ELEC – 310

MICROELECTRONIC CIRCUITS AND DEVICES

TERM PROJECT

WIRELESS AUDIO TRANSMITTER/RECEIVER W/ DIODE LASER

17.01.2022

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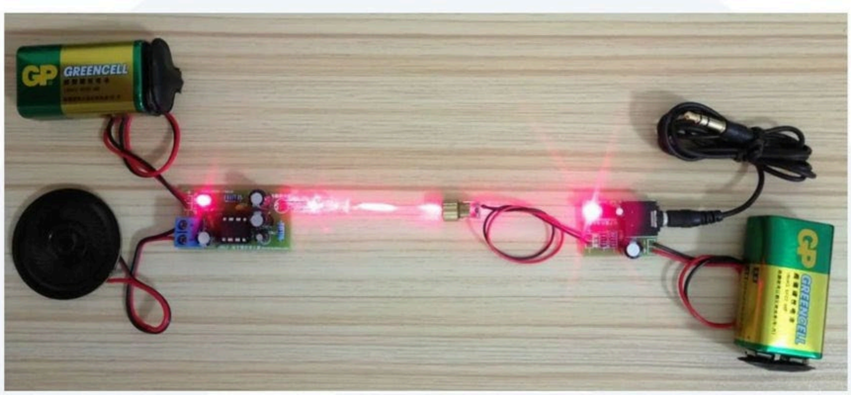
INTRODUCTION

This project aims to transmit an audio signal with a diode laser and receive it using a phototransistor to convert it back into an electric current. An adjustable resistor (potentiometer) at the receiver side enables the control of the output voltage, i.e., the sound level of the speaker.

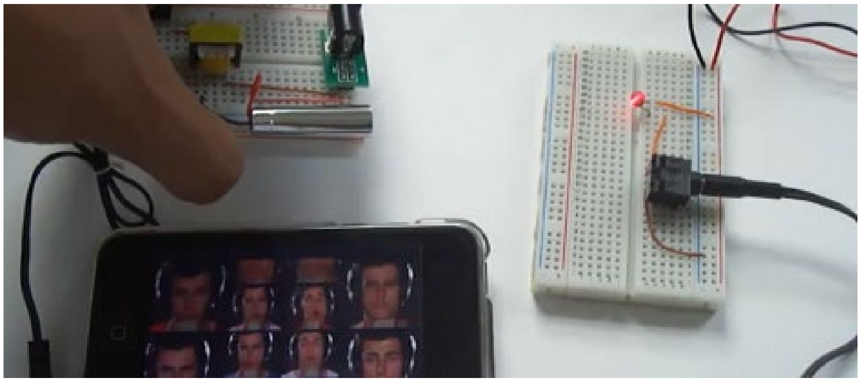
Using laser is an efficient method of information transmission due to its durability over long ranges. In more advanced cases, the signal can be modulated (amplitude modulation/frequency modulation) using different schemes to make the transmission more robust and durable against noise. In this simulation, the medium is assumed to be air. To compensate for the effect of noise, the signal is amplified before transmission. The use of laser transmission is not limited to the audio signals, but any kind of information (video, text, etc.) can be transferred through this scheme.

At both transmitter and the receiver sides, Bipolar Junction Transistors are used to obtain gain in the small signal. The circuit model is based on the Common Emitter (CE) amplifier model in the "Single-stage BJT Amplifier" Lab (#6). A CE amplifier model is chosen due to its high voltage, current, and power gain because a higher-amplitude unmodulated signal is likely to be corrupted less in a noisy environment. The types of transistors, resistor, and capacitance values are chosen such that it is easily constructible using the lab equipment we have been using throughout the term. The only missing components needed to be ordered would be laser diode and photoresistor. Therefore, the main objective of this model is to be easily understood and constructed, although more complex models with higher gain can be achieved (See section 6.11 (Neamen, 2010) for an audio amplifier with an overall gain of ≈ 144, where the whole circuit model and calculations are readily provided.)

Due to the pandemics, we could not it had not been possible to construct the circuit in the laboratory. If it were possible, the setup would look similar to the ones provided in Figure 1.



(a) An experimental setup where a laser diode is used to transmit audio signals. The batteries in the figure would be replaced with a function generator and oscilloscope in our case. (365 Online Editors, n.d.)



(b) Another experimental setup for the same purpose in (a). Note that the laser diode (shiny gray component mounted on the breadboard on the left) is receiving its audio signal input from the mobile phone jack output, and the laser signal transmitted is falling onto the photoresistor mounted on the breadboard at the right. (Herrero, n.d.)

Figure 1: Sample Experimental Setups

TECHNICAL SPECIFICATIONS

In this section, we start with the list of minimum components to construct this circuit (plus, to run the simulations) in Table 1. It is followed by the complete circuit schematics, including both the receiver and the transmitter as an introduction. Some minor notes and a general introduction are provided, followed by detailed explanations and calculations of transmitter and receiver components.

Components List, Circuit Diagram & A General Intro

The minimal list of components for this experiment is determined to be as follows:

Table 1: Components Table

Quantity	Equipment
2	160kΩ resistor
1	9.4 kΩ Resistor
1	50 kΩ Potentiometer
1	Photoresistor (LDR)
1	47μF Capacitor.
2	2N3904 NPN BJT
1	5V (max) DC Voltage Source (w/ 3 channels)
1	Laser Diode (1N4007 for the simulation)
1	Microphone (AC + DC Input Voltage Source)
1	Speaker

The complete circuit diagram with the input signal, transmitter, and receiver is provided in Figure 2 below.

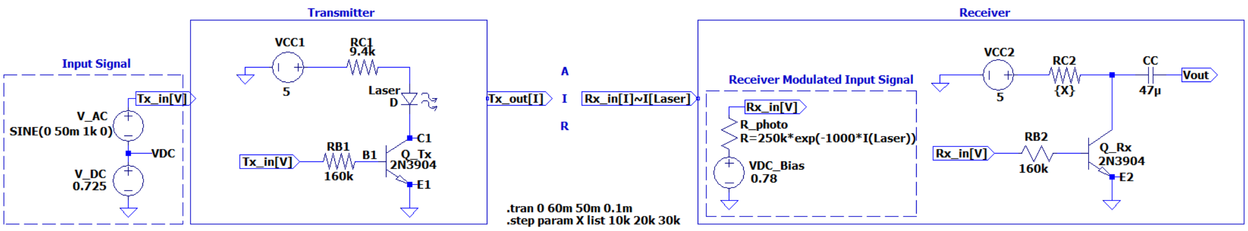


Figure 2: Circuit Schematics

Laser Diode (diode named 'Laser' in Figure 2)'s light intensity depends on the current that passes through it. Therefore, the goal of the transmitter circuit is to amplify gain. This transmitter model provides a current gain of ≈ 300, which is the maximum possible gain because $\beta_{max} = 300$ and $i_C = \beta i_B$. The receiver, on the other hand, aims to adjust the voltage gain of the received signal. R_{C2} is designed as a potentiometer whose resistance value is controlled through the parameter $X = \{10k, 20k, 30k\}\Omega$.

