

# Audible Light

(An experiment to transmit sound via light using the Small Signal Trick)

Ayngaran Adalarasu

May 5, 2020

## Contents

|          |                                                          |           |
|----------|----------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                                      | <b>1</b>  |
| <b>2</b> | <b>Key insights</b>                                      | <b>1</b>  |
| 2.1      | The Non-Linear problem . . . . .                         | 1         |
| 2.2      | The small signal method (Incremental analysis) . . . . . | 2         |
| 2.2.1    | How small signal trick works? . . . . .                  | 2         |
| <b>3</b> | <b>Prototyping</b>                                       | <b>3</b>  |
| 3.1      | Making the first transmitter . . . . .                   | 3         |
| 3.2      | Building a Receiver . . . . .                            | 3         |
| 3.2.1    | LDR based Receiver . . . . .                             | 3         |
| 3.2.2    | Solar panel based Receiver . . . . .                     | 4         |
| 3.2.3    | Improvising our receiver . . . . .                       | 7         |
| <b>4</b> | <b>A fun experiment</b>                                  | <b>9</b>  |
| <b>5</b> | <b>Other ideas</b>                                       | <b>9</b>  |
| 5.1      | Transmitting multiple signal channels . . . . .          | 9         |
| 5.2      | Using laser . . . . .                                    | 10        |
| 5.3      | Noise cancellation . . . . .                             | 10        |
| <b>6</b> | <b>Applications</b>                                      | <b>10</b> |
| <b>7</b> | <b>Summary</b>                                           | <b>10</b> |

## Abstract

In this article I have shared my experience in exploring the circuit analysis technique called Small signal method (incremental analysis) and how I built a simple system around that technique, which aims to transmit an audio signal via light beam.

I was inspired to build this after listening to the ‘Small signal trick’ lectures and ‘audio through light’ demo of MITx-6.002.1x course by Professor Anant Agarwal in edX.

# 1 Introduction

The system used to demonstrate the Small Signal Trick is a simple transmitter-receiver system. In this the sound signal is extracted out using aux cable in electrical form. This is fed to the transmitter (through Aux), which converts to an optical signal (visible light of Electromagnetic Spectrum) and transmitted. Upon receiving the optical signal, the receiver will convert it back into an electrical signal which when provided to a speaker produces the audio.

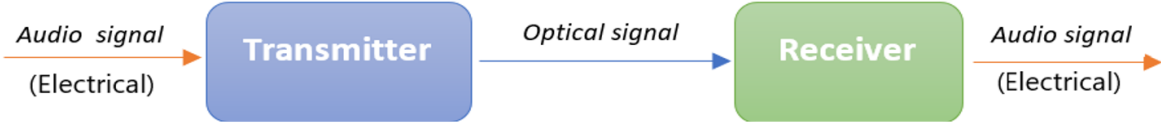


Figure 1: Audio transmission block diagram

In this system a LED is used for transmitting the optical signal and a photo sensor for receiving the signal. The small signal trick will be employed to transmit the audio signal linearly through the LED (a non-linear device).

The approach followed in building the system is as follows,

1. Build a transmitter which modulates the optical signal based on the Audio signal. Here a simple Blue LED is used
2. Then a small study is made to choose the best optical sensor for our receiver
3. Finally, a complete receiver is built which is tested with various audio input signals like sine, square waves... of various frequencies and music
4. Towards the end of this project the range of the transmitter is extend by some interesting optics

## 2 Key insights

### 2.1 The Non-Linear problem

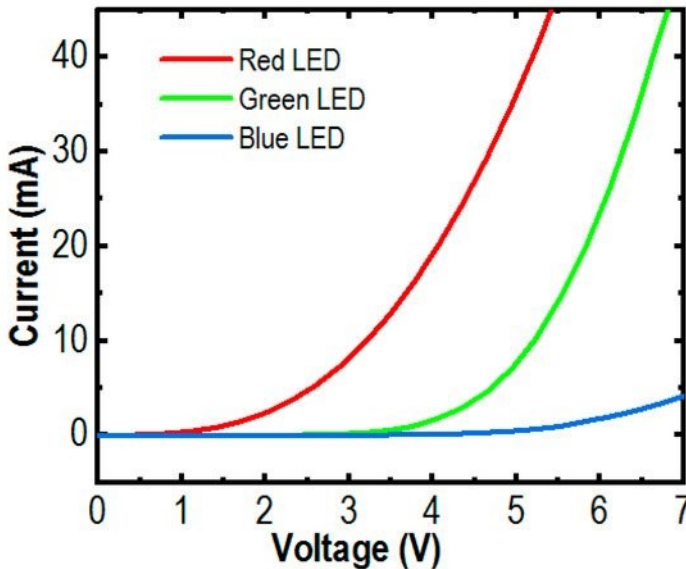


Figure 2: V-I graph of different colour LEDs (A non-linear device)

Non-Linear device is a device which does not have a linear voltage-current relation. That is, a change in voltage across does not cause a corresponding linear change in the current through the device.

