Design of An Optoelectronic Integrated Circuit

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Report Title

Design of An Optoelectronic Integrated Circuit

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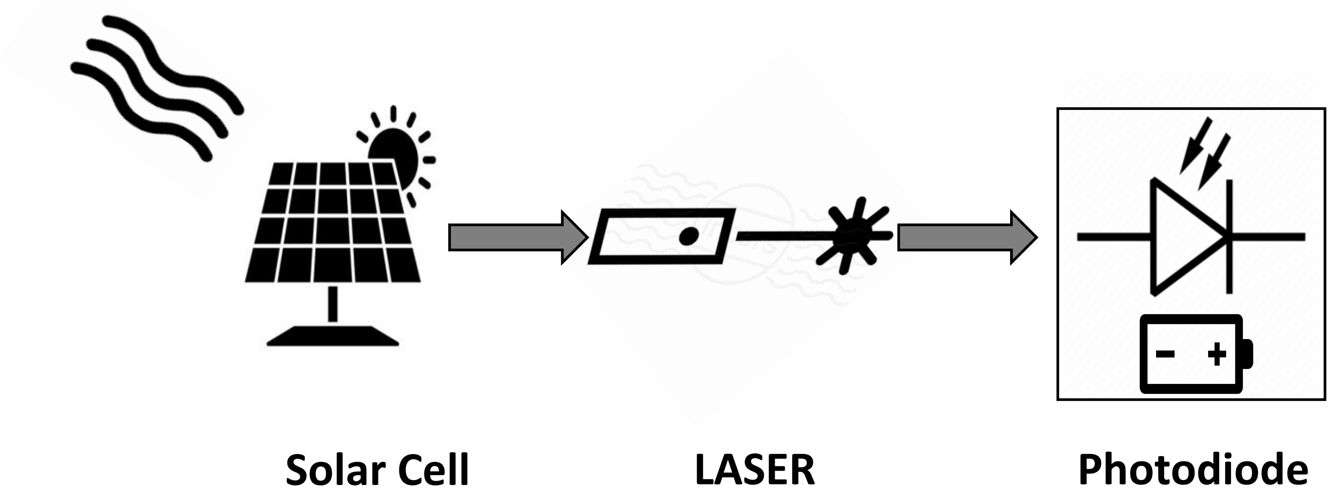
1. Introduction

The fundamental idea of this project is to design an optoelectronic integrated circuit the block diagram of which is shown below:



In the circuit shown above, there are three major building blocks, which are as follows:

1. Solar Cell: The solar cell shown on the left provides the input current to drive the LASER based on the optical power incident on it
2. LASER: The LASER generates an optical signal of a particular wavelength
3. Photodetector: The detector takes the optical power output from LASER as input and generates a photocurrent

The rest of the report is organized as follows: In sections 2, 3 and 4, we will explain the theory of the solar cell, LASER and photodetector respectively in brief along with the specifications we have used. We will also mention the how the whole system works together along the way. Finally, in section 5, we will discuss the results of our project.

2. Solar Cell

2.1. Basic Principles

A photovoltaic device or a **solar cell** converts the incident radiation energy into electrical energy. Incident photons are absorbed to charge carriers, which then pass through an external load to do electrical work. Figure 1 shows a typical pn junction solar cell[1].

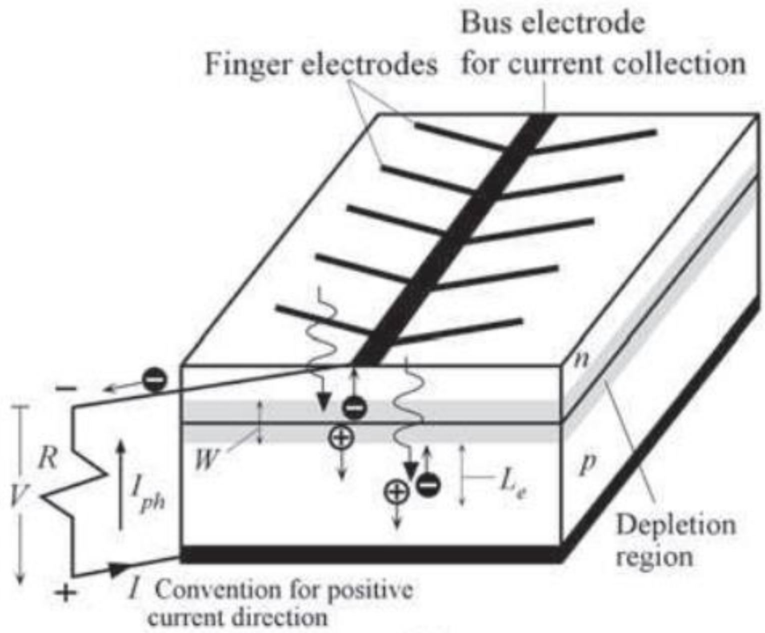


Figure 1: Typical pn junction solar cell

The I–V characteristics of a typical Si solar cell are shown in Figure 2[1]. The dark I–V is the usual forward biased pn junction diode equation,

$$I_{diode} = I_o[\exp\left(\frac{eV}{\eta k_B T}\right) - 1 \dots \dots \dots (1)$$

where η is the diode ideality factor which is between 1 and 2.

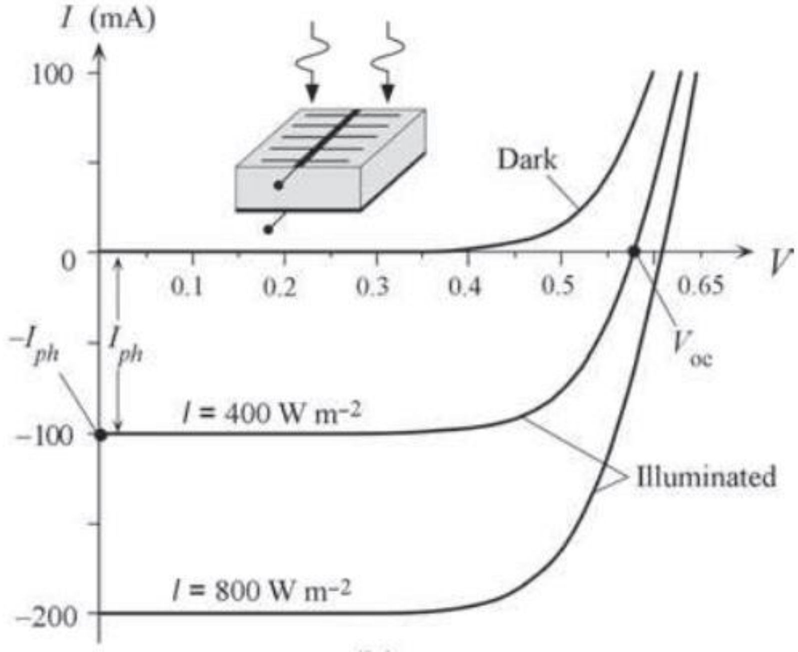


Figure 2 : I–V characteristics in the dark and under illumination]

Under illumination, the I–V dark characteristics are shifted down by an amount that is equal to the photocurrent I_{ph} . The photocurrent I_{ph} is proportional to the photogeneration rate and hence to the incident light intensity **I**, i.e.,

$$I_{ph} = K\mathbf{I} \dots \dots \dots (2)$$

where K is a device specific constant. As can be seen from Figure 2, doubling the light intensity has doubled I_{ph}.

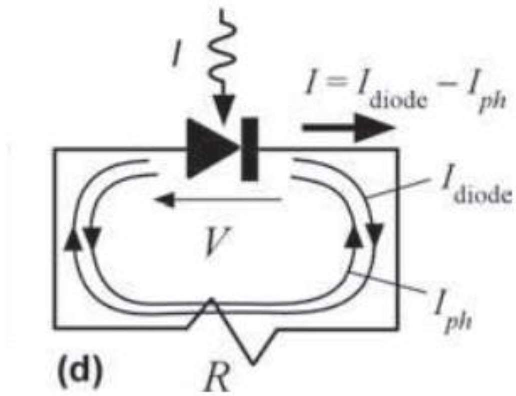


Figure 3: The solar cell driving an external load

Suppose that there is an external load R, as shown in Figure 3. The external current (no longer simply I_{ph}) will flow through R and generate a voltage V across it. I multiplied by V is the electric power dissipated in the external load. It should be apparent that the voltage V developed across R now forward biases the p-n junction, generates a diode current I_{diode} in the normal way and flows in the opposite direction to I_{ph}. The net current, as apparent from Figure 3 is

$$\mathrm{I} = -\mathrm{I_{ph}} + \mathrm{I_{diode}} = -\mathrm{I_{ph}} + I_o[\exp\left(\frac{eV}{\eta k_B T}\right) - 1] \ldots\ldots\ldots (3)$$

which represents the I–V characteristics of a solar cell[1]. The light intensity increases I_{ph} and hence shifts the normal diode characteristics down as shown in Figure 2.