Note that there is not a photoresistor available in the LTspice library. Therefore, R_{photo} is designed to mimic one, whose resistance value is controlled by the current of the laser diode. There is an inverse logarithmic relation between the intensity of light ($\propto I_{Laser}$) falling on the photoresistor and the resistance of the photoresistor. Thus, it is designed to be in the form $R_{photo} = A \times e^{-B \times I_{Laser}(t)}$. There is not a generic formula to obtain the constants A and B. They are determined to demonstrate the effect of air (diminished amplitude, noise) and to make the receiver work efficiently. The inverse proportionality between the laser current ($\propto$ laser diode light intensity) and photoresistor resistance is shown in the following Figure 3:

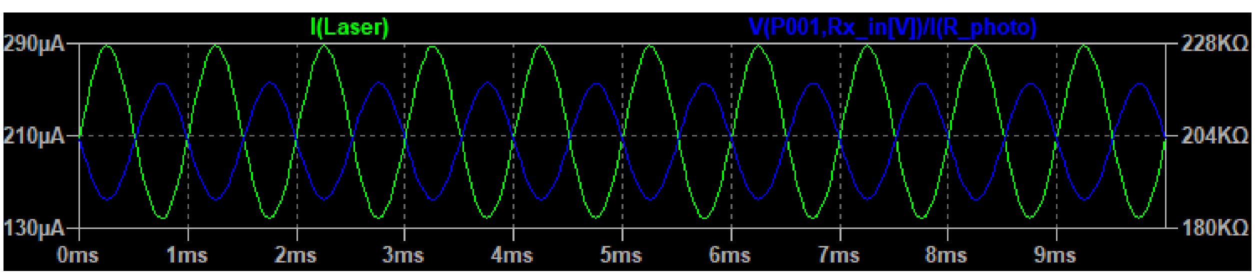


Figure 3: The inverse relation between the laser diode current and photoresistor (LDR (Light Dependent Resistor)) resistance.

When the current going through the laser diode starts to increase, LDR resistance decreases. Similarly, when the laser current starts to decrease, the resistance value of LDR starts to increase. Overall, LDR preserves the form (both are sine signals) of the input signal (light) with a phase and amplitude difference.

The bias voltage in the receiver acts as a DC offset on which the incoming light builds sinusoidal fluctuations to output an AC voltage signal. Alternating resistance is something we have not covered during the course and harms the linearity of the resistors, so further explanation and assumptions about its implementation will be provided in the upcoming parts of this report.

The potentiometer (R_{C2}) in the receiver controls the amplitude of the output signal. Coupling capacitor CC removes the DC offset from the V_C of the receiver. Voltage gain in the receiver is turned out to be ≈ 42. Both transistors in the transmitter and receiver function in the forward active region all the time. Although this is a simulation and there is no noise and other losses, the implementation of the laser diode-photoresistor system is designed to resemble a lossy system, therefore, the overall gain is <u>not</u> simply $A_{v,tx} \times A_{v,rx}$ (or $A_{i,tx} \times A_{i,rx}$). For the chosen potentiometer resistance range and imposing forward active region operation, overall small signal (voltage) gain goes up to $A_v = -3$.

Repeating once more, the transmitter is designed as a current amplifier because laser diode's brightness depends on the current (OdicForce Lasers Editors, n.d.), and the receiver is designed as a voltage amplifier because most of the modern audio amplifiers depend upon the voltage modulation (Self, 2012). The input signal is designed to mimic microphone input with a sine signal of the frequency $1\ kHz$ (low frequency) and has both DC and AC components. Because this model operates at low frequencies ($1\ kHz$), internal capacitances of the transistors are not taken into account. Furthermore, r_0 value of the transistors is taken to be infinite and ignored since they are much larger than the capacitors R_{C1} and R_{C2}, to which they are connected in parallel[1].

Let us start with DC and AC analysis of the transmitter. To obtain small-signal parameters (g_m, r_{pi}) of the transistor, it is first required to obtain I_{CQ}, and to verify forward active assumption.

Transmitter DC Analysis

The DC equivalent circuit is provided in Figure 4 below. Because the emitter is grounded, $V_E = 0$ all the time. This eases calculations, although emitter resistance plays a significant role in stabilizing the DC input voltage (Gingrich, 1999). As already discussed, it is favorable to add an emitter resistor (along with an emitter bypass capacitor) in a more advanced implementation, but this implementation aims to provide a complete model constructible with the equipment we already have and as simple as possible for better comprehension. Noting $V_E = 0\ V$:

$$V_C = 5 - 9.4k \times I_C - V_\gamma = V_{CE}$$

$$V_B = 0.725 - 160k \times I_B = V_{BE}$$

[1] In parallel connection of two resistors, the smaller one dominates. $R_{eq} = (R_1^{-1} + R_2^{-1})^{-1} \approx R_1$, if $R_2 \gg R_1$.

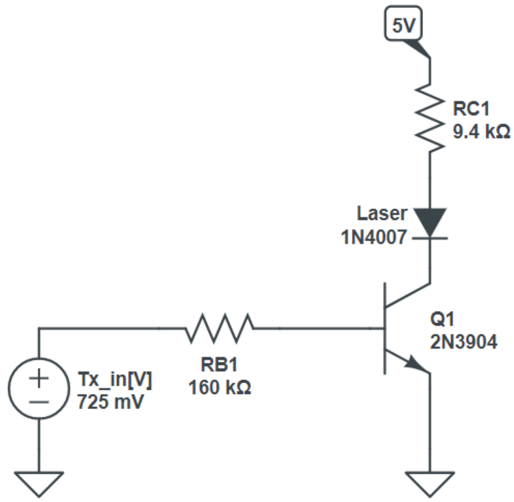


Figure 4: Transmitter DC Equivalent Circuit

where V_γ is the voltage drop across the diode. Taking $V_{BE}(on) = 0.614\ V$, I_B is obtained to be $0.684\ \mu A$. Since the operation is in the forward-active region, $I_C = \beta I_B$. Taking $\beta = 300$ (Onsemi, 2007), $I_C = 0.208\ mA$ is obtained. Similarly, $I_E = (\beta + 1)I_B = 0.209\ mA$. Noting $I_{CQ} = 0.208\ mA$, we verify the forward-active assumption by taking[2] $V_\gamma = 0.615\ V$:

$$V_C = 2.43\ V > V_B = 0.614\ V > V_E = 0$$

Finally, the choice of $0.725\ V$ for the input signal DC component should be explained. Similar to Lab #6, $V_{out}\ vs\ V_{in}$ (DC) is plotted to obtain the relation between the two for different $T_{x,in}[V]$ values. See Figure 5 for the plot and the explanation.

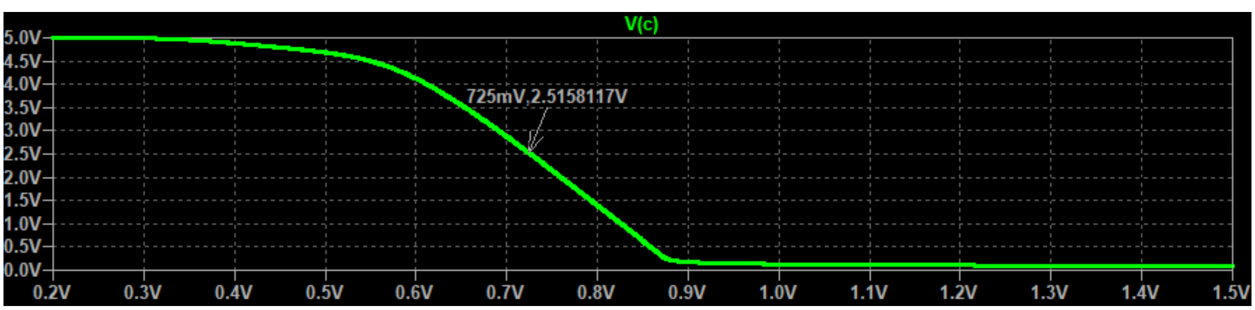


Figure 5: V_C vs V_{in} (V_{DC}).