From Figure 2 we can clearly infer that for especially the Red & Green LEDs, current through the LED is not linearly related to voltage across it. So, it is clearly a non-linear device.

Non-Linearity of an LED is a major problem we have to tackle. To transmit an audio signal linearly in the form of light, the amount of change in light produced by the LED should be linearly proportional to the signal.

If we connect our small voltage signal directly to the LED, this system will not work for 3 reasons:

1. The amount of light produced by an LED is almost proportional to the current flowing through it. But LED is a non-linear device, so connecting voltage signal directly to the LED does not produce light proportional to the voltage given. So, audio will not be transmitted properly.
2. Small audio signal from an aux cable has an amplitude of 0.5V which is way too less than the forward threshold voltage of an LED, so it will not even glow.
3. Furthermore, the audio signal has positive and negative voltages, as LED allows current to flow in one direction only, the negative audio signals will never be transmitted

In order to overcome the above-mentioned challenges, the ‘small signal trick’ can be used.

## 2.2 The small signal method (Incremental analysis)

In the V-I relationship of every non-linear device there might always be a small region in which the relation is linear or seems to be almost linear. The basic idea of this method is to decrease the amplitude of our signal such that it fits in the small linear region and then transmit our signal in that particular region by adding an offset bias voltage to it. By using this idea, we will be able to transmit our signal linearly (almost) through a non-linear device.

$$V_{device} = V_{signal} + V_{bias}$$

Such that  $V_{device}$  operates in a range where V-I Relation is linear.

### 2.2.1 How small signal trick works?

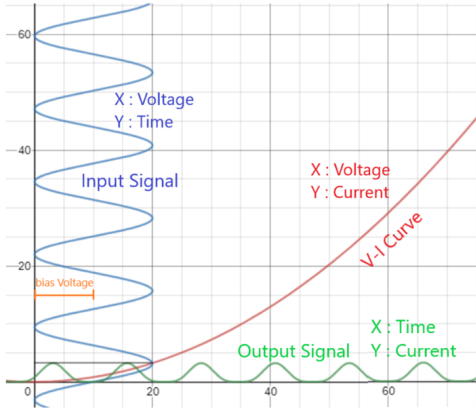


Figure 3: Graph of  $I_{device} = f(V_{device})$

$$I_{device} = f(V_{device})$$

(for example, Red V-I Curve in Figure 3)

When we now provide a voltage input as function of time ( $V_{in}(t)$ –sinewave) to the device at a Bias Point  $V_b$  the output will be  $I_{out}(t)$ .

$$I_{out}(t) = f(V_{in}(t) + V_b)$$

$V_{in}$  – Blue curve  $I_{out}$  – Green curve

From the Figure 3 we can see that  $I_{out}$  does not resemble input curve ( $V_{in}(t)$ –sinewave).

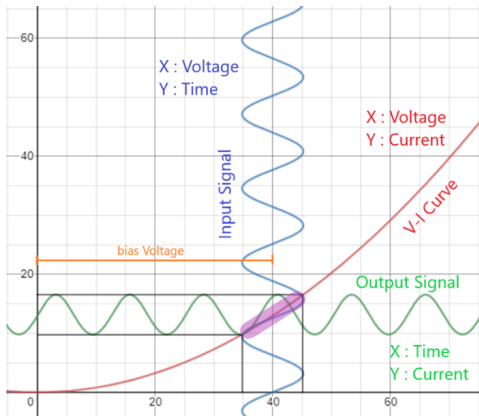


Figure 4: Graph of  $I_{out}(t) = f(aV_{in}(t) + V_{b2})$

By reducing the amplitude of  $V_{in}$  (multiply with a constant) and change the bias point to  $V_{b2}$  we can see in Figure 4 the output  $I_{out}$  is more resembling the input curve. This is because the  $V_{in}$  magnitude is reduced and  $V_b$  is moved to a position on the curve where it is more linear.