The fill factor (FF), which is a figure of merit for the solar cell, is defined as

$$FF = \frac{P_{max}}{I_{sc}V_{oc}} \ldots\ldots\ldots (4)$$

The FF is a measure of the closeness of the solar cell I–V curve to the rectangular shape (the ideal shape).

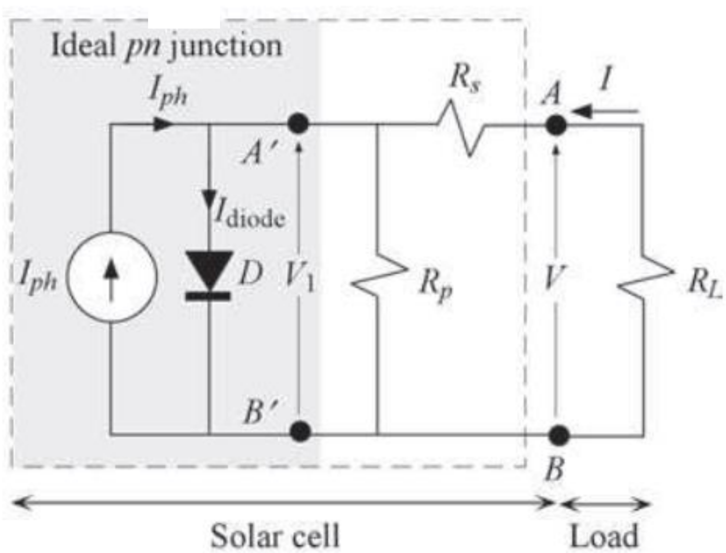


Figure 4 : Equivalent Circuit of a Solar Cell

Figure 4 shows the equivalent circuit of a pn junction solar cell[1]. If we apply Kirchoff’s current law at the A node in the picture and simplify, we get,

$$I = -I_{ph} + I_o\left[\exp\left(\frac{e(V - IR_s)}{\eta k_B T}\right) - 1\right] + \frac{V - IR_s}{R_p} \ldots\ldots\ldots (5)$$

The first term is dependent on the irradiance of the incident light. The second term is the diode current and the third term is the current through the parallel resistor R_p. As we know the reverse saturation current I_o depends on n_i^2, where n_i is the intrinsic carrier concentration and n_i is also dependent on the temperature,

So, the relation between the reverse saturation current and temperature is defined by,

$$I_{o_{new}} = I_{o_{old}} * \frac{\exp\left(\frac{qE_g}{k_b * T_{new}}\right)}{\exp\left(\frac{qE_g}{k_b * T_{old}}\right)} * \left(\frac{T_{new}}{T_{old}}\right)^3 \ldots\ldots\ldots (6)$$

2.2. Specification of Solar cell

The specifications of the solar cell used is shown below:

- Material: Monocrystalline Silicon
- Bandgap: 1.14 eV
- Diode ideality factor: 1
- Reverse saturation current: 25 nA at T = 300K[5]

Assume,

- Solar irradiance: 500 Wm^{-2}
- Device specific constant: 2
- Series resistance in equivalent circuit: 10 Ω
- Parallel resistance in equivalent circuit: 1 MΩ

3. Laser

3.1. Basic Principle

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. For our purposes, we will be using a semiconductor double heterostructure laser diode. Figure 5 shows the structure of the laser diode[1]:

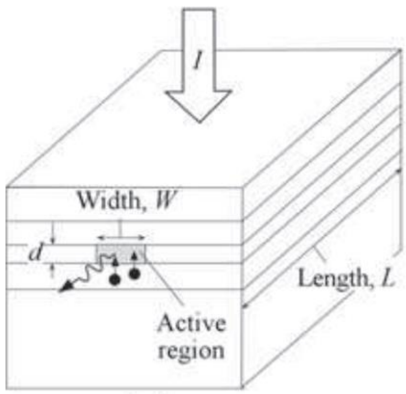


Figure 5: Typical structure of a double heterostructure laser diode]

The fundamental operation of a laser is that it takes an electrical current as input, and if the current is greater than a threshold current, then based it generates an optical power output. The output signal can have several wavelengths, depending on the length of the laser cavity. But it is desirable to have only a single wavelength as output.

Following is a sequence that is followed to get the single frequency output optical power from the electrical input:

- The first task is to determine the threshold gain from the following formula:

$$g_{th} = \Gamma\alpha_t = \alpha_s + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right) \ldots\ldots\ldots (7)$$

Where,

α_s is the total attenuation coefficient inside the cavity
L is the length of the active layer
$R_{1,2}$ represent the reflectance of the two mirrors at the cavity ends

Here, $R_1 = R_2 = R = \frac{(n_r-1)^2}{(n_r+1)^2}$, where n_r is the refractive index of the active layer.

- For operating the laser under single frequency, we want this threshold gain to be the same as the peak gain. From this peak gain, we will then determine the threshold injected electron concentration.

To extract the gain vs wavelength curve for different electron concentrations, we refer to the methodology proposed in [2] for InGaAsP/InP double heterostructure laser diode. The following equations are presented:

$$\begin{aligned} \overline{g_m(\lambda, N)} &= c_N[\lambda - \lambda_Z(N)]^2 + d_N[\lambda - \lambda_Z(N)]^3, \qquad && \lambda < \lambda_Z(N) \\ &= 0, && \lambda \geq \lambda_Z(N) \end{aligned}$$

……… (8)

Where,

$$c_N = 3\,\frac{g_p(N)}{\left[\lambda_z(N) - \lambda_p(N)\right]^2} \;\ldots\ldots\ldots 9(a)$$

$$d_N = 2\,\frac{g_p(N)}{\left[\lambda_z(N) - \lambda_p(N)\right]^3} \;\ldots\ldots\ldots 9(b)$$

The functions $g_p(N)$, $\lambda_p(N)$, and $\lambda_z(N)$ required in Eqs. 9(a) and 9(b) are the material gain versus carrier density at peak wavelength, the carrier dependence of the peak wavelength, and the wavelength at which the gain falls to zero for increasing λ at a given carrier density. These functions must be chosen such that they fulfill the physically reasonable conditions,

$$g_p(N) > 0 \text{ and } \lambda_z(N) > \lambda_p(N)$$

These three functions are approximated by the following equations,

$$g_p(N) = a_o(N - N_o) + a_o\bar{a}N_o e^{-N/N_o} \dots\dots\dots 10(a)$$

$$\lambda_p(N) = \lambda_o - [b_o(N - N_o) + b_1(N - N_o)^2] \dots\dots\dots 10(\mathrm{b})$$

$$\lambda_z(N) = \lambda_{z_o} - z_o(N - N_o) \dots\dots\dots 10(\mathrm{c})$$

where the coefficients N_0, a_o, $\bar{a}$, λ_0, b_0 , b_1 , λ_{z0} , and z_0 have to be determined from experiments. N_o represents the transparency carrier density at the band edge wavelength λ_o of the active layer and λ_{z0} is the value of λ_z at the transparency carrier density.

The parameter values taken from the paper are presented below:

Table 1: Summary of parameters used to model gain vs wavelength curve under different injection

Parameters to use	**Value taken from literature**
N_o	6.53×10^{23} m^{-3}
a_o	3.13×10^{-20} m^{-2}
$\bar{a}$	1.2
λ_0	1.595 um
b_o	3.17×10^{-26} m^3 um
b_1	0
λ_{z0}	1.625 um
z_o	-2.5×10^{-27} m^3 um

The simulated results are shown in Figure 6, 7 and 8. Figure 6(a) shows the gain vs photon energy curve under different injections and figure 6(b) shows the plot collected from literature[2]. We can see that we have been able to reliably reproduce the results judging from the two figures. Figure 7 shows the optical gain vs wavelength under different injections. This is the curve we will be using later for finding the operating wavelength. Figure 8(a) shows the peak optical gain coefficient for different injections and figure 8(b) shows the same plot collected from literature[2]. These two plots also match very well.