The middle point $2.5\ V$ is marked, which corresponds to $V_{DC} = 0.725\ V$. Around the middle point of V_C vs V_{in} graph corresponds to the point where the maximum small signal gain is obtained. Note that the initial decrease is not as sharp as the graph obtained in the lab because of the initial voltage drop caused by the diode.

[2] LTspice model parameter.

Transmitter AC Analysis

The following parameters are calculated using the simulation results, i.e., $I_{CQ} = 0.211\,mA$ instead of $0.208\,mA$. All the simulation results are provided in the section SIMULATION RESULTS, so please refer to this section for the explanations.

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.211}{25.85} \approx 8.162\,\frac{mA}{V}, \qquad r_\pi = \frac{\beta}{g_m} = \frac{300}{8.162\,m} = 36.756\,k\Omega, \qquad r_0 = \frac{V_A}{I_{CQ}} \approx \infty \ \text{(omitted)}$$

The small-signal parameter of the diode is r_d. It is calculated as follows:

$$r_d = \frac{V_T}{I_{DQ}} = \frac{V_T}{I_{CQ}} = \frac{1}{g_m} = 0.123\,k\Omega$$

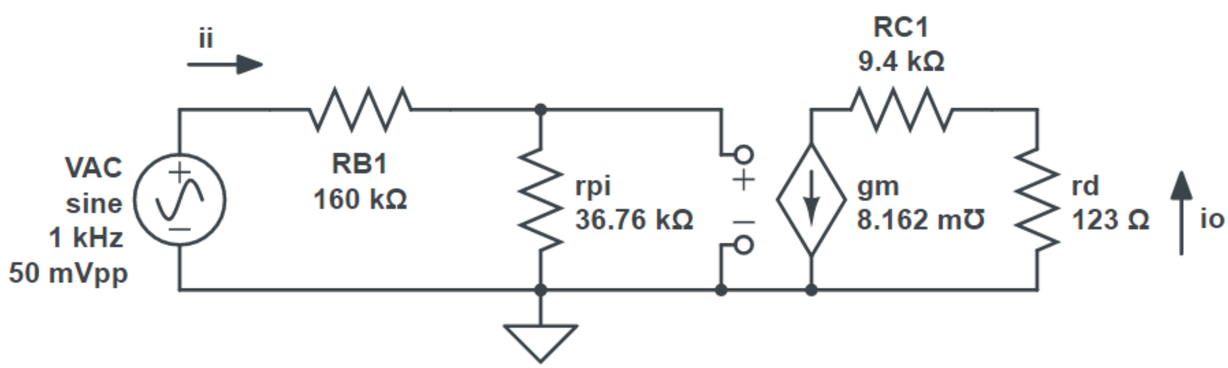


Figure 6: Transmitter AC Equivalent Circuit

$$v_\pi = v_{ac}\frac{r_\pi}{r_\pi + R_{B1}} \rightarrow i_i = i_b = \frac{v_\pi}{r_\pi} = \frac{v_{ac}}{r_\pi + R_{B1}}$$

$$i_o = g_m v_\pi = g_m v_{ac}\frac{r_\pi}{r_\pi + R_{B1}}$$

Combining the expressions for i_i and i_o, the small-signal current gain is found to be:

$$A_i = \frac{i_o}{i_i} = g_m v_{ac}\frac{r_\pi}{r_\pi + R_{B1}}\frac{r_\pi + R_{B1}}{v_{ac}} = g_m r_\pi = g_m\frac{\beta}{g_m} = \beta \approx 300$$

Receiver DC Analysis

To perform DC analysis, we must use the DC components of each component in the circuit. However, the resistor's resistance value varies with current, as it should be. This is a problem for DC analysis because 1) we cannot omit resistor because it affects the DC results, and 2) since it varies sinusoidally, we cannot include the photoresistor as it is into the DC equivalent circuit.

Similar to what we have done for AC + DC-coupled sources, we consider the photoresistor as a circuit element that has both AC and DC components[3]:

$$r_{LDR} = R_{DC} + r_{ac}$$

Thus, we can use R_{DC} for the DC equivalent circuit, and r_{ac} for the AC equivalent circuit. In fact, the explicit expression for r_{ac} is not required to obtain small-signal gain as we will soon see. To obtain R_{DC}, we integrate the full expression for its resistance over a period $T = \frac{1}{f}$, where $f = 1000\ kHz$ since r_{LDR}'s sinusoidal oscillation is determined by the I_{Laser}, i.e., i_o in Figure 6, which is also determined by v_{ac} (input signal). In the previous part, the following is obtained for $I_{Laser} = i_o$:

$$i_o = g_m v_{ac} \frac{r_\pi}{r_\pi + R_{B1}} = \underbrace{0.008162}_{g_m} \times \underbrace{0.050 \times \sin(2\pi 1000t)}_{v_{ac}} \times \underbrace{0.18681}_{\frac{r_\pi}{r_\pi + R_{B1}}})$$

$$= 76.237161 \times \sin(2000\pi t)\ \mu A$$

This is the AC component of I_{Laser}. The DC component of I_{Laser} is already calculated, and it is $I_{CQ} = 0.211\ mA$. Therefore, the complete expression for $I_{Laser}(t)$ is[4]:

$$i_{LASER}(t) = I_{CQ} + i_0 = 0.211 \times 10^{-3} + 76.237161 \times \sin(2000\pi t) \times 10^{-6}\ A$$

The resistance of the photoresistor is formulated (see Figure 2) as follows:

$$r_{LDR}(t) = 250 \times 10^3 \times e^{-1000 i_{LASER}(t)}$$

Putting in $i_{LASER}(t)$ above into this formula of $r_{LDR}(t)$, and integrating over $T = 10^{-3}\ s$:

$$R_{DC} = \frac{1}{0.001} \int_0^{0.001} 250000 \times e^{-1000\left(0.211\times10^{-3} + 76.237161\times\sin(2000\pi t)\times10^{-6}\right)} dt = \mathbf{202.738\ k\Omega}$$

This value is used for the DC equivalent circuit of the receiver. The circuit is provided in Figure 7 below.

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[3] r_{LDR} and R_{Photo} are the same quantities. In the simulation, R_{Photo} is used, but obeying the DC, AC variable naming rules, using r_{LDR} is more appropriate in here and in the following related parts of this report.

[4] Similar switch in the naming of the same quantity $I_{Laser}(t)$ and $i_{LASER}(t)$.

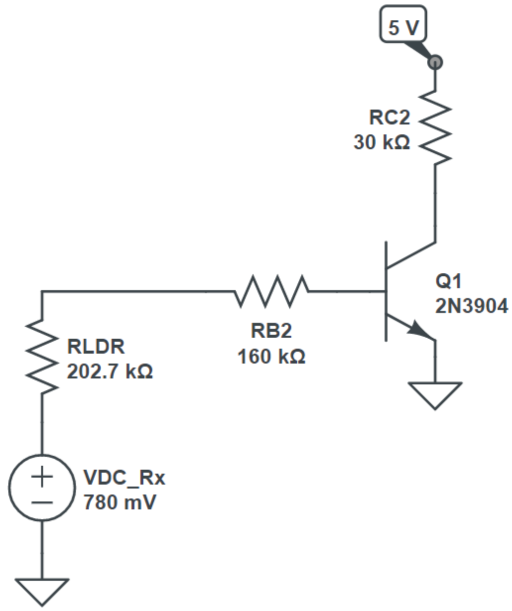


Figure 7: Receiver DC Equivalent Circuit

Note that due to the capacitor C_C, the output terminal is not included in the DC equivalent circuit, meaning that it has no DC component. Indeed, this is the reason why the capacitor is replaced in the first place: to remove the DC component of the signal and leave out the AC component only for the output.

