Lab Report: Experiment 5

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Experiment:
Measuring the I-V characteristics of a diode and determining Is and n. Finding small signal dynamic resistance(rd). Analyzing the DTFT of Id and determining harmonic amplitudes.

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1 Aim

1. Measure the DC I–V characteristic of a diode and extract diode parameters (ideality factor η and saturation current $\mathbf{I_s}$).

2. Measure the small-signal (dynamic) resistance $\mathbf{r_d}$ around a chosen bias point and verify the small-signal model.

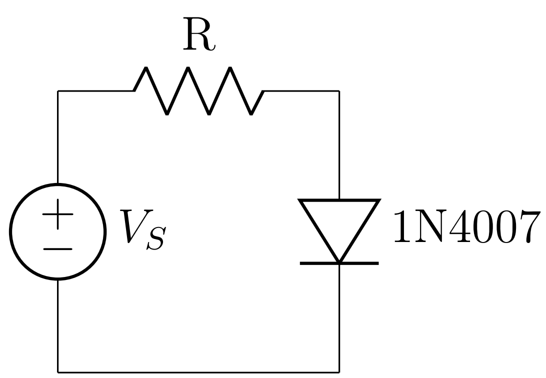
3. Further, bias the diode with a DC voltage and apply a small AC signal. Observe the output on the CRO and use FFT mode to see harmonics. The diode current is nonlinear,

$$I \approx I_0 + g_1 v + \frac{1}{2} g_2 * v^2.$$

   - For small V_{ac}, only the fundamental appears.
   - As V_{ac} increases, 2nd and higher harmonics appear, showing nonlinearity.
   - Measure fundamental and 2nd harmonic amplitudes vs V_{ac} and note slopes 1 and 2

2 I-V characteristics of Diode

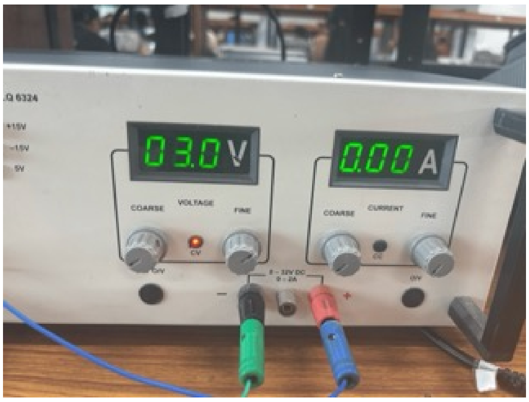
V_D (diode voltage) is calculated for multiple values of V_S (source voltage). The below circuit is used, along with a multimeter to take voltage readings for multiple V_S values



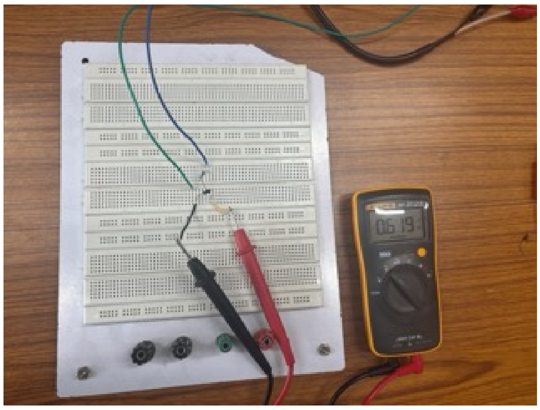
V_S (V)	V_D (V)
0.0	0.0
0.1	0.143
0.2	0.250
0.4	0.399
0.6	0.478
0.8	0.519
1.0	0.544
1.2	0.560
1.4	0.571
1.6	0.579
1.8	0.588
2.0	0.595
2.2	0.601
2.4	0.608
2.6	0.614
2.8	0.617
3.0	0.621
3.2	0.626
3.4	0.629
3.6	0.633
3.8	0.636
4.0	0.639
4.2	0.641
4.4	0.644
4.6	0.647
4.8	0.649
5.0	0.652

We require the exponential curve that is closest to all the obtained data points. So curve-fitting must be done. Scipy's curve_fit was used. I_s, η was calculated using the same python code.
Schokley's equation for the diode was used for curve fitting with parameters I_S, η.