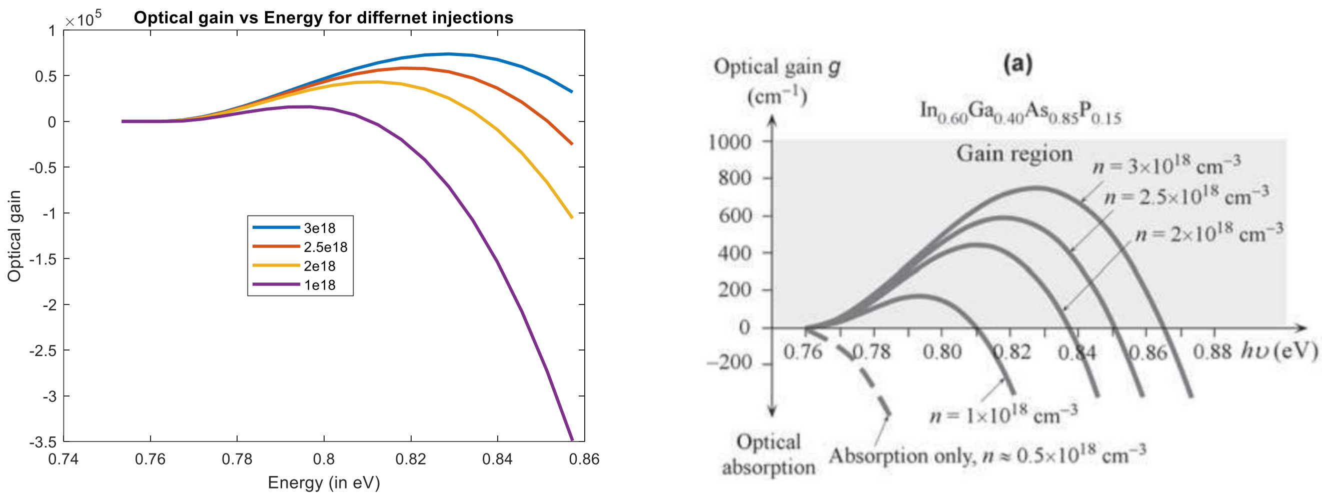


Figure 6 : Optical gain vs photon energy for InGaAsP active layer from (a) Simulation (b) Literature

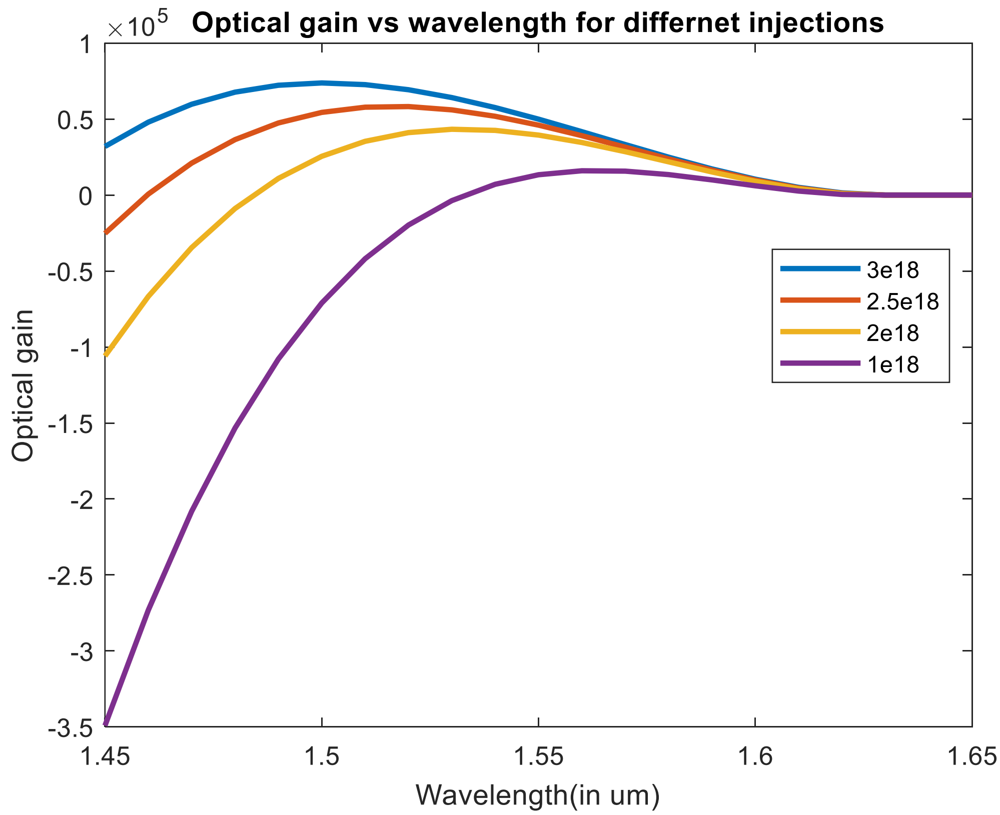


Figure 7: Optical gain, g vs wavelength for an InGaAsP active layer as a function of injected carrier concentration

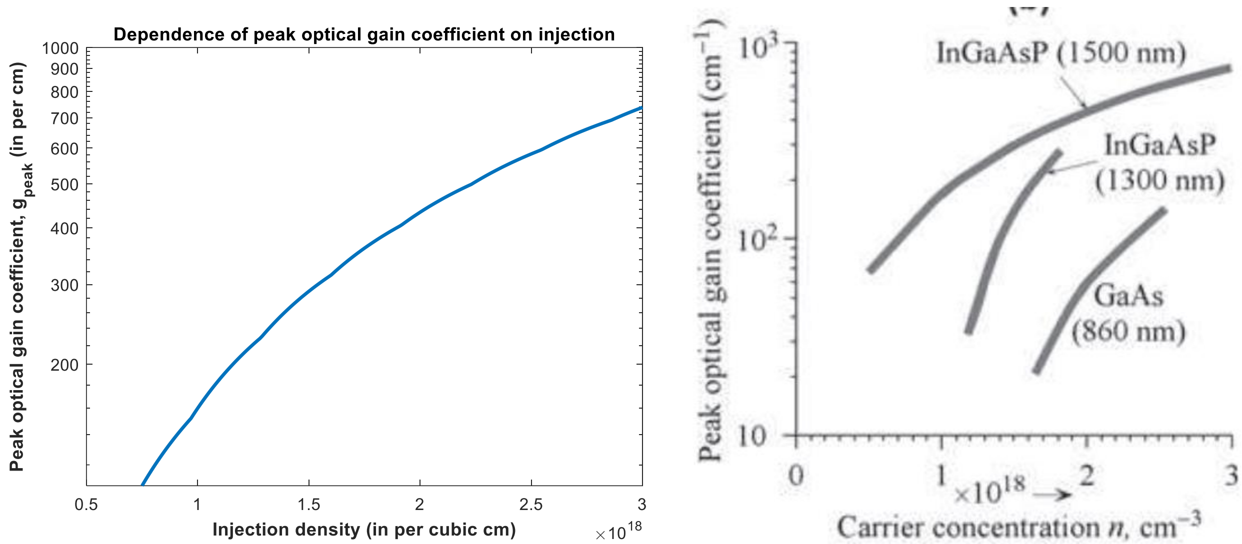


Figure 8: Peak optical gain coefficient vs injected electron density for InGaAsP active layer (a) Simulated (b) From literature

To summarize, we now have data points from which we can tell what value of injection electron density we need to reach a particular gain. We will set the threshold gain for the laser equal to the peak gain and from figure 7, extract the value of the threshold injection electron density.

- Now that we have the required injection electron density to drive the laser, we can readily determine the threshold electrical current from the following equations:

We will first determine the radiative lifetime, τ_r from the following equation,

$$\tau_r = \frac{1}{Bn_{th}} \ldots\ldots\ldots (11)$$

Where, B = Direct recombination coefficient and n_{th} = Threshold electron injection density

The threshold current density, J_{th} and threshold current, I_{th} is then derived from the following equation,

$$J_{th} = \frac{n_{th}ed}{\tau_r} \ldots\ldots\ldots (12)$$

$$I_{th} = (WL)J_{th} \ldots\ldots\ldots (13)$$

Where, d = Active layer thickness and W = Width of the active layer

The photon cavity lifetime, τ_{ph} is determined from the following equation,

$$\tau_{ph} = \frac{n_r}{c\alpha_t} \ldots\ldots\ldots (14)$$

Where, α_t = Total loss coefficient (same as threshold gain)

The optical power output from the laser, P_o is then defined by,

$$P_o = [\frac{hc^2\tau_{ph}(1-R)}{2en_r\lambda L}](I - I_{th}) \ldots\ldots\ldots (15)$$

The output intensity from the laser is defined by,

$$I_{out} = \frac{P_o}{Wd} \ldots\ldots\ldots (16)$$

- The final parameter we need is to calculate the resistance of the laser diode. We will need it because to determine the output current of the solar cell, we need to know the resistance of the load (in this case, LASER) that it is driving. The following equation is used to calculate the resistance of the LASER diode [6] :

$$R = \frac{2k_BT}{q} * \frac{1}{I_d} \ldots\ldots\ldots (17)$$

$$I_d = \frac{\tau_{sp}}{N_e aqd} \ldots\ldots\ldots (18)$$

Here, I_d represents a normalized current. τ_{sp} is the spontaneous recombination lifetime, N_e is the electron density, a is the active area equal to length multiplied by width, d is the thickness. The results are described in the results section.