$$V_C = 5 - 30k \times I_C$$

$$V_B = 0.780 - I_B \times (202.7 + 160)k = V_{BE} = 0.6\ V$$

This gives:

$$I_B = \frac{0.780 - 0.6}{(202.7 + 160)k} = 0.482\ \mu A$$

Assuming forward active region of operation:

$$I_C = \beta I_B = 0.1447\ mA$$

$$I_E = (\beta + 1)I_B = 0.1452\ mA$$

Therefore, $I_{CQ} = 0.1447\ mA$. As usual, to verify the forward active region of operation assumption, we calculate V_C:

$$V_C = 0.659\ V > V_B = 0.6 > V_E = 0$$

Clearly, we are around the limits of the forward active region. If $V_C \downarrow$, then $I_C \uparrow$, which increases the voltage output as we will derive the formula in the next section. However, it is not possible to significantly increase the gain from this point on (while staying in the forward active region) because further decrease in V_C causes $V_C < V_B$, which puts the transistor into saturation. Therefore, we conclude that the (approximate) maximum voltage gain possible with this configuration happens with the collector quiescent current of $I_{CQ} = 0.145\ mA$.

Receiver AC Analysis

At last, we move onto the final part where the receiver voltage gain is obtained. The steps are similar to those in Transmitter AC Analysis.

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.145}{25.85} \approx 5.609\,\frac{mA}{V}, \qquad r_\pi = \frac{\beta}{g_m} = \frac{300}{8.162\ m} = 53.483\ k\Omega, \qquad r_0 = \frac{V_A}{I_{CQ}} \approx \infty \ \text{(omitted)}$$

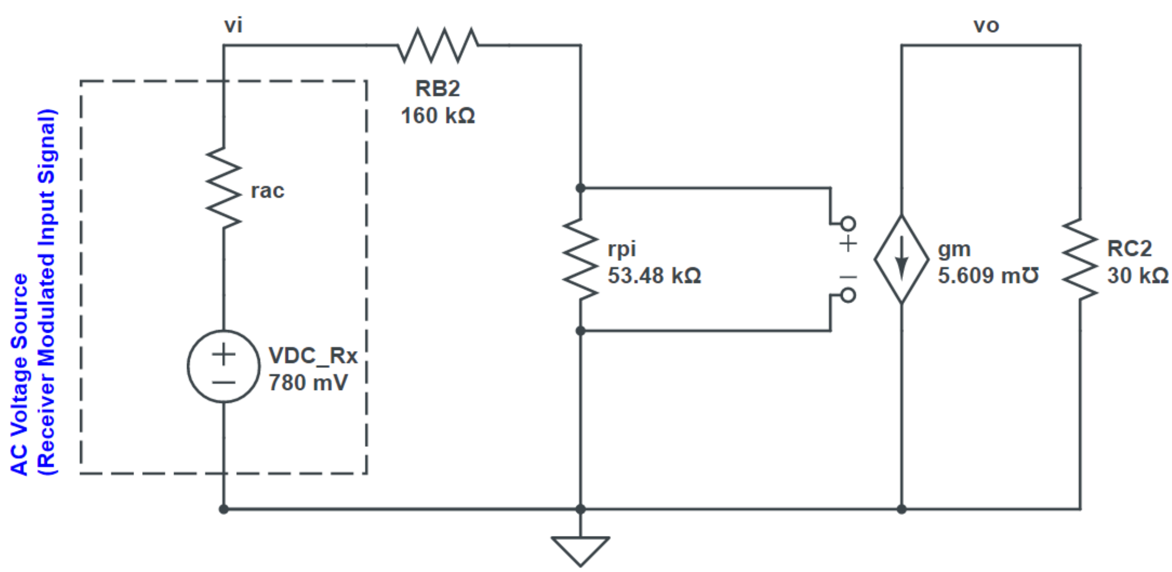


Figure 8: Receiver AC Equivalent Circuit

$$\left.\begin{aligned} v_0 &= -g_m v_\pi R_{C2} \\ v_\pi &= v_i \frac{r_\pi}{R_{B2} + r_\pi} \end{aligned}\right\} A_v = \frac{v_0}{v_i} = -g_m \frac{R_{C2} \times r_\pi}{R_{B2} + r_\pi} = -42.156$$

In other words, we expect an upside-down sinusoid whose amplitude is ≈ 42 times larger than v_i. Note that v_i here is not the input signal of the transmitter, but the AC modulated DC voltage input of the transmitter.

Overall Gain Analysis:

The transmitter takes the input sine audio signal and amplifies its current with a gain of $A_i \approx 300$. The receiver receives the light ($\propto$ diode current I_C), photoresistor's varying resistance modulates the bias DC voltage to create an AC voltage input and amplifies its voltage with a gain of $A_v \approx -42$. To obtain the overall gain, we cannot simply multiply A_v and A_i because they are different kinds of gain, and voltage and current gain in a common emitter are usually not the same. Also, there are losses during the transmission, which are modeled using the diode-photoresistor model in the transmitter and the receiver. The purpose of the transmitter is not to amplify voltage in the first place because the information is being transferred from the transmitter to the receiver in the form of light, which is controlled by the diode laser current. Nevertheless, it is favorable that the overall gain is larger than 1 and controllable for a speaker system. This is done by varying the resistance of the collector resistance R_{C2} in the receiver.

A potentiometer can take continuous values in its operating range. For the sake of simplicity, the potentiometer R_{C2} in this simulation is modeled with three values only: $10\ k\Omega, 20\ k\Omega$, and $30\ k\Omega$. We have already noted that maximum gain in the receiver is achieved with the configuration provided with $30\ k\Omega$ resistance. Increasing it further increases the gain (see below) but takes the BJT out of the forward active region. This is because of the relation $V_C = 5 - 30k \times I_C$ between V_C and R_C obtained in the Receiver DC Analysis section. Therefore, resistance values larger than $30\ k\Omega$ for the potentiometer are not advised using this configuration.

In the Receiver AC Analysis section, we have reached the following result for voltage gain:

$$A_v = -g_m \frac{R_{C2} \times r_\pi}{R_{B2} + r_\pi}$$

So, other methods (other than increasing R_{C2}) would increase the voltage gain in the receiver, which puts the transistor out of the forward active region. This expression can be written in terms of DC quiescent parameters by replacing r_π with β / g_m and g_m with I_{CQ}/V_T. After some algebraic manipulations, it becomes:

$$|A_v| = \alpha \frac{I_{CQ}}{1 + I_{CQ} R_{B2} \kappa}$$

where $\alpha = \kappa \beta R_{C2}$ and $\kappa = 1/\beta V_T$. The parameters used in α, κ are taken to be constant for this design and operation region. Therefore, we have left out it I_{CQ} and R_{B2} for the control of the voltage gain. Using the relation $V_B = 0.780 - I_B \times (202.7 + 160)k = V_{BE} = 0.6\ V$ obtained in Receiver DC Analysis section, we can further express R_{B2} in terms of I_{CQ}:

$$I_B = \frac{I_C}{\beta} = \frac{0.180}{202.7k + R_B} \rightarrow R_B = \frac{0.180\beta}{I_C} - 202.7k$$

$$1 + I_{CQ} R_{B2} \kappa = 1 + 0.180\beta\kappa - I_{CQ}\kappa 202.7k$$

Denoting $\kappa' \coloneqq \kappa 202.7k$ and $\zeta = 1 + 0.180\beta\kappa$:

$$|A_v| = \alpha \frac{I_{CQ}}{\zeta + I_{CQ}\kappa'}$$

To understand how A_v depends on I_{CQ}, we look for the first derivative of A_v w.r.t. I_{CQ}:

$$\frac{\partial |A_v|}{\partial I_{CQ}} = \frac{\alpha(\zeta + I_{CQ}\kappa' - \kappa' I_{CQ})}{\left(\zeta + I_{CQ}\kappa'\right)^2} = \frac{\alpha\zeta}{\left(\zeta + I_{CQ}\kappa'\right)^2} > 0$$

Thus, it is concluded that $|A_v|$ increases with the increased I_{CQ}. On the other hand, the relation between I_C and V_C is the same with the relation between R_C and V_C, i.e., further increase in I_{CQ} puts the transistor in saturation.