$$I_{out}(t) = f(aV_{in}(t) + V_{b2}) \quad 0 < a < 1$$

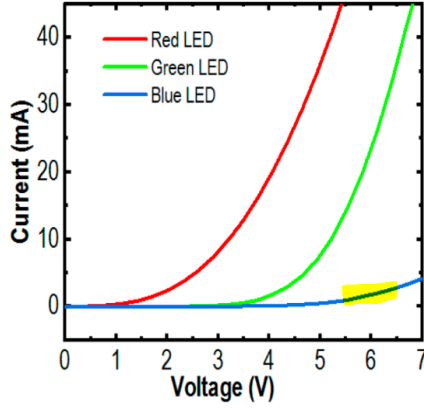


Figure 5: V-I relation of LED

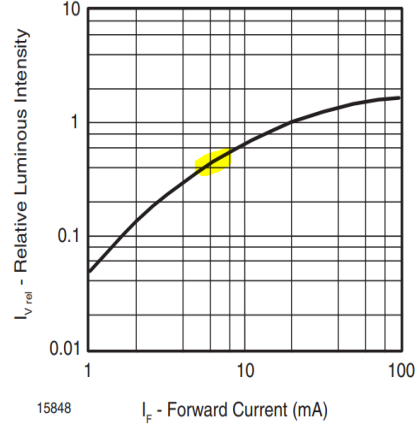


Figure 6: Light Intensity vs Current

### 3 Prototyping

#### 3.1 Making the first transmitter

The blue LED will be used for our transmitter because it can give way more high light intensities than the red or green ones. The voltage versus current (From Figure 5), Blue LEDs seems to be behaving linearly between 5.5V and 6.5V. As our audio signal also ranges from -0.5V to 0.5V, by offsetting our signal by 6V we can fit it into the linear region and transmit our signal linearly.

On the Luminous Intensity Vs Current Graph (Figure 6), we can further notice that at the voltage range in which we planned to pass our signal: the intensity of light produced (Vs forward current) is also almost linear.

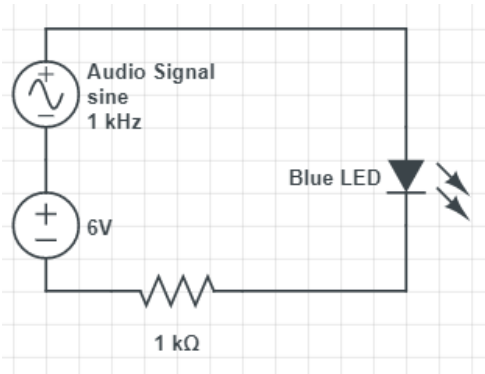


Figure 7

$$V_{LED} = 6V + V_{signal}$$

This circuit (Figure 7) makes the LED change its intensity linearly with respect to the audio signal. The audio signal is connected in series with a 6V battery to offset it to operate between 5.5v to 6.5v (linear region of LED). A 1kΩ resistor is added to limit the current through the audio source (a phone jack) to 6.5mA and prevent it from damage.

#### 3.2 Building a Receiver

##### 3.2.1 LDR based Receiver

An LDR is a device whose resistance varies based on received light. The higher the intensity of Light the lesser its resistance.

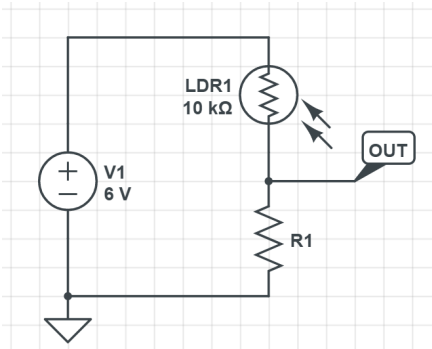


Figure 8

$$Outsignal = 6V * \frac{R_1}{R_1 + R_{LDR}}$$

From Figure 8 we can infer that, as the light intensity increases the magnitude of output signal also increases.

##### Performance

The above circuit is constructed and is placed in front of the transmitter. Upon giving a square wave as input to the transmitter and probing  $V_{out}$  of the receiver.

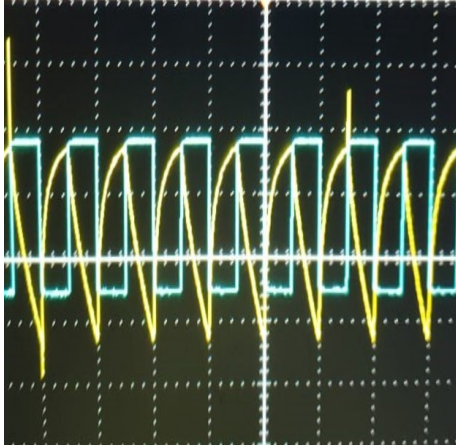


Figure 9: Blue signal: Input square wave to transmitter  
Yellow Signal: Output from LDR receiver