In turbulent atmosphere, the laser beam intensity decreases exponentially with distance as [3][4]

$$I'_{out} = I_{out} * \exp(-\alpha x) \quad \dots\dots\dots (19)$$

Where, α is the attenuation constant and x is the distance travelled by laser beam.

3.2. Specification of Laser

- Material for active layer: p-$In_{0.6}Ga_{0.4}As_{0.85}P_{0.15}$
- Bandgap of active layer: 0.762 eV
- Operating wavelength: 1570 nm
- Refractive index = 3.491
- Material for confining layer: p-InP
- Substrate: n-InP
- Contacting layer: p-InGaAsP
- Width = 5 um, Active layer length = 100 um, Active layer thickness = 0.15 um
- Attenuation coefficient = 2500 m^{-1}
- Direct recombination coefficient = 2×10^{-16} m^3s^{-1}

4. Photodetector

4.1. Basic Principles

Photodetectors convert an incident radiation to an electrical signal such as a voltage or current. Figure 9 shows the simplified structure of a typical pn junction[1] photodiode that has a p^+n type of junction, that is, the acceptor concentration N_a in the p-side is much greater than the donor concentration N_d in the n-side.

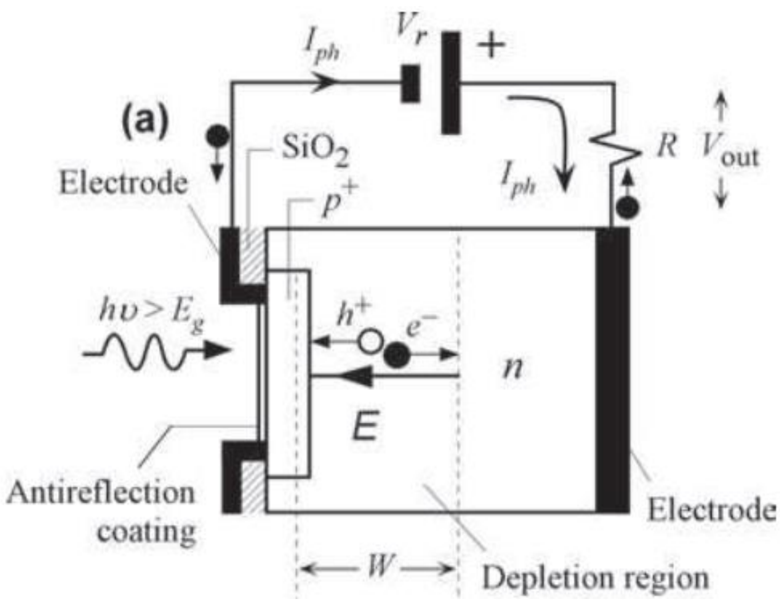


Figure 9: A schematic diagram of a reverse biased pn junction photodiode region [1]

When a photon is incident on the depletion region, a free electron hole pair is generated. Under the influence of the electric field, the electron is drifted towards the n-side and the hole is drifted towards the p-side. At the same time, there is an electron flowing from the n-side towards the positive terminal of the battery and there is an electron flowing from the negative side of the battery to the p-side of the structure to recombine with the hole. The result is that there is an external current I_{ph} flowing in the circuit. This current is opposite in direction to the diode current. In the photoconductive region, if a reverse bias voltage is applied, this negative current flows in the circuit. The target is to get a large enough current at the output of the photodetector that is designed to detect light of a particular wavelength.

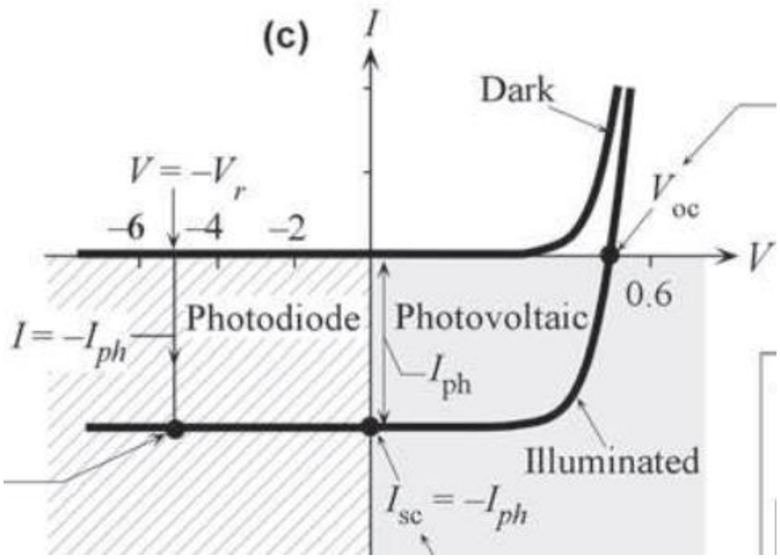


Figure 10: The I–V characteristics of a pn junction in the dark and under illumination

Figure 10 shows the I–V characteristics of an ideal pn junction in the dark and under illumination[1]. In the dark, the I–V characteristic follows the usual diode equation, i.e.,

$$I = I_o[\exp\left(\frac{eV}{\eta k_B T}\right) - 1] \dots \dots \dots (20)$$

In the dark, there is a small reverse current, which usually increases with the reverse bias. Upon illumination, a photocurrent I_{ph} is generated in the photodiode; I_{ph} is proportional to the incident light power P_o through the responsivity R.

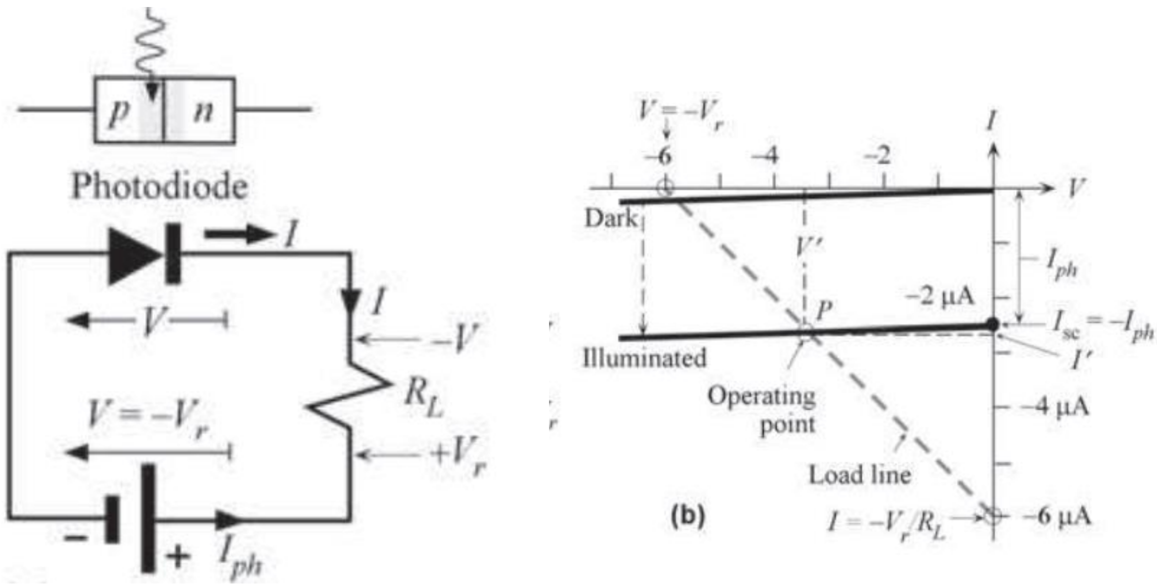


Figure 11: (a) A representative circuit consisting a photodetector (b) Photodiode I-V characteristic under load

Figure 11(a) shows the circuit containing the photodetector[1]. The detector is reverse biased by a voltage V_r. There is a current I flowing through the photodiode. The I-V characteristic along with the load line is shown in Figure 11(b). The equation of the load line is as follows:

$$I = \frac{[(-V) - (+V_r)]}{R_L} = -\frac{V + V_r}{R_L} \dots\dots\dots (21)$$

The operating point is then determined by the intersection of the load line and the I-V characteristic. The output current of the photodetector is equal to the value at the intersection point.

4.2. The pin Photodiode

The pin refers to a semiconductor device that has the structure p^+ - intrinsic – n^+ as schematically illustrated in the idealized structure in Figure 12[1]. The intrinsic layer has much smaller doping than both p^+ and n^+ regions and it is much wider than these regions. When the structure is first formed, holes diffuse from the p^+ side and electrons from n^+ side into the intrinsic layer where they recombine and disappear. This leaves behind a thin layer of exposed negatively charged acceptor ions in the p^+ side and a thin layer of exposed positively charged donor ions in the n^+ side.

