardous. It cannot exceed the power of 0.5W for exposure time equal or greater than 0.25s. For an exposure time less than 0.25s the wavelength is between 0.18  $\mu\text{m}$  and 0.4  $\mu\text{m}$  or between 1.4  $\mu\text{m}$  and 1 mm

### 6) Class 4

The lase who exceeds the limit of class 3B AEL. It is very hazardous for eye and skin. All the higher power laser fall into this category. A special care should be taken while using this type of laser like key switch and interlock safety.

## Appendix B: Publication

# Simulating the charging of electric vehicles by laser

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### Abstract

At present, wired and wireless charging methods for electric vehicles (EVs) have a number of drawbacks including short charging ranges and long charging times. Laser power transfer (LPT) is a wireless power transfer technique which can be used for UAV (unmanned aerial vehicle) and satellite charging. Recent developments in photovoltaic cells and laser technology allows the transfer power using light which might overcome many of the issues related with other charging methods. In this paper, we describe the design and implementation (in MATLAB) of a novel, high-power charging method using a laser (monochromatic light) to charge electric vehicles. The paper examines the overall efficiency of the LPT for a various input power-level. In addition, it also examines the safety and the possible charging infrastructure for LPT technology. Using this technique, we believe that an overall efficiency of 10-37% can be achieved using existing technology.

### 1. Introduction

Electric vehicles (EVs) are a clean alternative to conventional liquid fuel vehicles if the electricity comes from clean energy sources. Consequently, EVs are becoming increasingly popular worldwide [43]. However, their uptake is limited by their costs, slow charging rates, and lack of charging infrastructure [44, 3].

This research examines EV charging methods. Broadly speaking there are two types of charging: wired (or plug-in) and wireless. Wired charging requires a cable to charge the EV. At present, a variety of wired charging system exist, including level-1 (Home charger) which takes typically eight hours of charging for a full charge [45], level 2 (home and public charger) charger which takes less than eight hours [45], and the DC fast charger (level 3) which takes 30 minutes to charge the full depleted battery of EV [45]. However, a problem with wired charging is that even with significant capacity, most chargers are limited to one vehicle at a time and in some cases wired charging can be a lengthy process (overnight in many places) [46]. In addition, it is unable to charge the vehicle while it is in motion. These problems can be overcome with wireless charging.

Wireless charging does not require cables. There are two techniques of wireless charging: near- field and far-field. Near field wireless charging can be further divided into magnetic coupling, magnetic resonance coupling and capacitive coupling. Magnetic coupling and magnetic resonance coupling work on the principle of electromagnetic induction while capacitive coupling transfer power through the electric field. The microwave radiation in the far field technique works on the principle of electromagnetic radiation [7]. The above-mentioned methods have drawbacks; for example, these coupling techniques have limited charging ranges and, complex implementation while microwave radiation has the additional disadvantage of low charging efficiency and is not safe when radio frequency density exposure is high [10].

To overcome these problems, we are proposing a novel wireless charging method using monochromatic or coherent light, that is, laser charging of electric vehicles. Research is currently being conducted in the wireless charging of UAVs (unmanned aerial vehicle) have successfully charged UAVs over long distances [11]. Lasers have the potential to deliver high power to the receiver making it an ideal source for the wireless power transmission. In 1970, lasers were proposed to provide thermal energy for the beamed energy propulsion spacecraft and in 1990, the transfer electricity from one location another was suggested [12].

In this method, electricity will be transferred to the automobile in the form of light using a laser and converted back to electricity using photovoltaic cells. In practice, it can be achieved by fitting PV panel under the carriage of the car and laser beam is propagated through air to the PV panel.<sup>10</sup> During the application of EV charging, the distance between the laser source and the PV panel is assumed to be not more than 2-3m.