There is one last possibility to increase the gain, and it is the DC voltage bias (V_{DC}) at the receiver and included in ζ above. Decreasing it decreases ζ, which increases $|A_v|$. However, the relation between DC bias voltage and I_C is proportional; so, decreasing V_{DC} also decreases I_{CQ} and $|A_v|$. To understand whose impact on $|A_v|$ is larger, we once again check the first derivative of $|A_v|$, but w.r.t. V_{DC} this time:

$$\frac{\partial |A_v|}{\partial V_{DC}} = \frac{\partial}{\partial V_{DC}}\left(\frac{\alpha I_{CQ}}{1 + V_{DC}\kappa + I_{CQ}\kappa'}\right) = -\frac{\kappa\alpha I_{CQ}}{\left(1 + V_{DC}\kappa + I_{CQ}\kappa'\right)^2} = -\frac{\kappa\alpha I_{CQ}}{\left(\zeta + I_{CQ}\kappa'\right)^2} < 0$$

Comparing $\kappa\alpha I_{CQ} = \alpha\frac{I_{CQ}}{\beta V_T}$ with $\alpha\zeta = \alpha\left(1 + \frac{V_{DC}}{V_T}\right)$, we observe $\alpha\zeta \gg \kappa\alpha I_{CQ}$ for typical values[5]. This implies the effect of decreasing V_{DC} in increasing $|A_v|$ is much smaller than the effect of increasing I_{CQ}. Since $I_{CQ} \propto V_{DC}$, decreasing V_{DC} overall decreases the small-signal voltage gain.

It is analytically possible, but tedious, to establish an expression for the overall voltage gain of the complete circuit. Since the connection between the transmitter and receiver is through the current i_o, signal input and receiver output voltages must be referenced to it. For the transmitter, $A_i = i_o/i_i$ and $v_i A_i = i_o(R_{B1} + r_{\pi 1})$, which gives:

$$v_i = i_o \frac{R_{B1} + r_{\pi 1}}{A_i}$$

At the receiver, we have $v_{in} = V_{DC} - i_{in} r_{ac} = i_{in}(R_{B2} + r_{\pi 2})$ that leads to:

$$v_{in} = V_{DC} \frac{R_{B2} + r_{\pi 2}}{R_{B2} + r_{\pi 2} + r_{ac}}$$

[5] Take $V_{DC} = 0.7\ V, V_T = 0.026\ V, I_{CQ} = 1\ mA, \beta = 300$ for a rough calculation to observe the great difference in results.

Using the expression for r_{ac} and numerical values for $R_{B2}, r_{\pi 2}$, the denominator reduces to $250 \times 10^3 \times e^{-1000 i_{LASER}(t)}$:

$$v_{in} \approx \frac{V_{DC} + 213k}{11k + e^{-1000 i_0}} \approx \frac{213}{11 - i_0}$$

$$\rightarrow v_o = A_v v_{in} = \frac{A_v\, 213}{11 - i_0}$$

Finally, the ratio v_o/v_i gives the overall voltage gain:

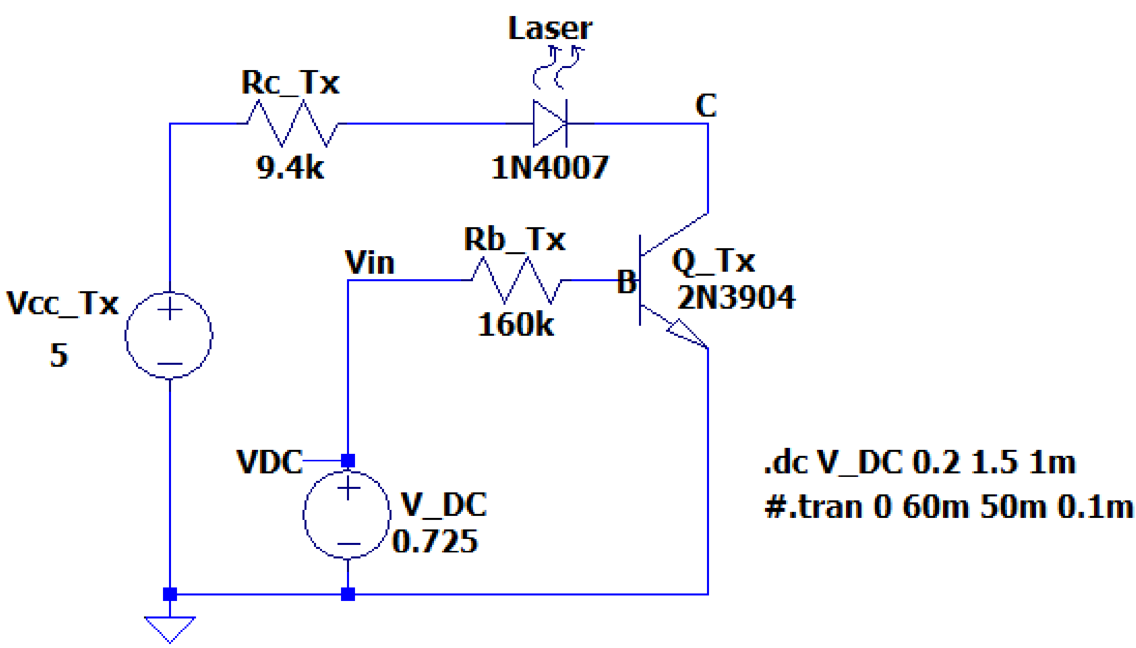
$$\frac{v_o}{v_i} = \frac{A_v A_i (213)}{R_{B1} + r_{\pi 1}} \left(\frac{11}{i_0} - 1 \right) \underset{\approx}{\overset{\Delta}{\rightarrow}} -10$$

Of course, this is a very rough approximation since the exact analytical result is very complex to calculate and this much insight is sufficient to understand the overall behavior of the circuit. In Overall Gain Analysis:, it will be shown that the overall voltage gain turns out to be -3.