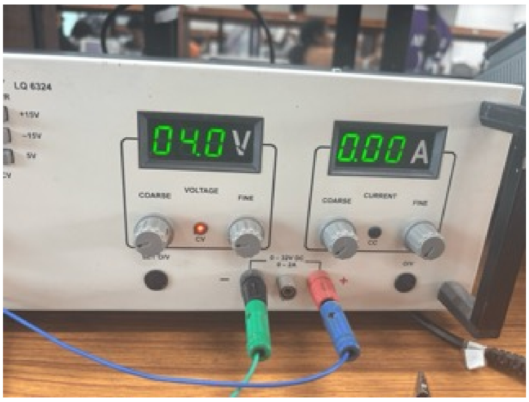
$$I_D = I_S(e^{\frac{V_D}{\eta V_T}} - 1)$$



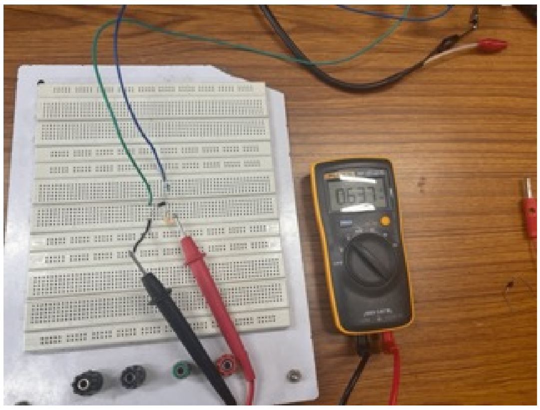
(a) Input V_S



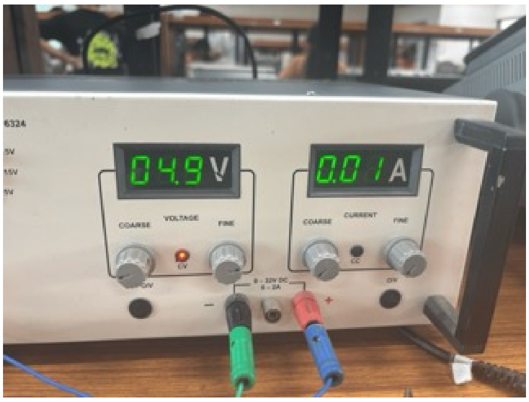
(b) Output V_D



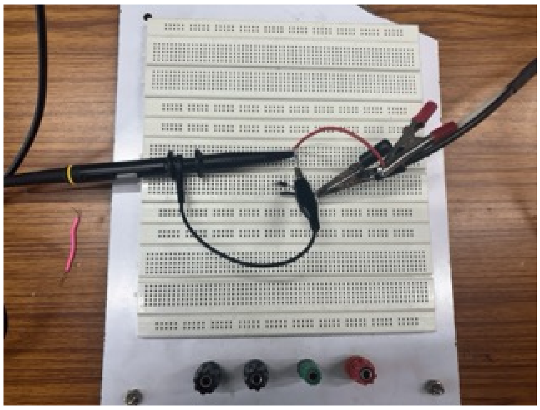
(a) Input V_S



(b) Output V_D

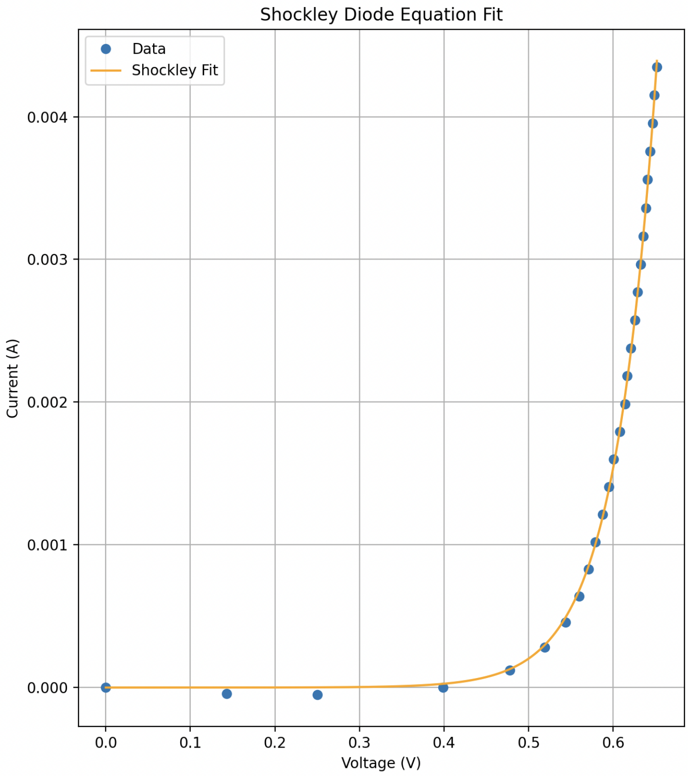


(a) Input V_S



(b) Output V_D

Curve (I_S vs V_D) obtained through curve-fitting



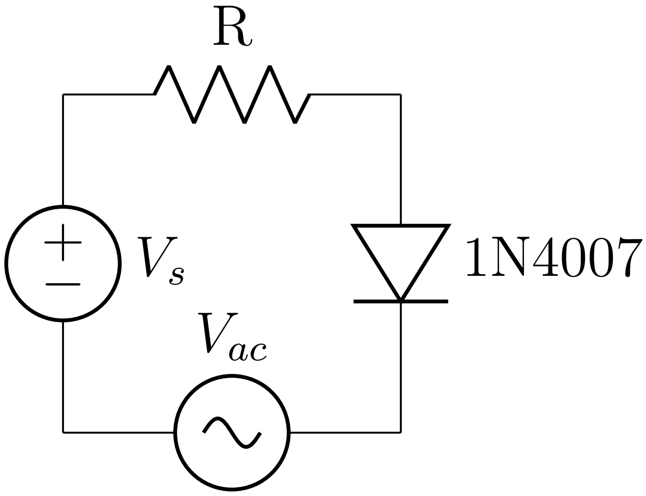
We obtain diode parameters,