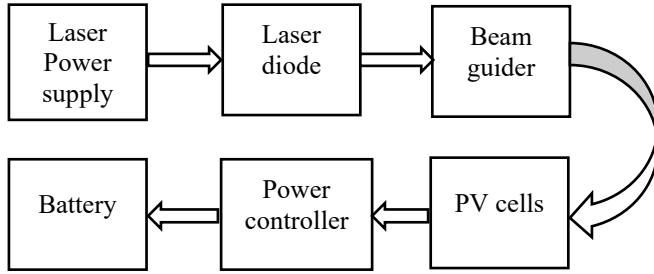


Figure 1: Proposed method

Figure 1 shows a block diagram of proposed technique. To successfully charge the EV using this procedure a vehicle can be in a stationary or mobile. Here, we will be examining a static method, where the car will be in stationary position in parking space.

The main problem with the laser power transfer is the efficiency of the laser (electricity to light) and PV cells (light to electricity).<sup>11</sup> Current advancements in laser and PV cell technology allows the

transfer power using these devices with greater efficiency and higher power transferring capability [12].

## 2. Technical approach

### 2.1. Selection of wavelength

Atmospheric gases can absorb laser energy at a given wavelength, thereby reducing its efficiency. Therefore, it is necessary to find the range of wavelength which allows the free transmission in the atmosphere with minimal energy absorption. Atmospheric data transmission, shows that there is a range between 780nm to 1100nm which is ideal for wireless power transfer to get the required output power to the receiver end [12].

### 2.2. Selection of Laser Source

There are various types of laser sources available, all of which have their own characteristics and capabilities. For LPT (Laser Power Transfer) the available laser technologies shown in Table 1. Output power of PV cells depends on the laser intensity (W/m<sup>2</sup>). Therefore, it is a necessary factor which can be obtained from the laser flux (see equation (1)) [12].

Table 1 Available laser technology [8]

Laser type	Wavelength $\lambda$ (nm)	Efficiency $\eta$ (%)	Radiance (W/m <sup>2</sup> -sr)
Diode laser 10 kW	850	50	$1 \times 10^{10}$
Thin disk laser 25 kW	1060	25	$2.4 \times 10^{15}$
Fiber laser 10 kW	1060	25	$4 \times 10^{13}$
Fiber laser 20kW	1060	25	$1.4 \times 10^{13}$

$$\phi = \frac{R \cdot A \cdot n_{trans}}{L^2} \quad (1)$$

Here,

$\phi$  = Laser flux

R= Radiance (Power per unit area per steradian) (W/m<sup>2</sup> -sr)

A=Area of the beam source (m<sup>2</sup>)

<sup>10</sup> PV panel is frame where PV cells were connected in series and parallel to form a module [17].

<sup>11</sup> A photovoltaic cell is a semiconductor device usually made from silicon and gallium arsenide which can convert solar light into electricity [18].



$L$ =Transmission distance (m)  
 $n_{trans}$ = laser transmission efficiency in atmosphere (%)

Solid state lasers such as a thin disk and fiber have the advantage of good beam quality and high-power transfer capabilities over long distance, but their efficiency is low [9]. On the other hand, high power diode lasers are not good for long range, but they are more efficient, compact and inexpensive. This project deals with a short range therefore laser diode is ideal for this application [12].

For EV charging, the distance between the laser source and the PV panel is assumed to be less than 2-3 meters and laser is coherent beam therefore there is a very low divergence over a small distance. In case of laser beam divergence, it can be controlled by beam guider. A device containing a beam expander optics which can control the beam divergence. Beam divergence can be measured only in the practical application as it requires to measure beam spot size and its height from the ground at the receiving and origin [12, 20].

### 2.3. Selection of photovoltaic cell

To generate an electricity from the PV, a photon's energy must be greater than the bandwidth of the PV material. There are many types of photovoltaic cells available in the market that can provide the good efficiency.

Spectral response of different PV material for a various wavelength can be seen in Figure 3, PV cells like Ga-As and Si can give the highest efficiency when it is illuminated by monochromatic light at wavelength between 800nm-950nm [12].