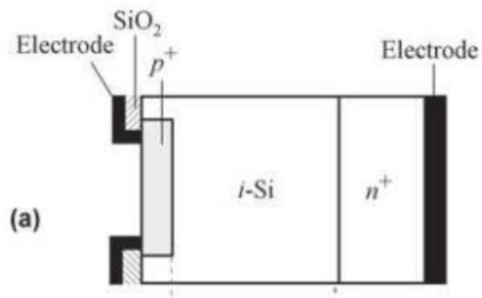


Figure 12: Schematic structure of an idealized pin photodiode

The pin photodiode is better than the normal p-n photodiode because there is a uniform electric field in the intrinsic region. Now, even long wavelengths will not simply pass through the intrinsic layer, rather they will be absorbed within the intrinsic region where there is a field to separate the electron hole pairs. We will be using a pin photodiode for our project.

4.3. Calculation of Steady State Current in pin photodiode

Consider a pin photodiode that is reverse biased and illuminated, as in Figure 12, and operating under steady state conditions. Assume that the photogeneration takes place inside the depletion layer of width W, and the neutral p-side is very narrow. If the incident optical power on the semiconductor is $P_o(0)$, then $TP_o(0)$ will be transmitted, where T is the transmission coefficient.

At a distance x from the surface, the optical power $P_o(x) = TP_o(0) \exp(-\alpha x)$. In a small volume dx at x, the absorbed radiation power is $\alpha P_o(x)dx$, and the number of photons absorbed per second is $\alpha P_o(x)dx/h\omega$. Of these absorbed photons, only a fraction will photogenerate EHPs, where η_i is the internal quantum efficiency, IQE. Thus, $\eta_i a P_o(x)dx/h\omega$ number of EHPs will be generated per second. We assume these will drift through the depletion region and thereby contribute to the photocurrent. The current contribution dIph from absorption and photogeneration at x within the SCL will thus be

$$\delta I_{ph} = \frac{e\eta_i \alpha P_o(x)\delta x}{h\upsilon} = \frac{e\eta_i \alpha T P_o(0)\delta x}{h\upsilon} \exp\left(-\alpha x\right)\delta x \ldots\ldots\ldots (22)$$

We can integrate this from x = 0 (assuming /p is very thin) to the end of x = W, and assuming $W >> L_h$ to find

$$I_{ph} \approx \frac{e\eta_i \alpha P_o(0)}{h\upsilon}\left[1 - \exp(-\alpha W)\right] \ldots\ldots\ldots (23)$$

Equation represents the steady state photocurrent in a pin photodiode.

To summarize, we will take the output intensity from the laser diode as input to the detector which will then be multiplied by the detector area to get the incident optical power $P_o(0)$. This will be used to get the value of the photocurrent.

4.4. Specification of Photodetector

- Material: $In_{0.53}Ga_{0.47}As$
- Wavelength range: 800 - 1700 nm
- Peak wavelength: 1550 nm
- Bias voltage (Reverse): 20 V (Max)
- Reverse current: 2 mA (Max)
- Active area diameter[7]: 0.12 mm
- Absorption coefficient at peak wavelength [1]: 4×10^5 m^{-1}
- Optical Power Damage Threshold: 18mW

- Transmission coefficient: 1 (perfect anti-reflection coating)
- Internal quantum efficiency: 1
- Bandwidth : 1Mhz

We will design the photodetector such that the minimum responsivity is 0.7 around the peak wavelength, and for that the width of the depletion region will be varied.

5. Results

5.1. LASER

Using the specifications mentioned in section 3, we show that from the peak optical gain vs injected electron density curve, we can superimpose the threshold line and determine the required threshold electron density.

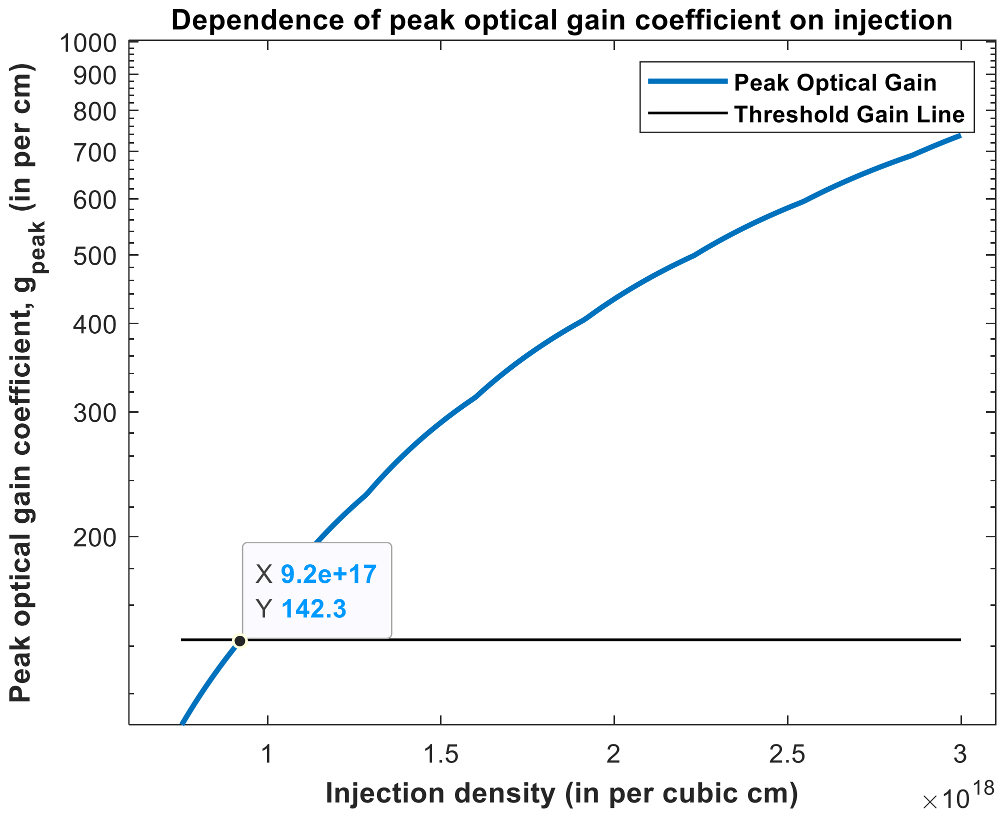


Figure 13: Peak optical gain vs injection density. Black line represents threshold gain

We can see from Figure 13 that for the threshold gain (found from calculation based on equations and specifications in section 3), the threshold injection electron density is 9.2×10^{17} cm^{3}.

In the following plot, we show the gain vs wavelength characteristic for the threshold injected electron density:

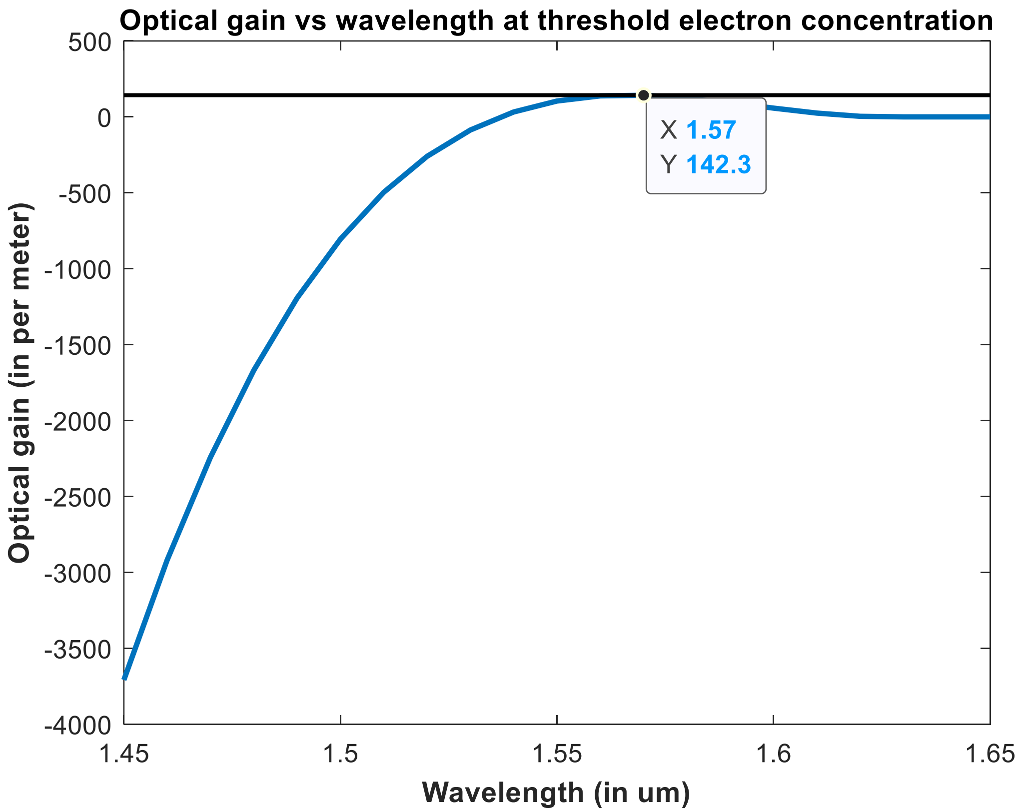


Figure 14: Optical gain vs wavelength at threshold electron concentration. The plot shows only single mode is allowed at 1.57 um

We can see from Figure 14 that the threshold gain line touches the gain curve. And, the only allowed mode of frequency in the cavity corresponds to the wavelength 1.57 micrometer.