- Ideality factor (η) $= 1.907$
- Saturation current (I_s) $= 8.109nA$

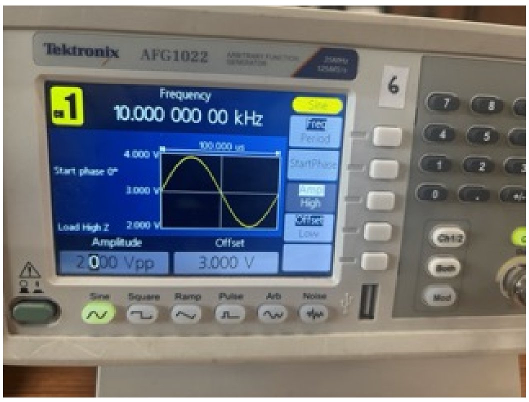
Code used for curve-fitting can be found at, https://github.com/ArjunPavanje/EE2301/blob/main/Experiment_5/codes/diode.py

3 Small Signal Analysis

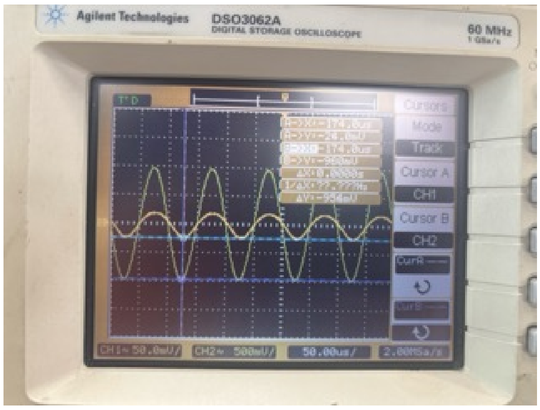
After fixing a bias point, a sine-wave of very small amplitude was applied to calculate small signal characteristics.



We pick 2 points and note V_S, V_D values.