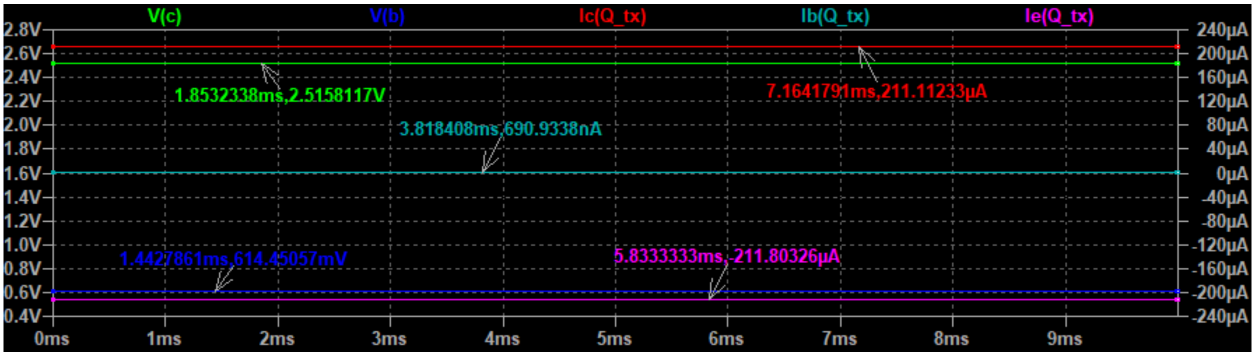
SIMULATION RESULTS

Transmitter DC Analysis

The following schematic is used to verify the calculations:



(a) DC Equivalent Circuit



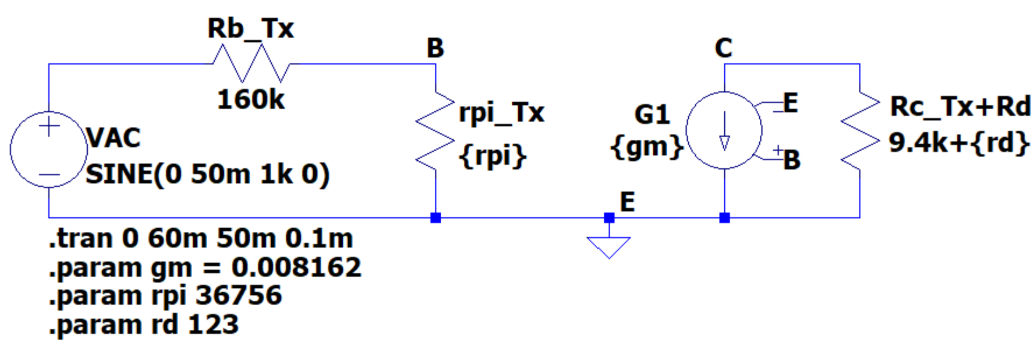
(b) Simulation Results

Figure 9: Transmitter DC Equivalent Circuit and Simulation Results

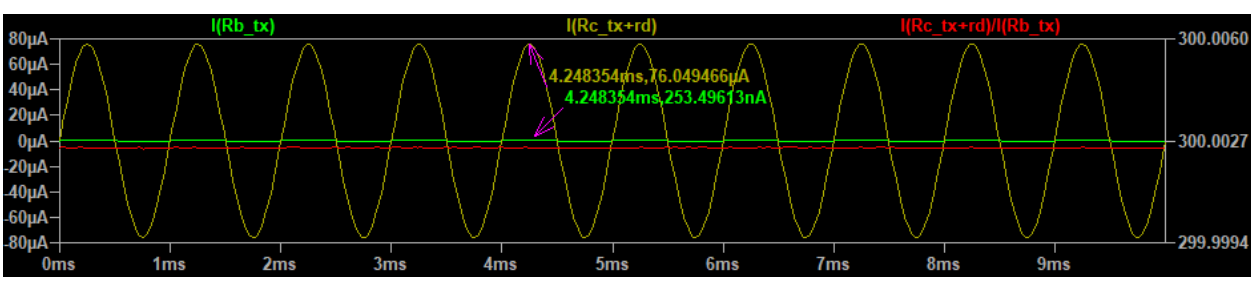
Note that I_E is negative because it goes out of the transistor, whereas I_B and I_C goes into. The calculations and simulated results match to a great degree with a difference of a few microns and millivolts.

Transmitter AC Analysis

The following schematic is used to verify the calculations:



(a) AC Equivalent Circuit



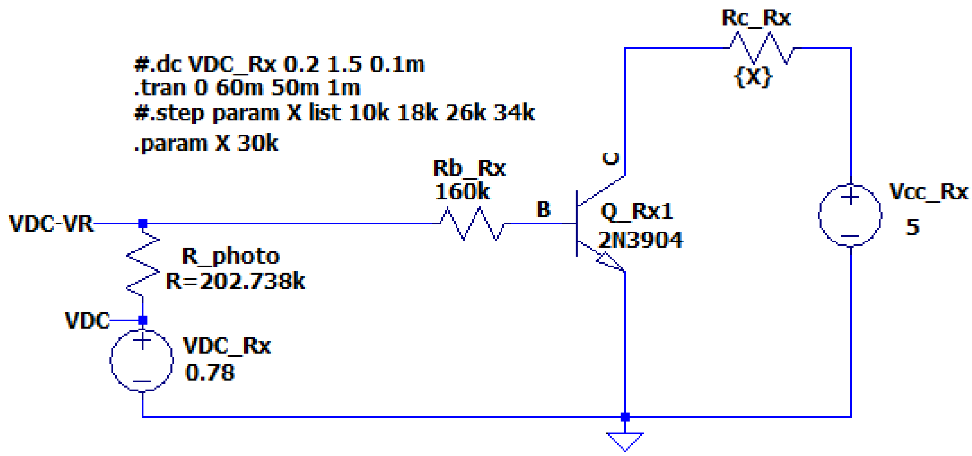
(b) Simulation Results

Figure 10: Transmitter AC Equivalent Circuit and Simulation Results

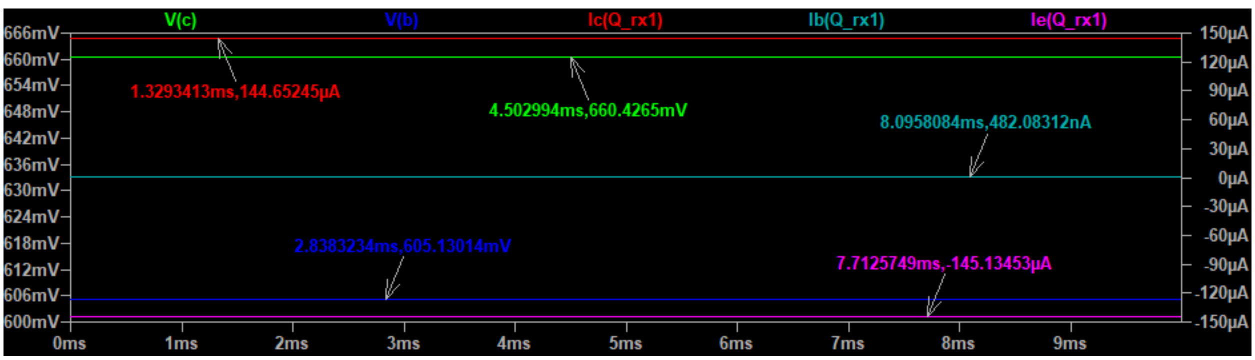
The simulation results show (the red line in Figure 10) that the current gain is ≈ 300, which agrees with the ideal, calculated result of $A_i = \beta = 300$.