The spectral response of Ga-As can give the highest efficiency between 810nm-850nm and for Si this range is 900nm-950nm. However, it appears from the Figure 2 that the atmospheric absorption is very high for the region of 900nm to 1000nm [12]. So, Si wouldn't be the best choice as a PV cell for this method, but for the wavelength 840nm-890nm disturbance is very less and Ga-As PV cell gives the highest output in this range. Spectral transmission data shows that there is another range available beyond 1000nm which have low disturbance and it will be useful for laser transmission, but the problem with this range is that the associated PV receiver with longer wavelength such as InGaAs, InGaP, and CIS have a low power withstand capacity [12]. Therefore, the optimized Ga-As cell has been chosen because it can withstand much higher power intensities, greater than 1000 sun [21]. There are list of available PV materials and their efficiency associated with their laser intensity is shown in Table 2.

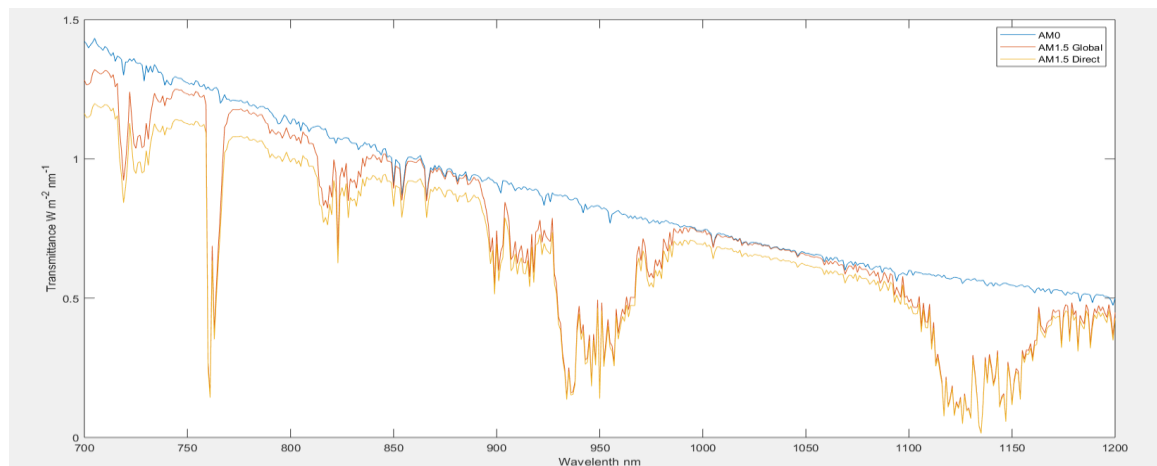


Figure 2: Atmospheric transmission spectrum [21]

Table 2 shows that Ga-AS can give the highest efficiency with a high laser intensity. As the laser intensity increases efficiency decreases gradually. The other noticeable fact is that other PV cells can't operate an intensity as high as that of Ga-As.

To charge high-powered batteries associated with electric vehicles, we need a high-power laser diode and efficient PV cells that can withstand high intensity power. The available types of laser matched with their PV cells shown in Table 3.

Table 2 Various PV cell's efficiency for laser illumination [12]

PV material	Ga-As		Si		InGaAs / InP	InGaP	CIS
Wavelength(nm)	810		950		>1000		
$n_{trans}$ (%)	53.4	60	27.7	28	40.6	40	19.7
Laser intensity (kw/m <sup>2</sup> )	430	110	10	110	2.37	2.6	10