After further calculations,

- We find the threshold current to be 4.1 mA. We need the solar cell to provide a current at least greater than this value to drive the LASER.
- We have calculated the resistance of the LASER as 13.94 **Ω**. This will act as the load to the solar cell.
- At the same time, we find the output intensity to be 6.6941 $\times 10^8$ Wm^{-2}. This output will be fed as input to the photodetector.

<u>Efficiency Calculation:</u>

Laser diode operating voltage at I = 9.38 mA, V = .1307 V

Energy of a photon, hω = $\frac{hc}{\lambda}$ = 0.791 eV

- Slope efficiency, $\eta_{slope} = \frac{P_o}{I - I_{th}} = 18.93\%$

- Power conversion efficiency, $\eta_{PCE} = \frac{P_o}{IV} = 81.56\%$

- External quantum efficiency, $\eta_{EQE} = \frac{P_o/h\omega}{I/e} = 13.47\%$

- External differential quantum efficiency, $\eta_{EDQE} = \frac{\frac{P_o}{h\omega}}{\frac{I - I_{th}}{e}} = 23.94\%$

- Extraction efficiency, $\eta_{EE} = \frac{\frac{1}{2L}\ln\left(\frac{1}{R^2}\right)}{\frac{1}{2L}\ln\left(\frac{1}{R^2}\right) + \alpha_s} = 82.50\%$

- Internal differential quantum efficiency, $\eta_{IDQE} = \frac{\eta_{EDQE}}{\eta_{EE}} = 29.01\%$

5.2. Solar Cell

Using the specifications mentioned in section 2, we get the following I-V characteristics from simulation, as shown in Figure 15:

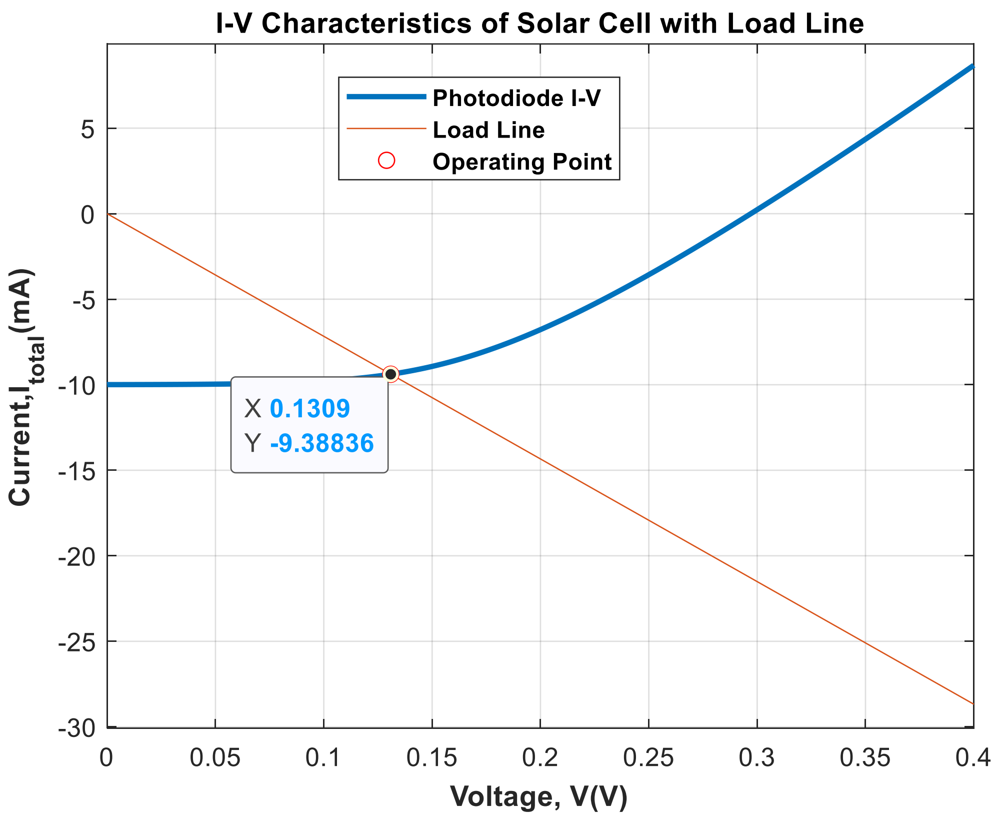


Figure 15: I-V characteristics of solar cell with load line. Operating point is represented by red dot.

Here, to get the load line, we have used a load resistance, R_L in series with the LASER. The reason is that we already know the threshold electric current that we need to supply to the laser from the solar cell. So, we will need to find an operating point where the current exceeds that value. We will use R_L to maneuver the load line such that we can achieve such a current. In our case, even when R_L is set to zero, we see that the current is 9.3 mA which is greater than 4.1 mA, so we will get lasing action. The fill factor of our solar cell is found to be 0.47.

5.3. Photodetector

Using the specifications and equations mentioned in section 4, we first vary the width of the photodetector and plot the responsivity curve. We will assume that the minimum responsivity needs to be 0.7.

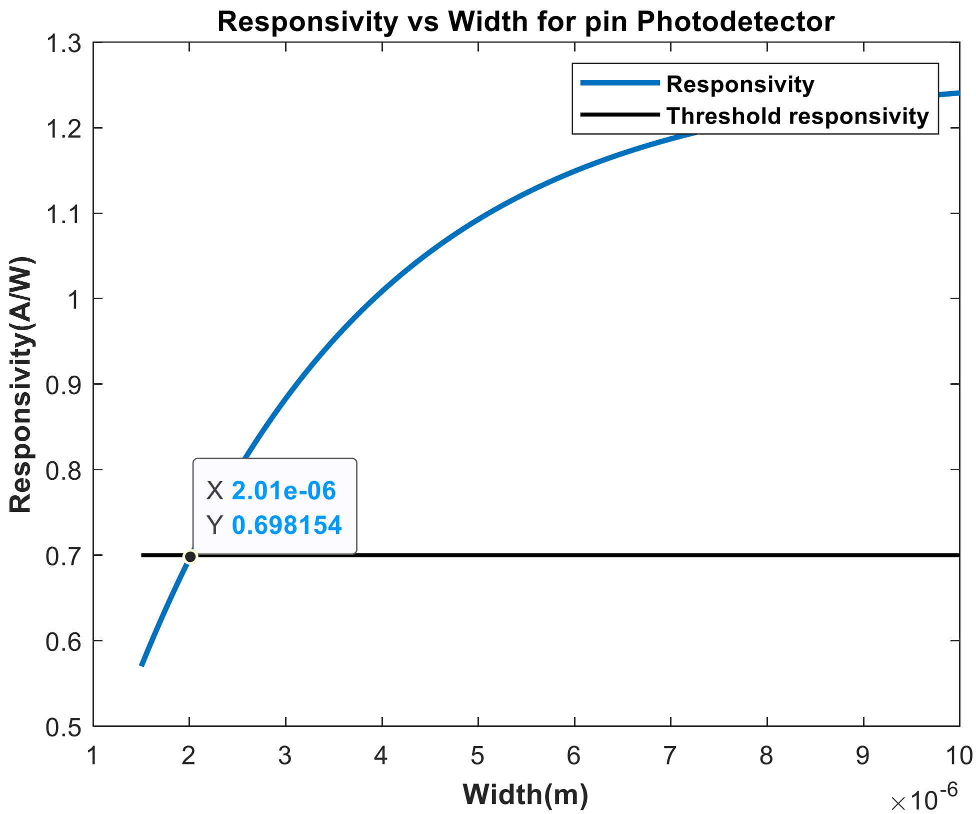


Figure 16: Responsivity vs width for pin photodetector is shown. Black line represents threshold responsivity.

From Figure 16, we can see that the width at the required responsivity is around 2 um. As responsivity increases with width, this will be the minimum width for our photodetector. We have used a width of 3 um which gives us a responsivity of 0.88.