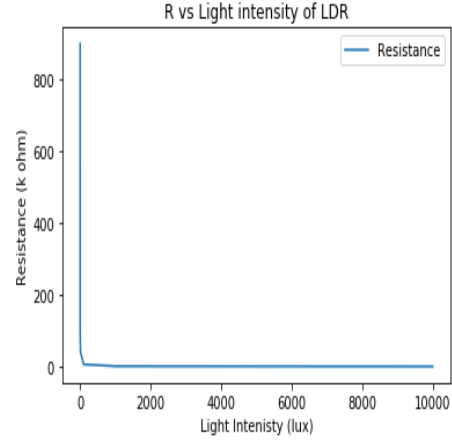


Figure 10: R Vs Light Intensity of LDR

From Figure 9, we can see that the output given by our LDR receiver clearly does not match the input signal, upon further investigation it was found that this is because the reactive time of LDR is pretty slow and the Light intensity vs Resistance relation of LDR is also non-linear (as seen in Figure 10)

As there is no linear region in this graph, LDR is not suitable to act as a receiver for our purpose, it can more or less only be used for detecting the presence of light, not for linearly detecting intensity of our signal.

### 3.2.2 Solar panel based Receiver

Solar Panel is a device which produces electricity proportional to the amount of light it receives. More light a solar panel receives the more voltage it produces across its ends.

I tried using a solar panel as receiver, by connecting its ends directly to the probes of an oscilloscope. As the LED has a bias voltage it never dims beyond a certain minimum brightness, so it never completely turns off, because of this, the solar panel also produces a bias voltage. The actual transmitted signal rides on this bias voltage. I subtracted the bias voltage, using the voltage offset feature of an oscilloscope and magnified the signal.

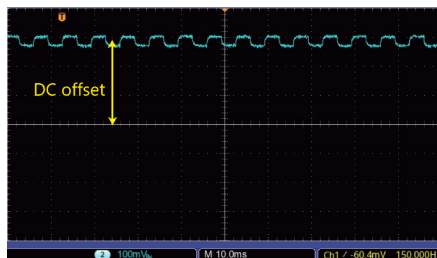


Figure 11: Amplitude of output signal

#### Perormance

When a 150Hz square wave is inputted at the transmitter, this is the raw output measured across the receiving solar panel.

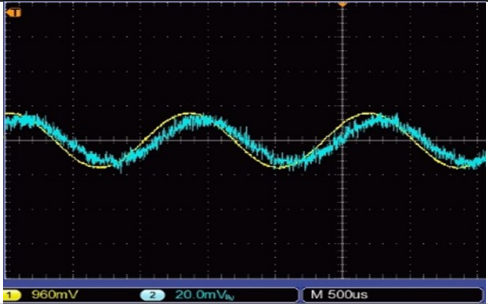
We can clearly see the signal riding on a DC offset.

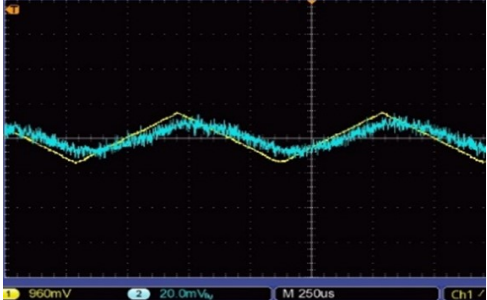
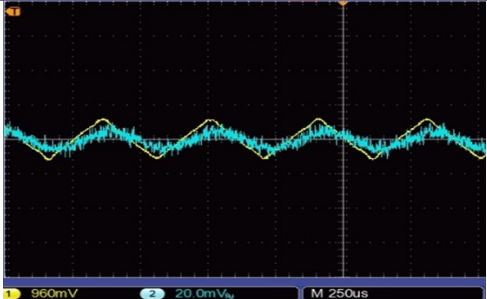
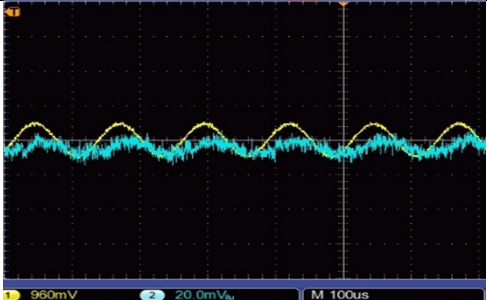
$$OutputSignalAmplitude \approx 25mV$$

(Receiver is placed  $\sim 5cm$  from transmitter)

Upon passing different kinds of waves with different frequencies to the transmitter, similar waves were reproduced by the solar panel at the receiver; these results are summarised in the table below:

Blue signal: Input signal to transmitter; Yellow Signal: Output signal from receiver

| Frequency | Wave   | Offset time | Ouput waves (Magnified & subtracted)                                                 |
|-----------|--------|-------------|--------------------------------------------------------------------------------------|
| 150Hz     | Square | $40\mu s$   |    |
| 750Hz     | Square | $40\mu s$   |   |
| 750Hz     | Sine   | $50\mu s$   |  |
| 1200Hz    | Square | $30\mu s$   |  |
| 1200Hz    | Sine   | $60\mu s$   |  |

|        |          |           |                                                                                      |
|--------|----------|-----------|--------------------------------------------------------------------------------------|
| 1200Hz | Triangle | $40\mu s$ |    |
| 2500Hz | Square   | $30\mu s$ |    |
| 2500Hz | Sine     | $40\mu s$ |   |
| 2500Hz | Triangle | $40\mu s$ |  |
| 8000Hz | Sine     | $30\mu s$ |  |

We can notice that the waves are reproduced pretty accurately and the offset time (i.e., time delay between the signal transmission and reception) is also pretty low in the order of a few microseconds( $\sim 40\mu s$ ), thus the solar panel should function as a perfect photo receptor for our system.

As the range of the raw solar panel's output is within aux standards, it can be directly connected to the aux port of a speaker. Then if some music is transmitted in the transmitter, on the receiver end (from the speaker) the transmitted music is indeed heard. But however, this music is very feeble and is extremely hard to hear, this might be because, the actual amplitude of the signal transmitted is still pretty low( $\sim 25mV$ ).

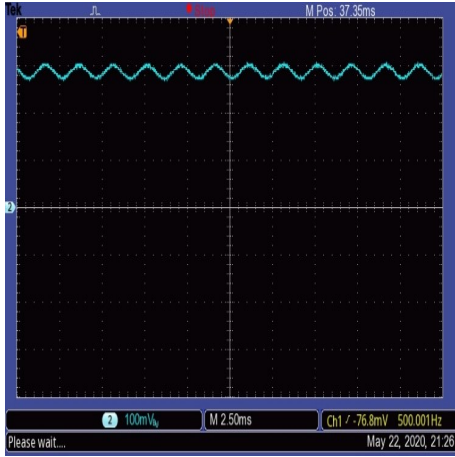


Figure 12: Raw signal

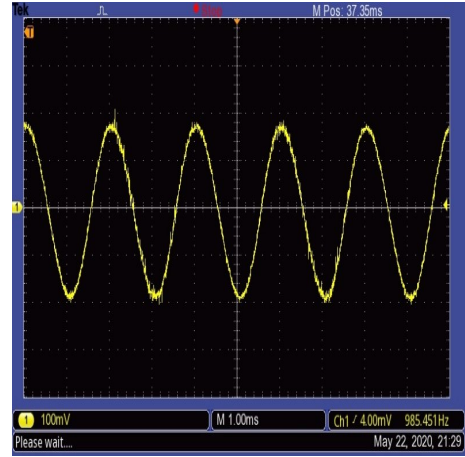


Figure 13: Desired Output

### 3.2.3 Improvising our receiver

#### What to improvise?

1. The output across our solar panel will have our signal voltage riding on a DC bias offset (Figure 12). In order to receive proper Audio, we should figure out a way to subtract this bias (Figure 13)
2. The actual amplitude of the signal across the solar panel is pretty low ( $\sim 25mV$ ), we need to amplify it to the voltage standards of Aux Audio Jacks (Figure 13)
3. Amplifying the signal across solar panel will also automatically increase the range of the receiver