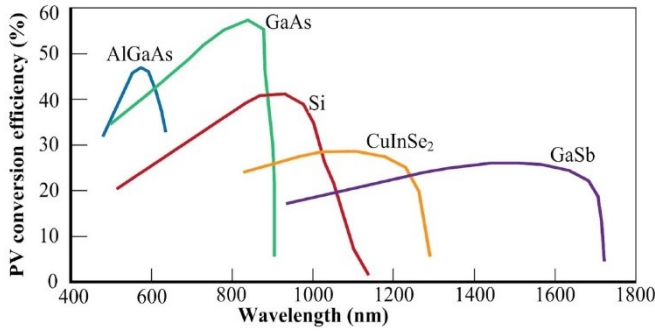


Figure 3: PV materials and their response for various wavelength [9]

Another factor which needs to be considered is to decide a PV cell with how many junctions will be required for this operation. There are two types of PV cell junction: single and multi-junction. A single junction PV cell responds to only on specific wavelength range, while multi junction PV cell comprise more than one junction; these junctions responds on a specific range of wavelength [22]. Here, a single junction PV cell is used rather than multi junction since multi junction cells cannot be illuminated fully using a single laser wavelength. For efficient operation of multi junction cells all the junctions need to illuminate by source light. In multi junction cells, if one of the junctions was not illuminated, most likely it will not provide output. Therefore, the single junction PV cell chosen over multi junction cell [20].

Furthermore, PV cells used in LPT technology are optimized Ga-As with low anti-reflection coating from 0% to less than 2% at 810nm wavelength [12, 21].

Table 3 PV cell's matched with their laser source [12]

Laser type	Wavelength (nm)	Laser efficiency (%)	Types of PV cell	PV cell efficiency (%)	Possible transmission distance
Diode laser (10kW)	850	50	Ga-As	>50	<10km
Fiber laser (20kW)	1060	25	CIS	17	<100km

#### 2.4. Laser Safety

Since the proposal deals high powered 10kW laser diode, safety needs to be addressed in this project.

The top three issues associated with the high-powered laser is addressed below.

- Eye safety: Here, laser operates between 810nm-850nm wavelength which is near to infrared and invisible to the human eye. Therefore, direct viewing to the laser beam and exposure to reflections can cause retina damage.
- Skin burning: Direct exposure to beam or reflection exposure can be led to tissue burning.
- Fire: A high-power laser can ignite a fire easily when the laser beam comes into the contact with a flammable material.

In this approach, to avoid the unintentional shooting of the laser beam. A proximity sensor can be mounted on the transmitter and receiver end. The laser will energize the beam only when the sensors can come in

contact with each other. These sensors can work as a lock and key to prevent unauthorized activation of laser. In addition, a proper laser related precaution and rules can be implemented before their application [20].

### 3. Simulation and analysis

As mentioned above, to generate electricity from the PV cell, the photon energy must be greater than the band gap energy of that material. A wavelength is inversely proportional to the bandgap energy of the material. The wavelength of a PV material can be found using equation (2) [29]. This technique is associated with high temperature therefore, the temperature effect on the band gap of that material. The band gap of the material depends on the temperature and it can be found using Varshni's equation (3) [29].

$$\lambda = \frac{1240}{E_g} \quad (2)$$

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta} \quad (3)$$

For a Ga-As,

$\lambda$  = Wavelength of the material

$E_g(T)$  = Band gap energy at particular temperature (eV)

$E_g(0)$  = Band gap energy at room temperature (298K) = 1.527 eV

Coefficient  $\alpha = 5.5$  and  $\beta = 225$

Generally, a PV cell is made to respond efficiently to sunlight, but the monochromatic light has single wavelength therefore there is a need to use specialized PV cell to respond on the specific wavelength. Tiquang, Shan, and Qi described optimized Ga-As required for laser power beaming [21]. This single junction optimized Ga-As PV converter contains n-GaAs substrate ( $5 \times 10^{18} \text{ cm}^{-3}$ ,  $350 \mu\text{m}$ ), n-GaAs buffer ( $5 \times 10^{18} \text{ cm}^{-3}$ ,  $1.0 \mu\text{m}$ ), n-AlGaAs BSF (Back Surface Field) ( $5 \times 10^{18} \text{ cm}^{-3}$ ,  $0.05 \mu\text{m}$ ), n-GaAs base ( $1 \times 10^{17} \text{ cm}^{-3}$ ,  $3.5 \mu\text{m}$ ), p-GaAs emitter ( $2 \times 10^{18} \text{ cm}^{-3}$ ,  $0.5 \mu\text{m}$ ), p-GaInP window ( $5 \times 10^{18} \text{ cm}^{-3}$ ,  $0.05 \mu\text{m}$ ) and p++-GaAs cap layer ( $5 \times 10^{19} \text{ cm}^{-3}$ ,  $0.5 \mu\text{m}$ ) [21].