Receiver DC Analysis

The following schematic is used to verify the calculations:



(a) DC Equivalent Circuit



(a) Simulation Results

Figure 11: Receiver DC Equivalent Circuit and Simulation Results

Receiver AC Analysis

To simulate the small-signal circuit for verification of the calculated results, we use the $r_{LDR} = R_{DC} + r_{ac}$ results obtained in the Receiver DC Analysis section. r_{LDR} and R_{DC} are already known and/or calculated. For AC equivalent circuit simulation, we need an AC expression for the resistor such as r_{ac} that will make the input of the overall transmitter circuit alternating current/voltage. So, we use R_{DC} and r_{RLD} to obtain r_{ac}:

$$r_{ac}(t) = r_{LDR(t)} - R_{DC}$$
$$= 250 \times 10^3 \times e^{-1000\left(0.211\times10^{-3}+76.237161\times\sin(2000\pi t)\times10^{-6}\right)} - 202.738 \times 10^3\ \Omega$$

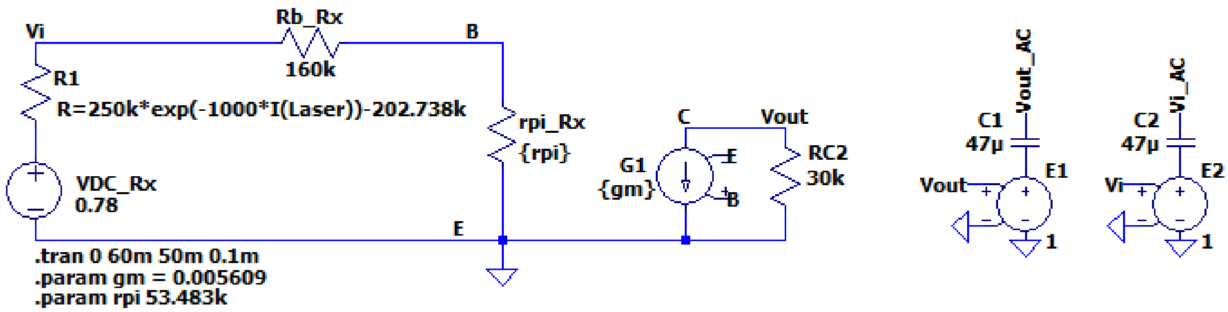


Figure 12: Receiver AC Equivalent Circuit

As explained, it was not possible to remove the DC voltage source for the small-signal equivalent circuit in this implementation because without it, the circuit would be:

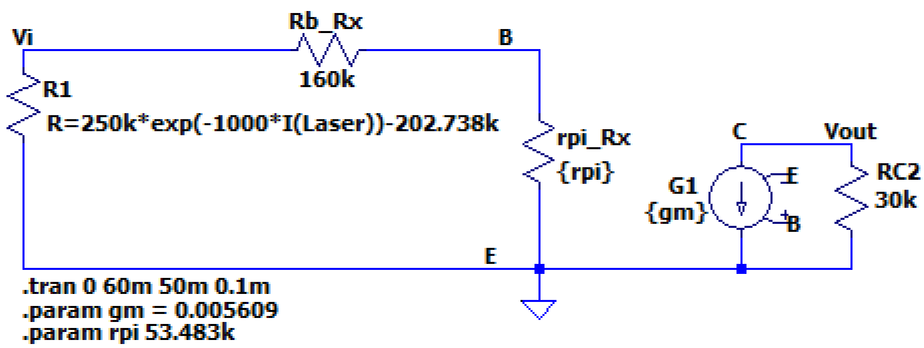


Figure 13: Receiver AC Equivalent Circuit (not working)

Since there is no source feeding the circuit with electricity, $v_i = v_{out} = 0$ in Figure 13. An oscillating resistance is not an AC source by itself and requires the DC offset provided by $V_{DC,Rx}$ to generate an oscillating voltage/current. Therefore, the circuit in Figure 12 must be used to obtain small-signal gain.

The dependent voltage sources at the right of Figure 12 are used to remove DC offsets from v_i and v_{out}. They have DC offsets because there is a DC voltage source in the circuit. Nevertheless, a single 47 μF capacitor easily removes the DC offsets, and we left out with v_i and v_o without any DC offset, as it should be.

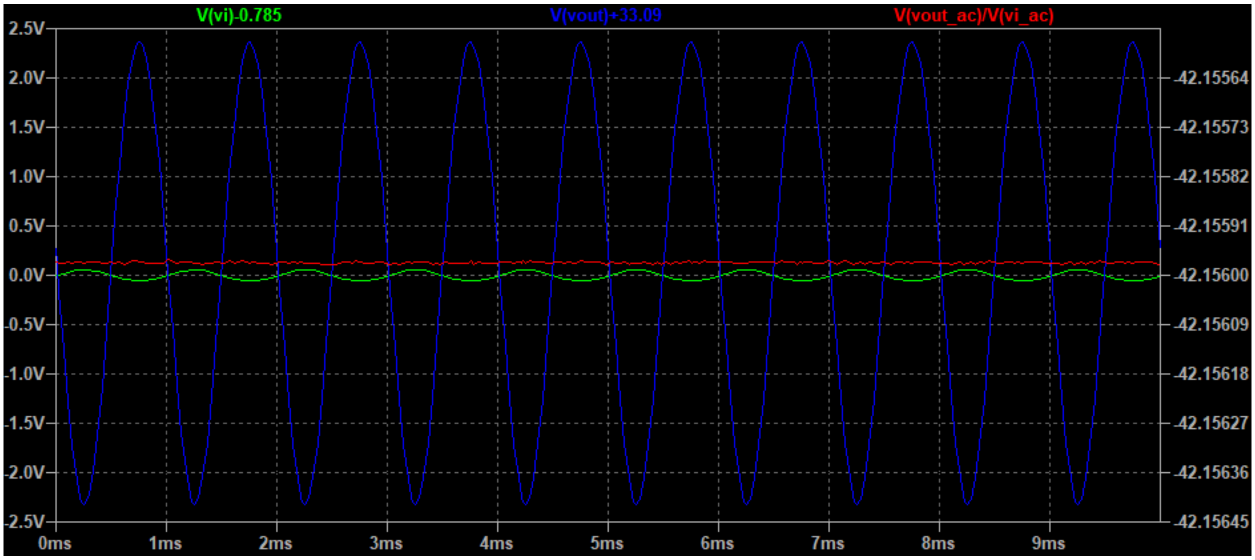


Figure 14: Receiver AC Equivalent Circuit Simulation

The red line in Figure 14 gives the voltage gain $A_v = v_o/v_i$. It is approximately -42.156, which matches the calculated result obtained in the Receiver AC Analysis section to a great degree.

Overall Gain Analysis:

The complete circuit in Figure 2 is used to obtain the following plots.

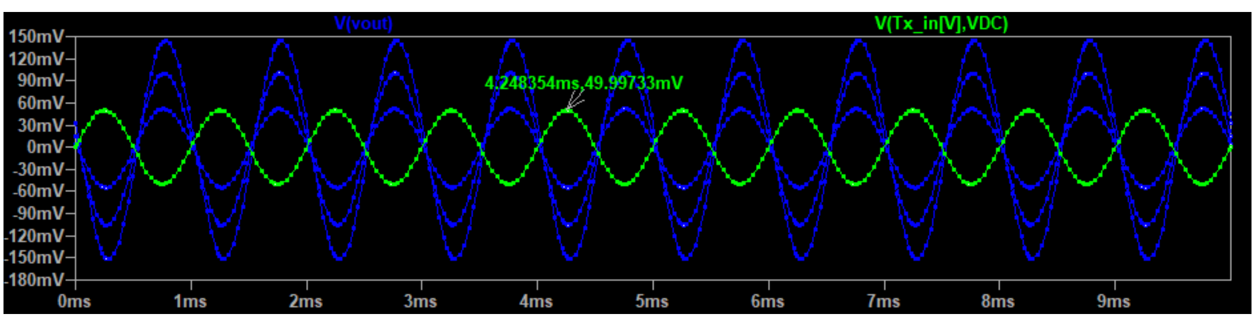


Figure 15: V_{out} *vs* $V_{in}(AC)$ *for* $R_{C2} = \{10, 20, 30\}\ k\Omega$

The largest small-signal output with $V_{pp} \approx 150\ mV_p$ is obtained when $R_{C2} = 30\ k\Omega$, and the smallest one with $V_p \approx V_{p,input} = 50\ mV_p$ is obtained when $R_{C2} = 10\ k\Omega$. The following Figure 16 shows the output versus input plots for each R_{C2} value in more detail.