#### Working of circuit

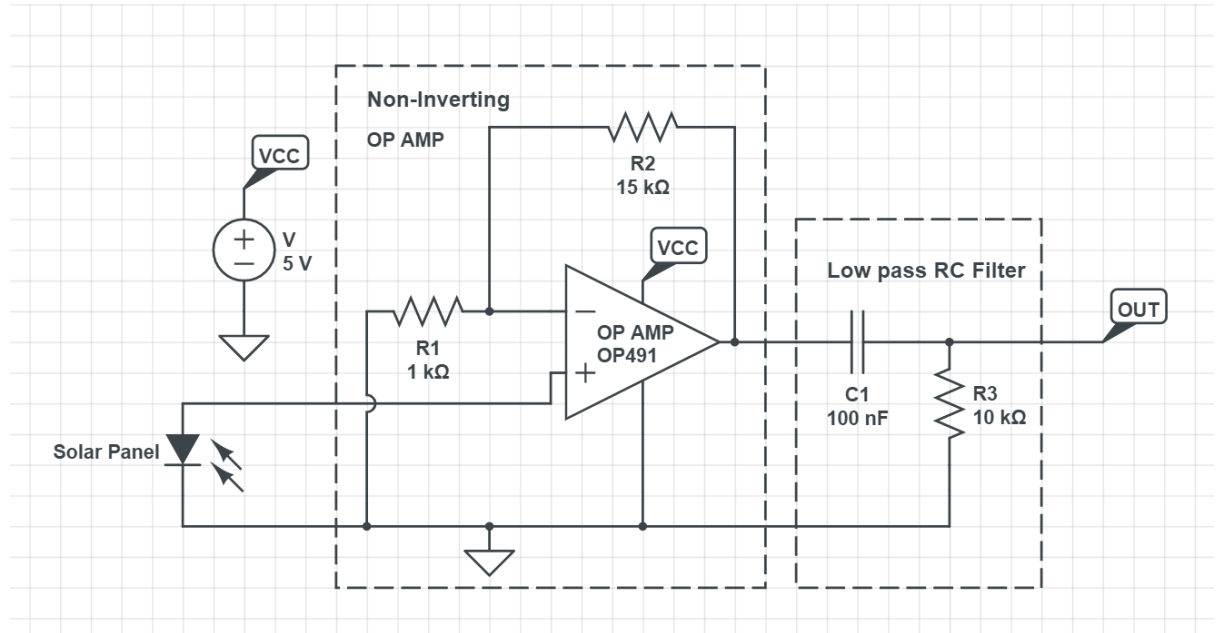


Figure 14: Circuit Schematic of Receiver

**Amplification stage** The raw signal from the solar panel is first needs to be amplified by an op amp in order to fit the signal into the Aux channel range ( $\pm 500mV$ ). Based on simple non-inverting op amp reference the above circuit was made. As the signal is already riding on an offset it does not have any negative voltage ranges, so an op amp in non-inverting configuration can be used.

$$Gain = 1 + \frac{R2}{R1} = 1 + \frac{15k}{1k} = 16$$

In this circuit the op-amp has a gain of 16 which means the voltage across the solar panel will be 16 times larger. If the entire voltage across it is multiplied, then the signal riding on it is also multiplied.

Amplitude of Signal at op amp out =  $25mV * 16 = 400mV$

This stage has successfully fitted our signal's amplitude within Aux channel range ( $\pm 500mV$ ).

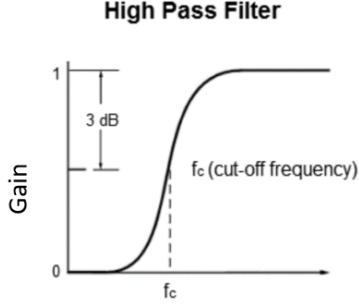


Figure 15

**RC Filter stage** In this stage a high pass filter is used to remove the DC bias offset on which our amplified signal is riding.

A high pass RC filter is a circuit that passes only signals with a frequency higher than its cut off frequency and attenuates (dampens) all signals with a frequency less than its cut off. The Frequency of a DC bias is 0 Hz, so if we use a high pass filter with a low cut off frequency, after the amplification stage, all the bias will be attenuated and ultimately only the transmitted signal (riding on offset) will be outputted.

$$\nu_{cut-off} = \frac{1}{2\pi RC} = \frac{1}{2\pi * 10k * 100nF} = 159.15Hz$$

Generally, in music frequencies do not go as below as 160Hz, so by using this RC filter we will be able to successfully dampen the DC offset and extract only the audio signal.

### Why to use a filter?

The offset DC voltage on which our desired signal is riding on is dynamic. It depends on the average brightness level of our LED in our transmitter and also on the brightness of ambient light, if the receiver is in a brighter environment then the solar panel will produce more voltage, hence the offset will be more. So we need to subtract the offset irrespective of its amplitude, in this scenario a simple constant voltage source would not have worked because it can only subtract a constant offset, whereas a filter would be able to dampen DC offset of all amplitudes because all of them have a frequency of 0 Hz.

**Does solar panel size (area) matter?** It was observed that using a solar panel with a smaller area is more beneficial, because the optical signal from our transmitter is pretty narrow. On the contrary a large panel will pick up a lot of noises from the ambient light.

### Circuit in action

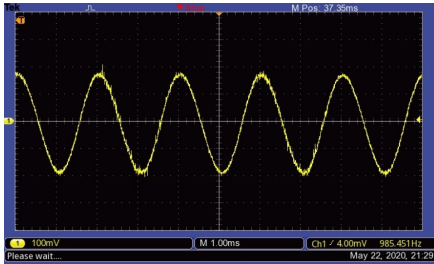


Figure 16

Figure 16 shows output at receiver when 500Hz sine wave is inputted at transmitter. We can see that the signal is amplified and reproduced properly.

Amplitude =  $\pm 200mV$  (within Aux range)

**Experiment setup** A music source (mobile phone) is connected to the transmitter with an Aux cable. The transmitter is placed such that the solar panel and LED are aligned properly. The transmitter's output is connected to a speaker via a Class D Audio Amplifier.