Furthermore, this cell is coated with the antireflective material  $\text{TiO}_2$  (61nm) and  $\text{SiO}_2$  (94nm) [21]. This model provides 0% reflectance with double layer of coating on the surface, which is necessary for human safety and the protection of the surrounded equipment. This Ga-As cell has a photosensitive surface area of  $10 \times 10 \text{ mm}^2$  [21].

Currently, the simulation of Ga-As single junction PV cell and laser diode is being conducted. A simulation of PV cell can be formed using these equations. The PV output current can be described using equation. (3), where  $I_{ph}$  is light source current,  $I_0$  is reverse saturation current,  $R_s$  is series resistance,  $R_{sh}$  is shunt resistance,  $k$  Boltzmann constant,  $q$  carrier charge,  $T$  temperature and an ideality factor. The ideality factor, series resistance and shunt resistance value obtained from this paper [30].

Output current,

$$I = I_{ph} - I_0 \left( \exp \frac{q(v+IR_s)}{nkT} - 1 \right) - \frac{v+IR_s}{R_{sh}} \quad (3)$$

Diode current,

$$I_d = I_0 \left( \exp \frac{qv_d}{nkT} - 1 \right) \quad (4)$$

Reverse saturation current,

$$I_0 = \frac{I_{ph} - I - (v+IR_s)/R_{sh}}{\exp(q(v+IR_s)/(nkT)) - 1} \quad (5)$$

The photovoltaic simulation using MATLAB is shown in Figure 4. The simulation has been done on a single PV cell giving efficiencies of less than 5%. The overall efficiency is low because the existing PV-cell design does not operate on high-power and the laser software does not produce the correct wavelength.

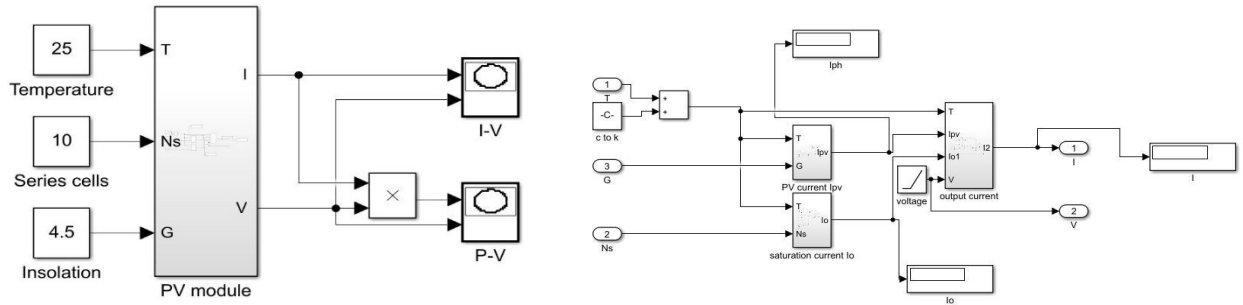


Figure 4: PV cell MATLAB simulation

We are in the process of increasing the range of laser intensity varies from  $2 \text{ W/cm}^2$  to  $5 \text{ W/cm}^2$ . The result suggest that the PV cell simulation will provide 50-54% efficiency. Furthermore, a laser beam with wavelength of 808nm, 840nm and 890nm to decide the efficient wavelength for this project. In practical condition laser shoots the beam on flat-plate PV array which contains a Gaussian beam. Therefore, power loss occurred during this operation. There are various methods available to eliminate the effect of Gaussian beam [12]. For example, using a solar array configuration, which is low cost and doesn't require any extra components for its operation. In a solar array configuration, a various type of series-parallel combination of PV cell is required to eliminate the Gaussian beam effect. It is believed that 25-76% efficiency can be obtained.