(a) Function generator input



(b) Oscilloscope output

V_s	V_d
3.960	3.018
2.040	2.982

Small signal parameter r_d is calculated (for bias point $V_D = 3V$) as,

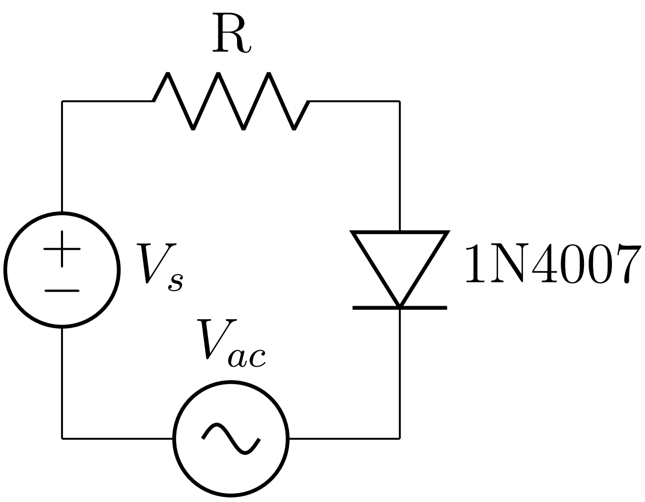
$$r_d = \left(\frac{dI_D}{dV_D}\right)^{-1} = \frac{d}{dV_D}(I_S(e^{\frac{V_D}{\eta V_T}} - 1))$$
$$r_d = \frac{\eta V_T}{I_D + I_S}$$
$$r_d \approx \frac{\eta V_T}{I_D}$$

- Theoretical: $\frac{\eta V_T}{I_D} = 20.697829278523 49\Omega$
- Calculated: $\frac{\Delta V_D}{\Delta I_D} = 19.108280254776847\Omega$

I_D is found by $\frac{V_S - V_D}{R}$. η value calculated previously is used in theoretical calculation. Thus, small signal parameter r_d is calculated and verified. Code used to calculate and verify small signal parameter (r_d) can be found at, https://github.com/ArjunPavanje/EE2301/blob/main/Experiment_5/codes/rd.py

4 FFT Harmonics

To observe FFT harmonics we reuse the circuit built previously,



To observe harmonics of I_D we can just observe resistor voltage $(V_S - V_D)$ as it is just a scaled version (RI_D) of diode current. When V_{ac} is very small, we observe only one peak at frequency f (frequency of sinusoidal signal). As we increase V_{ac}, number of peaks increases and the peaks occur at $f, 2f, 3f, \cdots$.

This happens due to the fact that the DTFT of a sinusoidal wave has a single peak at the fundamental frequency of the wave. Now as we expand I_D using taylor series, we get:

$$WKT,$$
$$I_D = I_S(e^{\frac{V_D}{\eta V_T}} - 1)$$
$$Also,$$
$$I_{D0} = I_S(e^{\frac{V_{D0}}{\eta V_T}} - 1)$$

Since, the input signal is a sinusoidal small signal with a DC offset, we can write:

$$V_D = V_{D0} + v(t)$$

Substituing this in the previous equation:

$$I_D = I_S(e^{\frac{(V_{D0}+v(t))}{\eta V_T}} - 1)$$
$$I_D = I_S(e^{\frac{v(t)}{\eta V_T}}(\frac{I_{D0}}{I_S} + 1) - 1)$$
$$I_D = I_{D0} + I_S e^{\frac{V_{D0}}{\eta V_T}}(e^{\frac{v(t)}{\eta V_T}} - 1)$$

Expanding Taylor series for $e^{\frac{v(t)}{\eta V_T}}$,

$$e^{\frac{V_{D0}+v(t)}{\eta V_T}} = e^{\frac{V_{D0}}{\eta V_T}} e^{\frac{v(t)}{\eta V_T}}$$
$$= e^{\frac{V_{D0}}{\eta V_T}} \left[1 + \frac{v(t)}{\eta V_T} + \frac{1}{2!}\left(\frac{v(t)}{\eta V_T}\right)^2 + \frac{1}{3!}\left(\frac{v(t)}{\eta V_T}\right)^3 + \frac{1}{4!}\left(\frac{v(t)}{\eta V_T}\right)^4 + \cdots\right]$$

So I_D becomes,

$$I_D = I_{D0} + I_S e^{\frac{V_{D0}}{\eta V_T}} \left[\frac{v(t)}{\eta V_T} + \frac{1}{2!}\left(\frac{v(t)}{\eta V_T}\right)^2 + \frac{1}{3!}\left(\frac{v(t)}{\eta V_T}\right)^3 + \frac{1}{4!}\left(\frac{v(t)}{\eta V_T}\right)^4 + \cdots\right]$$
$$I_D = I_{D0} + \left(\frac{I_S e^{\frac{V_{D0}}{\eta V_T}}}{\eta V_T}\right) v(t) + \frac{1}{2}\left(\frac{I_S e^{\frac{V_{D0}}{\eta V_T}}}{(\eta V_T)^2}\right) v(t)^2 + \cdots$$