Since our input power intensity is 6.6941×10^{8} Wm^{-2}, due to attenuation at the photodetector end, the intensity becomes1.23×10^{6} Wm^{-2} & we find the incident optical power by multiplying this quantity with the area of the photodetector. Finally, we can find the output current generated by the detector from responsivity as 201.34 nA. The Signal to noise ratio is found to be 30.53db.

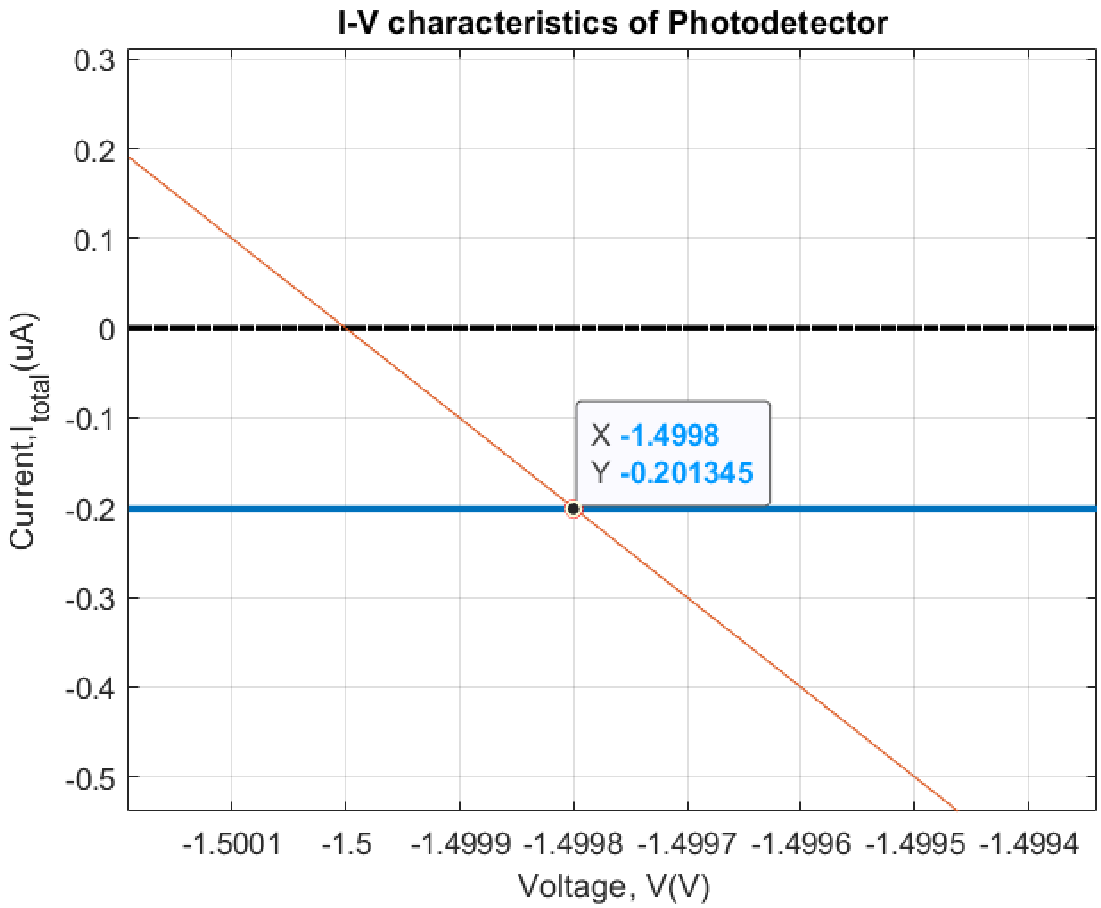


Figure 17: I-V characteristic of photodetector shows operation in the photoconductive region

6. Conclusion

In this project, we have simulated an optoelectronic integrated circuit. The idea is to use a solar cell to drive a LASER, the output of which will be an optical signal of single frequency. This output is fed to a photodetector designed to detect that particular wavelength. Among notable challenges were the modelling of the gain vs wavelength curve for different injections from literature, and choosing the width of the photodetector such that a reasonable photocurrent is generated. As a part of future work, we can design the circuit to include a modulator that will modulate the output of laser to a different frequency. We can also include an LED that will turn ON to indicate that every block is working fine.

7. Acknowledgement

We would like to thank Dr. Muhammad Anisuzzaman Talukder and Shoriful Islam for their guidance in this project.

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Appendix

A. Code

```
clc;
close all;
clear all;

%% Parameter

Temp = 290; %temperature in kelvin
Irr = 500; %Irradiance(Wm-2)

%% Solar cell
[Iout_sc,FF] = solar_func(Irr,Temp);
fprintf("Output current from solar cell=%.2f mA, Fill
factor=%.2f\n", Iout_sc*1e3, FF);

%% Laser
I = -Iout_sc;
[lambda_in,Intensity,Rd] = laser_func(I);
fprintf("Output intensity from laser=%.2f MW per square
meter at wavvelength %.2f micrometer\n", Intensity/1e6,
lambda_in*1e6);

%% Photodetector
%[Iout_pd] =
photodetector_func(lambda_in,Pout_laser,Temp)
[Iout,SNR_db] =
pin_photodetector_func(lambda_in,Intensity,Temp);
fprintf("Output current from detector=%.2f nA, SNR in
dB=%.2f", Iout*1e9, SNR_db);
```

A.1. Solar Cell

```
function [Iout,FF] = solar_func(Irr,Temp)

close all;
%% parameter

e = 1.6e-19;
kb = 1.38e-23;

T = 300; % temperature in kelvin
I0 = 25e-9; %reverse saturation current(A)
K = 2e-5; % for Si solar cell
Iph = K*Irr; %Photocurrent of the solar cell(A)
Eg = 1.14; % Bandgap of Si
n = 1; %Ideality factor
Rs = 10; %series resistance of the equivalent model
Rp = 1e6; %parallel resistance of the equivalent model

%% Temperature Effect
T_new = Temp;
I0_old = I0;
I0=((T_new^3)*exp(Eg./(kb*T_new/e)))*I0_old/((T^3)*exp(
Eg/(kb*T/e))); %reverse saturation current(A)

%% Calculation of current, power(considering Rp and Rs)
V=0:0.0001:0.4;
I_total = zeros(1,length(V));
for i = 1:length(V)
    fcn = @(I) -I - Iph + I0*(exp(e*(V(i)-
I*Rs)/(n*kb*T))-1) + (V(i)-I*Rs)/Rp;
    I = fzero(fcn,Iph);
    I_total(i)= I;
end
Power = (-I_total.*V);


%% Load Line
R = 13.9476;
err = (-V/R-I_total);
```

```
index = find(abs(err) == min(abs(err)));

%% I-V Curve Plot
figure
plot(V,I_total*1e3,'Linewidth',2)
xlabel('Voltage, V(V)', 'FontWeight','bold')
ylabel('Current,I_{total}(mA)', 'FontWeight','bold')
grid on;
hold on
%line([V(1), V(end)], [0, 0], 'Color',
[0,0,0],'LineStyle','-.','linewidth',2);
plot(V,(-V/R)*1e3);
plot(V(index),I_total(index)*1e3,'ro');
title('I-V Characteristics of Solar Cell with Load
Line')
legend({'Photodiode I-V', 'Load Line', 'Operating
Point'}, 'FontWeight','bold')
Iout = I_total(index);
% Vout = V(index);
% Pout = (-Iout)*Vout;

% figure
% plot(V,Power)
% xlabel('Voltage, V(V)')
% ylabel('Power(W)')

%% Fill Factor calculation

Isc = Iph;
Pmax = max(Power);
index = find(min(abs(I_total)) == abs(I_total));
Voc = V(index);
FF = Pmax/(Isc*Voc);

end
```