When the music is played at the transmitter, then we can clearly hear the music from the speaker at the receiver side.

When the optical signal from transmitter is blocked, then the audio is not heard. Hence, we are able to successfully transmit an audio via light. Thanks to our amplifier now our receiver can still receive audio signal up to 30cm away from the transmitter.

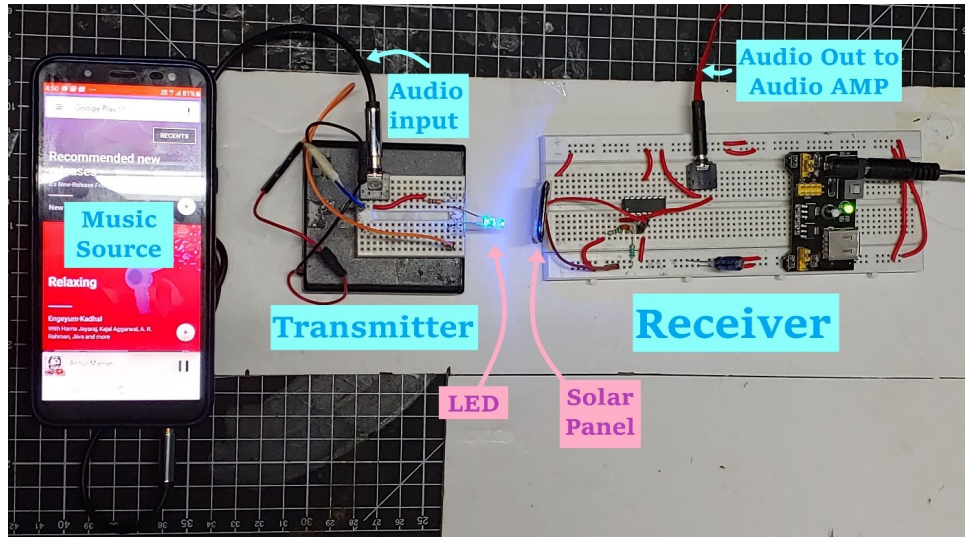


Figure 17: Experiment Setup

Video Link - <https://youtu.be/9QVhTBOSbC8>

## 4 A fun experiment

Our new receiver has a range of about 30 cm, if we go beyond that then slowly our audio signal dies, and ambient noises take over. This is because light rays from LED keep diverging, so as we go farther and farther very less light from LED falls on receiver solar panel. By using a Convex Lens, we can converge the diverging rays from LED and focus it on the panel, hence by doing this we will be able to get even longer ranges.

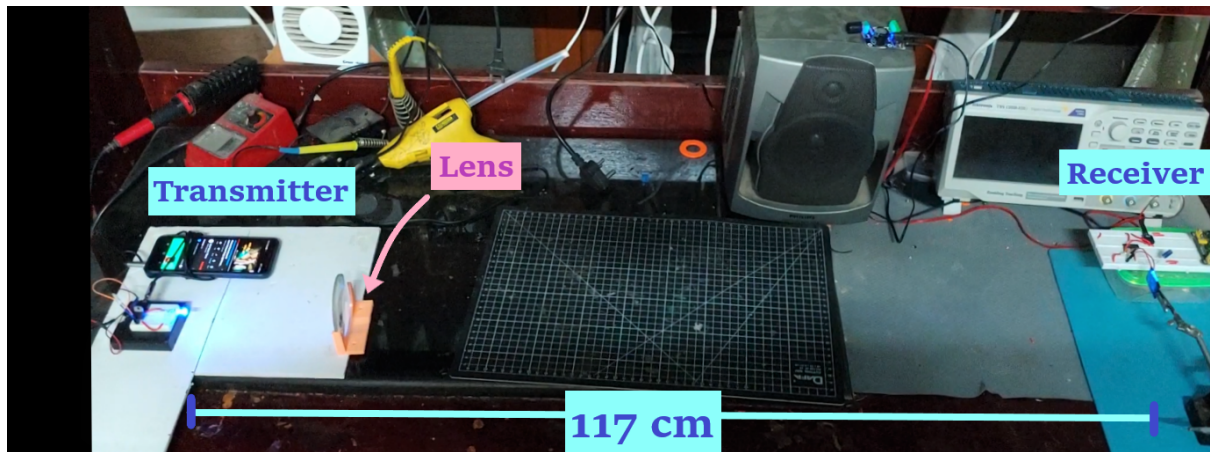


Figure 18: Fun experiment - Setup

(Figure 18) I have used a 16cm focal length convex lens to focus light coming from transmitter on receiver's solar panel. Using the lens, we have boosted our range to 117cm, now we are able to transmit clear audio over such a large range.