Taking $g_1 = \frac{I_S e^{\frac{V_{D0}}{\eta V_T}}}{\eta V_T}$ and $g_2 = \frac{I_S e^{\frac{V_{D0}}{\eta V_T}}}{(\eta V_T)^2}$,

$$I_D = I_{D0} + g_1 v(t) + \frac{1}{2} g_2 v(t)^2 + \cdots$$
$$\implies I_D \approx I_{D0} + g_1 v(t) + \frac{1}{2} g_2 v(t)^2$$

Since terms like $v(t), v(t)^2, ...$ are present, and the v(t) is a sum of sines in itself, we get sum of sines of different frequencies, all being the multiples of the fundamental frequency of the input sine wave. So we get peaks at every multiple of input frequency due to the fact that I_D is a sum of sines.

Harmonic Amplitudes:

At small $v(t)$ values, we can neglect all the other terms in the Taylor series expansion of I_D except the fundamental and the first harmonic. At this small $v(t)$, we can consider it to be just a simple sinusoidal signal which is a scaled down version of the input signal.

The amplitude of $v(t)$ can be written as:

$$A = V_m \frac{r_d}{r_d + R_L}$$

where V_m is the amplitude of the input sine signal. So, applying this in the equation,

$$I_D = I_{D0} + g_1 A sin(2\pi f t)$$

where f is the frequency of the input sine wave.
So the first peak occurs at f with amplitude $g_1 A$. By plugging in the values, we get

$$\text{Amplitude} = 4.993 \times 10^{-4}$$

When we increase V_m by a bit such that the second harmonic also is seen, I_D can be written as:

$$I_D = I_{D0} + g_1 A sin(2\pi f t) + \frac{1}{2} g_2 A^2 sin^2(2\pi f t)$$
$$I_D = I_{D0} + g_1 A sin(2\pi f t) + \frac{1}{2} g_2 A^2 (1 - cos(4\pi f t))$$

So, the second peak occurs at $2f$ with amplitude $\frac{1}{2} g_2 A^2$. By plugging in the values, we get

$$\text{Amplitude} = 15.96 \times 10^{-4}$$

Interpretation of Slopes for Fundamental and Second Harmonic

When we plot the amplitudes of the fundamental and second harmonic components of the diode current with respect to the amplitude of the applied AC voltage V_{ac} on a log–log scale, we observe different slopes corresponding to the order of nonlinearity.

For small signal amplitudes, the diode current can be expressed as

$$I_D(t) = I_{D0} + g_1 v(t) + \frac{1}{2} g_2 v(t)^2 + \cdots$$

where $v(t) = V_m \sin(\omega t)$.

The amplitude of the fundamental component is proportional to V_m, i.e.,

$$I_{\text{fundamental}} \propto V_m$$

and the amplitude of the second harmonic component is proportional to V_m^2, i.e.,

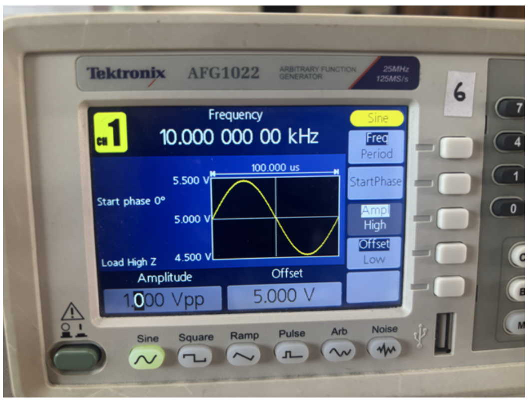
$$I_{\text{2nd harmonic}} \propto V_m^2$$

Therefore, when plotting $\log(I_{\text{fundamental}})$ and $\log(I_{\text{2nd harmonic}})$ versus $\log(V_{\text{ac}})$:

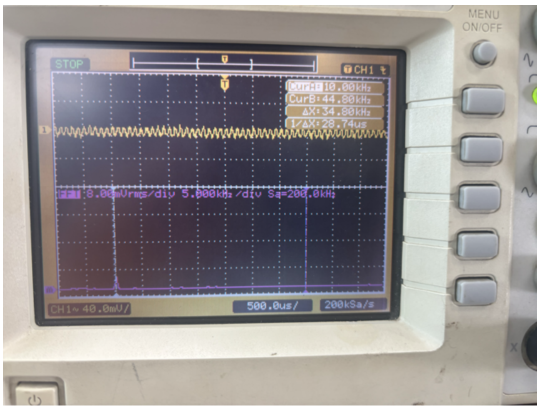
$$\text{slope of fundamental} \approx 1, \quad \text{slope of 2nd harmonic} \approx 2$$

This indicates that the fundamental component arises from the first-order (linear) term, while the second harmonic arises from the second-order (nonlinear) term in the diode's exponential I–V characteristic.