In this approach, the electricity to laser conversion can achieve efficiencies of 25-76%. The current generation of PV cells can get 45-53% efficiency using monochromatic light. Since, the lithium-ion battery can give the 99% of efficiency for charging and discharging, this technique has an overall efficiency of 10-37% because of the number of conversion and PV cell's efficiency [21].

#### 4. Future scope

The overall efficiency that can be obtained from this technique is 10-37% improve this, we need to improve the efficiency. As the technology is improving research will improve the efficiency of this component. Currently, most of the researchers are trying to improve the efficiency of solar cell therefore, there is need to improve the efficiency of PV cell and laser diode which is specifically used for LPT. If we able to improve the efficiency of these two components to greater percentage than this method can be used for commercial purposes [12].

This technology can also be useful for the simultaneous transfer power and information. In this technique a PV cell can work as a detector and receive the information in conjunction with the power beam [12].

#### 5. Conclusion

Laser Power Transfer can be an alternative of conventional charging method as it is more convenient and able to transfer high power to the receiver wirelessly. In this paper charging electric vehicle using laser discussed here. This paper explains that the Ga-As PV cell is the ideal choice for LPT technology. In addition, the laser technology matched with their PV cell is also been discussed here which shows the high-power laser diode will be the good choice as a laser source. However, a laser diode and PV cell operates in 900nm-950nm wavelength which is near infrared region and it is harmful for the human therefore necessary steps were explained to increase the safety. A MATLAB based simulation method is used for implementation of a PV cell. Using this method, it is possible that we can achieve 10-37% overall efficiency. There is more chance is available to improve the efficiency. Researchers around the world is trying to increase the efficiency of solar

cell but the more efforts need to improve the efficiency of PV cell which is specifically used for LPT technology then only we will be able to improve the overall efficiency significantly. This technique has the potential of being used for long range charging as well as simultaneously transferring power and information.

#### Appendix A. Area and number of PV cells required for an electric vehicle PV array

Table 4 shows the laser and PV cell characteristics of the proposed electric vehicle PV array.

Table 4 Laser and PV cell characteristics [21, 32]

Wavelength	808 nm-840 nm
Pulse mode	QCW (more efficient)
Power supply capacity per laser source	8 kW, 12 kW and 20 kW
Beam distribution	Top hat
Beam profile	Elliptical
Medium	Air
Distance	< 5 m
Cell size	0.1 cm <sup>2</sup>
Efficiency	53.23 %
Power withstand capacity of PV cell with highest efficiency	5 W/ cm <sup>2</sup>

A vehicle undercarriage area of  $150 \times 100 \text{ cm}^2 (= 15000 \text{ cm}^2)$  is required for the PV array. Given a cell size of  $0.1 \text{ cm}^2$ , for a  $1 \text{ cm}^2$  area we required 10 cells and for  $15000 \text{ cm}^2$  we will require 200000 cells. (Note- PV array size and number cells required for it can be reduce according to power requirements of EV). The laser density at the target is  $5 \text{ W/cm}^2$  and PV cells with  $1 \text{ cm}^2$  can give us  $2.5 \text{ W/cm}^2$  power [21]. If the vehicle has a PV panel array with an area of  $15000 \text{ cm}^2$ , then the radiated power on the PV array will be 75 kW (excluding the losses in the air). If the PV cells have 50% efficiency, the achievable power is 37.5 kW (excluding the losses occurred in PV array configuration as the incident light distribution is not same at surface area of PV cell [12].)

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