A.2. Laser

```
function [lambda_in,Intensity_out,Rd] = laser_func(I)

close all

%% parameter definition

N0 = 6.5e23;
a0 = 3.13e-20;
a_bar = 1.2;
lambda_0 = 1.575e-6;
b0 = 3.17e-26*1e-6;
b1 = 0;
lambda_z0 = 1.625e-6;
z0 = -2.5e-27*1e-6;

%% plotting for discrete concentration values

N = [3 2.5 2 1]*1e24;
lambda = [1.45:0.01:1.65]*1e-6;
hw = 1243./(lambda*1e9);

gp = zeros(1,length(N));
lambda_p = zeros(1,length(N));
lambda_z = zeros(1,length(N));
cn = zeros(1,length(N));
dn = zeros(1,length(N));
gm = zeros(length(lambda), length(N));

for j=1:length(lambda)
    for i=1:length(N)

        gp(i) = a0*(N(i)-N0) + a0*a_bar*N0*exp(-
N(i)/N0);
        lambda_p(i) = lambda_0 - (b0*(N(i)-N0) +
b1*((N(i)-N0)^2));
        lambda_z(i) = lambda_z0 - z0*(N(i)-N0);

        cn(i) = 3*gp(i)/((lambda_z(i)-lambda_p(i))^2);
```

```
        dn(i) = 2*gp(i)/((lambda_z(i)-lambda_p(i))^3);

        if lambda(j)<lambda_z(i)
            gm(j,i) = cn(i)*((lambda(j) -
lambda_z(i)).^2) + ...
                dn(i)*((lambda(j) - lambda_z(i)).^3);
        end
    end
end

figure()
for i=1:length(N)
    plot(hw, gm(:,i), 'LineWidth', 2);
    hold on
end
xlabel('Energy (in eV)')
ylabel('Optical gain')
legend('3e18', '2.5e18', '2e18', '1e18')
title('Optical gain vs Energy for differnet
injections')

%% plotting for continuous concentration values

N = [0.75:0.01:3]*1e24;
lambda = [1.45:0.01:1.65]*1e-6;
hw = 1243./(lambda*1e9);

gp = zeros(1,length(N));
lambda_p = zeros(1,length(N));
lambda_z = zeros(1,length(N));
cn = zeros(1,length(N));
dn = zeros(1,length(N));
gm = zeros(length(N), length(lambda));
gpeak = zeros(1,length(N));

for i=1:length(N)
    for j=1:length(lambda)

        gp(i) = a0*(N(i)-N0) + a0*a_bar*N0*exp(-
N(i)/N0);
```

```
        lambda_p(i) = lambda_0 - (b0*(N(i)-N0) +
b1*((N(i)-N0)^2));
        lambda_z(i) = lambda_z0 - z0*(N(i)-N0);

        cn(i) = 3*gp(i)/((lambda_z(i)-lambda_p(i))^2);
        dn(i) = 2*gp(i)/((lambda_z(i)-lambda_p(i))^3);

        if lambda(j)<lambda_z(i)
            gm(i,j) = cn(i)*((lambda(j) -
lambda_z(i)).^2) + ...
                dn(i)*((lambda(j) - lambda_z(i)).^3);
        end
    end

    gpeak(i) = max(gm(i,:));

end

figure()
plot(N*1e-6,gpeak*1e-2, 'LineWidth', 2);
xlabel('Injection density (in per cubic cm)',
'FontWeight','bold')
ylabel('Peak optical gain coefficient, g_p_e_a_k (in
per cm)', 'FontWeight','bold')
title('Dependence of peak optical gain coefficient on
injection')
ylim([0 1000])
set(gca, 'Yscale', 'log')

%% parameter definition from book example for
semiconductor laser

L = 100e-6;
W = 10e-6;
d = 0.15e-6;
gamma = 2500; %loss coefficient per meter
nr = 3.491; %In0.6 Ga0.4 As0.85 P0.15
http://www.ioffe.ru/SVA/NSM/Semicond/GaInAsP/optic.html
R = ((nr-1)^2)/((nr+1)^2); %reflectance
B = 2e-16; %exercise 4.30
```

```
e = 1.6e-19;
c = 3e8;
h = 6.626e-34;


%% calculating loss
confinement = 1;
alpha_t = gamma + (1/(2*L))*log(1/(R*R)); %total loss
gth = alpha_t/confinement;
gth_arr = gth*ones(1,length(N));
% plot(N,gpeak);
% hold on
% plot(N, gth_arr);
err = gpeak - gth_arr;
tolerance = 120;
index = find(abs(err)<tolerance);
nth = N(index); %threshold electron conc

%% plot allowed modes on the same plot as optical gain
vs lambda
figure()
plot(lambda/1e-6, gm(index,:)*1e-2, 'LineWidth', 2)
%lambda(find(max(gm(index,:))))
hold on
line([lambda(1)/1e-6 lambda(end)/1e-6], [gth*1e-2
gth*1e-2], 'Color', [0 0 0], 'LineWidth', 1.5);
xlabel('Wavelength (in um)', 'FontWeight', 'bold')
ylabel('Optical gain (in per meter)', 'FontWeight',
'bold')
title('Optical gain vs wavelength at threshold electron
concentration')
max_index = find( gm(index,:) == max(gm(index,:)) );
lambda_in = lambda(max_index);


%% radiative lifetime calculation

tau_r = 1/(B*nth);

%% Threshold current density
```

```
Jth = nth*e*d/tau_r;
Ith = W*L*Jth;

%% Photon cavity lifetime

tau_ph = nr/(c*alpha_t);

%% Output Power

%lambda_in = 1500e-9; %from figure 4.48
Pout_slope = (h*c*c*tau_ph*(1-R)/(2*e*nr*lambda_in*L));
Pout = Pout_slope*(I-Ith);
Intensity_out = Pout/(W*d);

%% Rd calculation
h = 6.626e-34;
kb = 1.38e-23;
tau_sp = 300e-9;
Ni = 1.88e17; % in m^-3 In0.6 Ga0.4 As0.85 P0.15
T = 300;
V = 1;
Ne = Ni*exp(V*e/(2*kb*T));
Rd = (2*kb*T/e)*(tau_sp/(Ne*L*W*e*d));


end
```

A.3. Photodetector

```
function [Iout,SNR_db] =
pin_photodetector_func(lambda_in,Intensity,Temp)

close all;

%% parameter
e = 1.6e-19;
kb = 1.38e-23;
n = 1; %Ideality factor
T = 300; % temperature in kelvin
I0 = 25e-9; %reverse saturation current(A)
Eg = 0.784; %In0.53Ga0.47As
h = 6.626e-34;
c = 3e8;
Tr = 1; %perfect AR coating(assume)
ni = 1;% internal quantum efficiency(assume)
alpha = 4e5; %absorption coeff(in m^-1) %Figure 5.5
diameter = 0.12e-3; % in meter

%% Temperature Effect
T_new = Temp;
I0_old = I0;
I0=((T_new^3)*exp(Eg./(kb*T_new/e)))*I0_old/((T^3)*exp(
Eg/(kb*T/e))); %reverse saturation current(A)

%% Pout calculation
lambda_in = lambda_in*1e9; % from laser (in nm)
dia = 0.4e-6; % in meter
Area = (pi/4)*dia^2;
a = 10^(21/10); %considering very strong atmospheric
turbulence
dist = 5e-2;
Intensity_pd = Intensity*exp(-a*dist);
Pout = Intensity_pd*Area;
freq = c/(lambda_in*1e-9);

%% Finding Minimum W
```

```
Width = [1.5:0.01:10]*1e-6;
Iph_W = zeros(1,length(Width));
R_W = zeros(1,length(Width));

for i=1:length(Width)
    Iph(i) = e*ni*Tr*Pout*(1-exp(-
alpha*Width(i)))/(h*freq);
    R_W(i) = Iph(i)/Pout;
end

plot(Width,R_W, 'LineWidth',2)
hold on
line([Width(1) Width(end)], [0.7 0.7], 'Color', [0 0
0], 'LineWidth', 1.5);
legend({'Responsivity', 'Threshold responsivity'},
'FontWeight','bold');
xlabel('Width(m)', 'FontWeight', 'bold');
ylabel('Responsivity(A/W)', 'FontWeight', 'bold');
title('Responsivity vs Width for pin Photodetector');
Rmin = 0.7; %% from the chart of the book (as we
operate near the peak)
err = R_W-Rmin; % At peak lambda Rmin = 0.7
index = find(abs(err) == min(abs(err)));
W_min = Width(index);

%% Iph calculation
W = 3e-6; % in meter
Iph = e*ni*Tr*Pout*(1-exp(-alpha*W))/(h*freq);
R = Iph/Pout;
Iph_max = e*ni*Tr*Pout/(h*freq);

%% Calculation of current, power
Vr = 1.5;
V = -2:0.0001:0;
I_total = -Iph + I0.*(exp(e*V/(n*kb*T))-1);
Power = (-I_total.*V);
%index = find(V == -Vr);

%% Load Line
```

```
RL = 1000;
err = (-(V+Vr)/RL-I_total);
index = find(abs(err) == min(abs(err)));

%% I-V Curve Plot
figure
plot(V,I_total*1e6,'Linewidth',2)
xlabel('Voltage, V(V)')
ylabel('Current,I_{total}(uA)')
grid on;
hold on
line([V(1), V(end)], [0, 0], 'Color',
[0,0,0],'LineStyle','-.','linewidth',2);
plot(V,-((V+Vr)/RL)*1e6);
plot(V(index),I_total(index)*1e6,'ro')
title('I-V characteristics of Photodetector')
Iout = I_total(index); % in A
Vout = V(index);


%% SNR calculation
B = 1e6; %in Hz
signal_power = (Iph^2)*RL;
noise_power = [2*e*(I0+Iph)*B]*RL+4*kb*T*B;
SNR = signal_power/noise_power;
SNR_db = 10*log10(SNR);
end
```