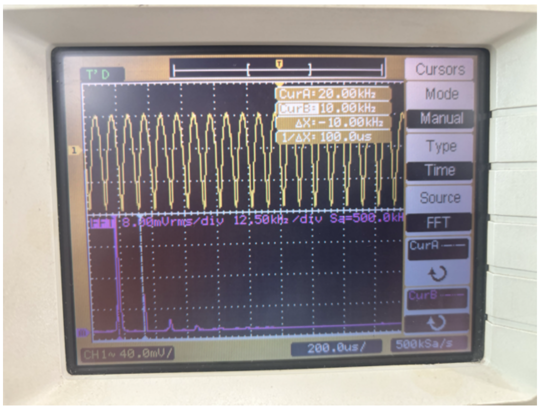
Below are the pictures of the FFT mode on the oscilloscope for increasing V_m values:



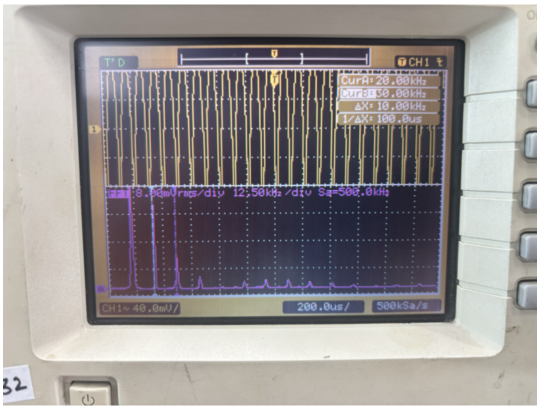
(a) Function generator



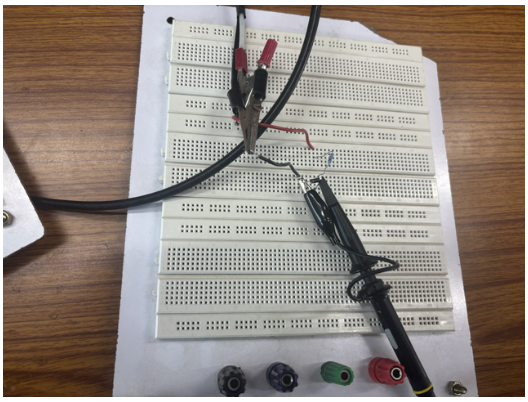
(b) Oscilloscope

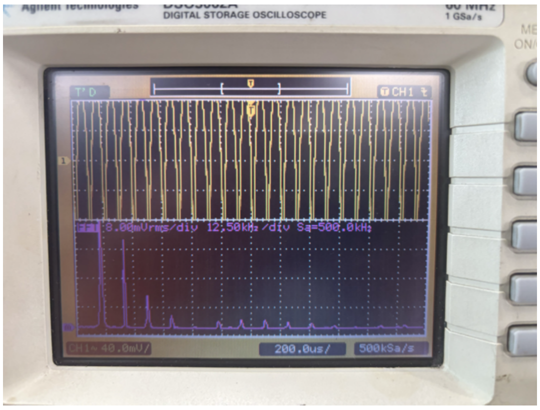


(a) Function generator (b) Oscilloscope



(a) Function generator (b) Oscilloscope





Code used to calculate amplitudes can be found at, https://github.com/ArjunPavanje/EE2301/blob/main/Experiment_5/codes/fft.py

5 Conclusion

In this experiment, I-V characteristics of diodes were plotted and diode parameters I_S (saturation current), η (ideality factor) were found. Next, by giving a small AC-signal at a particular bias point, we estimate small signal parameter r_d and verified it. Finally, using FFT mode, harmonics in diode current were observed by adjusting values of V_{ac}.