Video Link - <https://youtu.be/Lern1e0ekFM>

## 5 Other ideas

### 5.1 Transmitting multiple signal channels

We can use an RGB led in the transmitter and map 3 different signals we have to each color of led. On the receiver side we can have 3 different panels with different coloured filter installed on each(i.e.

red filter on one, green on other and blue on the last one). Each panel should have its own receiving circuit. The signal transmitted with the red led can be received with the solar panel with red filter and other signals on other channels can also be received in the same way. Using this setup, we would be able to transmit 3 signals simultaneously, without interference. In real life this setup can be used for transmitting left, right and woofer signals of audio.

## 5.2 Using laser

On the transmitter, if we use some circuit to boost the current given to the LED and connect a laser diode instead of a regular LED, then using our system we would be able to achieve even larger ranges without any lenses. As laser diode emits an almost parallel beam of light, it will not diverge even when travelling over long distances. In real life this can be used to transmit an audio signal from one end of an auditorium to speakers on the other end of it.

## 5.3 Noise cancellation

There are a lot of ambient light sources which keep blinking at very fast rate, for example a 240V AC LED bulb blinks at a 60Hz, when such light sources are near our receiver system, then the receiver panel starts capturing these noise signals along with our desired signal, hence our desired signals quality is degraded.

To get rid of such ambient noise issues we can add another solar panel of the same size in series with the primary one. This panel should be in reverse bias and should be made to face away from the direction where the transmitted signal is coming from. In such a configuration the primary panel might capture our desired signal + noise signals and the secondary one will only capture noise signal, as it is in reverse bias it would automatically subtract out the noise signal, hence if we measure across this series solar panels we would only get our desired signal.

# 6 Applications

This device transmits audio signals in a unique way, using light, not by using electromagnetic waves. In places where there is a lot of electromagnetic noises (like nuclear power plants, large generators) this system can be effectively used to transmit audio signals without interference.

This signal transmission technique was in fact used in the 1970s Film Industry to encode the sound accompanying a picture in the photographic film itself.

# 7 Summary

Building this project was an enriching experience, it made understand and visualise circuit analysis techniques like the small signal trick in new ways. I was really thrilled to see how by using such simple techniques we can build circuits which exhibit such interesting behaviour.

First while building the transmitter, I was amazed to see how the V-I relation varied based on even the color of a LED. Then when I started to build the receiver my assumption was that LDR will be the perfect photo sensor, but later upon further experimentation I was shocked to see that it could not reliably be used for signal transmission, it can only be used for switching applications. After the failure of LDR, I Remembered a demo in EE2,660x in which the professor told that he used a device which produced current proportionally to the light received. That is when I got the Idea to use Solar Panel, upon further experimentation the solar panel proved to be the best sensor for my device, I was really surprised to see how a device used for generating electricity can also be used for transmitting signals. Seeing how magically small signal trick transmitted a signal across the panel I was inspired to learn more circuit techniques, like using op amps and RC filters, in order to successfully receive sound. After learning these, I applied all of them to create a receiver and it worked fantastically, way better than I had expected.

Then to have more fun with my system I wanted to increase its range, to do this I used a lens. I used the Lens formulas I learnt in physics class to calculate the object's and image's position. I had a lot of fun doing this experiment and its result too thrilled me!!

## References

- [1] [www.edx.org/course/circuits-and-electronics-1-basic-circuit-analysi-2](http://www.edx.org/course/circuits-and-electronics-1-basic-circuit-analysi-2), *This experiment is based on Small signal trick and demonstration from this course*
- [2] [www.circuitlab.com](http://www.circuitlab.com), *tool used to create circuit schematics*
- [3] [www.vishay.com/docs/83019/tlhb540.pdf](http://www.vishay.com/docs/83019/tlhb540.pdf), *Datasheet of 5mm blue LED, Figure 6*
- [4] [www.sunrom.com/get/443700](http://www.sunrom.com/get/443700), *Datasheet of LDR, Figure 10 was plotted using data from this source*
- [5] [www.electronicshub.org/non-inverting-operational-amplifiers/](http://www.electronicshub.org/non-inverting-operational-amplifiers/), *Information about Op Amps*
- [6] [www.youtube.com/watch?v=FysV6XnDlQk](http://www.youtube.com/watch?v=FysV6XnDlQk), *Audio source used for testing and demonstration*
- [7] [www.desmos.com/calculator](http://www.desmos.com/calculator), *Graphing calculator App*
- [8] [en.wikipedia.org/wiki/High-pass\\_filter](http://en.wikipedia.org/wiki/High-pass_filter), *Information about High Pass RC filter*