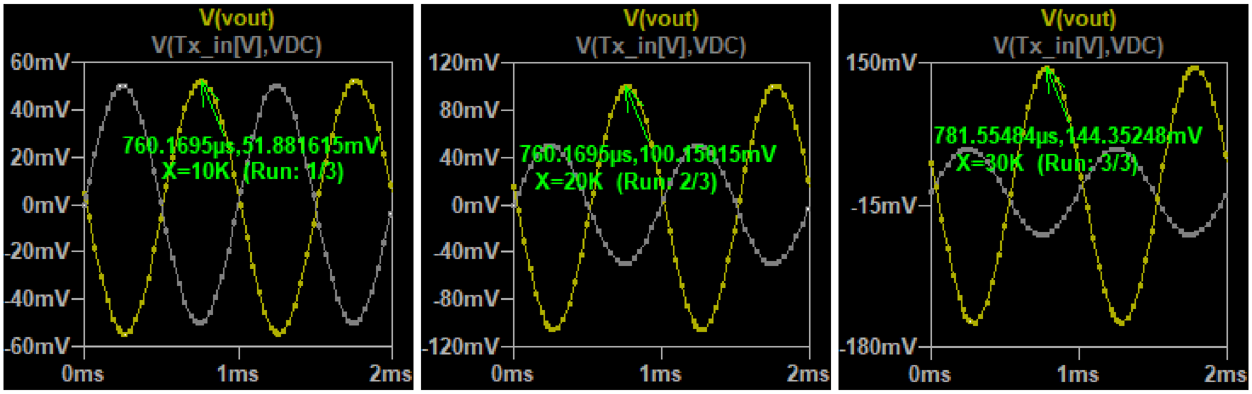


Figure 16: V_{out} vs $V_{in}(AC)$ plots for different $R_{C2} = \{10, 20, 30\}\ k\Omega$ value at each time

In summary, it is possible to control the volume (voltage output) of this system by using a potentiometer to achieve a volume gain up to $\times 3$ times while remaining in the forward active region of operation. Its proof is already provided, but see the following Figure 17 to observe that $V_C(DC)$ is always larger than $V_B(DC)$ for both BJTs.

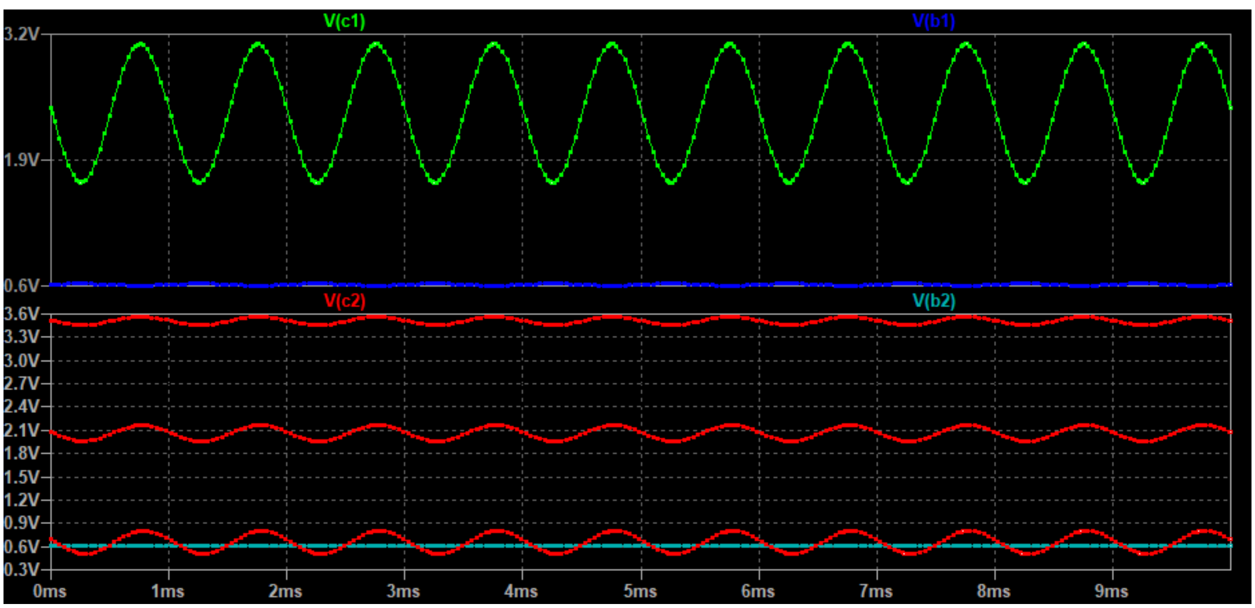


Figure 17: V_C and V_B plots for all cases of the transmitter and receiver circuits. Note that $V_E = 0$ since grounded (not shown).

Note the last plot's smallest V_C value where $V_C(DC)$ is slightly larger than $V_B(DC)$. Indeed, this is the case for $R_{C2} = 30\ k\Omega$, and the BJT is at the edge of saturation. A slight increase in R_{C2} puts it into saturation, but it is in the forward active region of operation throughout the simulation.

CONCLUSION

Overall, this project[6] can be used as a wireless audio transmitter and receiver using a diode laser. Common Emitter amplifiers used in the transmitter and the receiver were efficient to provide current and voltage amplification. Current amplification (with a gain of $A_i = 300$) in the transmitter served to modulate the laser going out of the laser diode, whose light intensity is controlled by the current passing through it. Voltage amplification (with a gain of $A_v = -42$) in the receiver served to obtain the input audio signal with the desired amplification. The amount of amplification is related to the volume of the speaker, which is controlled by the collector resistance (potentiometer). The overall gain of the system goes up to -3. Each Common Emitter amplifier adds a phase shift of π, and the inverse relationship between the light intensity (diode laser current) and photoresistor's resistance also adds a phase shift of π. In total, the total phase shift is $3\pi = -\pi$. This is not a problem, but it can easily be removed from the system with the help of an operational amplifier, or with the addition of another Common Emitter amplifier to the output terminal. Note that this addition can also be used to further amplify the output signal.

It is observed that adjusting gain is a complicated process since the parameters that control the amount of gain are interrelated. Therefore, they cannot be arbitrarily adjusted to obtain a larger or smaller gain. Moreover, while adjusting the parameters, it is crucial to consider the region of operation of the transistors. Because the gain expression is obtained in the forward active region, gain parameters cannot be changed arbitrarily which would put the transistor out of this region.

The addition of emitter resistance and bypass capacitor can increase the DC biasing voltage, and also the small-signal gain. They are not included in this design but can be crucial for real-life implementation because of external factors that cause noise in the received signal. Also, it should be once more noted that the implementation of the photoresistor in the simulation may be unconventional, and there may be more efficient methods to capture the laser diode current at the receiver. The effect of different implementations on output voltage can be further investigated.

The simulation results and analytical results agreed to a great degree, up to 100% up to three significant figures. Some minor differences are always expected since the assumed models and values used in hand calculations are not precise as the ones in the simulation program. Internal capacitances and r_o resistance values of the transistors may be included for better precision.

This design can be used in long-range information transmission and is not limited to the transmission of audio signals. For noisy environments, discretization and modulation also improve the overall performance of the transmission. It is also possible to use a laser diode whose light is invisible to the human eye since there are photoresistors sensitive to different wavelengths. Nonetheless, one should pay attention to the wavelength at which the detectivity of the photoresistor peaks. Diode laser operating at this wavelength may fairly increase the performance.

[6] LTspice models used can be found at https://github.com/aunal16/elec310_project_spice

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