

Optical Full Duplex Optical Transceiver Design

1. Background

Amateur radio has a history of enabling experimentation and testing environment that enables hobbyists and enthusiasts to try new things. The licenses granted by the FCC enable amateur operation and experimentation across the entire electromagnetic spectrum. Operation is traditionally focused on HF (1 MHz – 50 MHz) for worldwide communication and UHF/VHF (2m, 70cm) for local and line-of sight communication, however no band limitations are enforced above 275GHz (1.1mm wavelength). Optical communication offers unique challenges when compared with more common amateur radio wavelengths, but the rise of consumer optoelectronic products has created a wide range of cost-effective parts which are available for amateur operators to experiment with. Amateur radio modes often rely on multiple frequencies in order to transmit information (FM, SSB), but there are modes available that rely on a single frequency/wavelength for transmission (CW, AM). These modes are readily available for application in an optical system.

2. System Requirements

The goal of this project is to create a simple circuit and optical system which can be used to transmit an audio tone for the purpose of morse code transmission. This circuit should be cost-effective and easy to construct. Initial testing will be limited to indoor and short-range settings, but the system should be designed to enable line-of-site communication beyond 1km with proper conditions and site selection. The device should be portable

enough to hand carry or pack in for field use. The transmitter should use a 3.5mm audio jack for keying so any straight key can be used. The receiver should output line-level audio to a 3.5mm audio jack so an external portable speaker or headphones can be connected.

3. Eye Safety and Regulatory Concerns

Regulatory concerns must be considered for this device as it poses two potential risks.

One is the safety risk posed by using a bright emitter around people and second is the risk of interference to other services posed by operating an emitter in free space.

Light emitters are evaluated for eye safety against IEC 62471 for measuring and communicating photobiological hazards. Luxeon provides an IEC 62471 report for the C Color LED product line and this product was classified as Risk Group 1 (R1): “No photobiological hazard under normal behavioral limitations”. Other LEDs in the C Color LED product line were classified R2. Devices restricted to the R2 classification are deemed to pose a retinal blue-light hazard or retinal thermal hazard within the 0.25 seconds which will allow the individuals to protect themselves via the aversion response.

The FCC does not regulate visible emissions in free space, but the FAA offers some guidance for laser emitters in their Advisory Circular 70-1B2. For laser emitters operating in shared airspace the main concerns are affecting the eyesight or focus of pilots. The two limits to the regulation enforced by the FCC are Normal Flight Zones (NFZ) which simply restrict visible and non-visible lasers to less than the MPE for eye safety and Laser Free

¹ IEC 62471 is available for purchase from the IE webstore for USD 377 and was not directly consulted for this project. <https://webstore.iec.ch/en/publication/7076>

² FAA Report: https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC70-1B_Final_Final_Unsecured.pdf

Zones (LFZ) which limit laser power to 50 nW/cm². While this system does not employ any laser-collimated light, it is reasonable to consider these limits in evaluating the power output by the system. Given a starting luminous flux of 49 lm and the continuous dispersal of the emitted light, this device may be reasonably used in the general public, though it would be unwise to direct it towards critical airspace.

4. Electrical Design

The transmitter circuit requires modulation in order to create an audio signal and an additional switching circuit in order to send morse code. An Arduino Nano (ATMEGA 328p) is used to generate a PWM signal at the desired audio frequency. This signal is used to control a TIP120 acting as a low-side transistor switch to the emitter. Circuits are designed to receive 9V or 12V inputs so either voltage can be supplied via a battery for portable operation or using a switching power supply for bench top testing. **Appendix 1** shows a prototype circuit designed in KiCad. Preliminary testing was done using a passive receiver circuit with a BPW34 photodiode, however the output of this circuit requires additional amplification. Without external amplification the raw photodiode was able to produce a measured signal, but only when direct, focused light strikes the surface of the photodiode. This circuit was replaced with the Amplified Receiver Circuit using an OPT101P which offers internal as well as adjustable gain options for higher receive sensitivity. The additional gain offered by the OPT101P allow for creating a more sensitive detector circuit, however the fully integrated nature of the amplification circuit eliminates the ability to add a DC filter capacitor between the photodiode and the amplification circuit. For

testing in higher-noise environments, this is important in removing the bias from the photodiode output caused by a high amount of background light.

The final receiver circuit returns to the BPW34 photodiode and added a LM386 audio amplifier. This device was selected as it is a single-supply op-amp and is advertised for use in audio applications. A circuit was designed to set the op-amp gain used and is shown in **Appendix 2**. This creates a much more sensitive circuit. The current circuit design is suitable for classroom testing, however additional gain is desired for long-distance communication.

The diode used is a LumiLED L1C1-RED1000000000 with a typical forward voltage of 2.0V and a DC forward current limit of 1.05A (peak pulsed forward current of 1.3 A). An LED star board from LED Dynamics hosts 3 of these diodes in series. Eye safety and regulatory restrictions are discussed in a later section. The forward voltage of 3 diodes will be 6.0V and the forward voltage of the TIP120 (Collector-Emitter Voltage) is between 2.0V and 4.0V. This circuit can be driven at 9V safely. Driving it at 12V seems to be working for low duty cycles, however higher duty cycles may damage the diodes.

5. Optical Design

Without additional optics, this design was capable of audio transmission over very short distances of less than 1m. The raw emitter could be placed directly next to the raw photodiode and the output externally amplified in order to demonstrate opto-isolated audio transmission as a proof-of-concept. In order to improve the audio transmission capabilities several optical elements were added to collimate and focus the light on both ends.

The light emitters used are Luxeon C-Color LEDs mounted on LuxDrive star boards for easy handling of multiple LEDs. The datasheet for these diodes advertises a wide total angle³ of 175°. A secondary optic directs more of the light forward, but does not adequately collimate the light for long-distance testing.



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Figure 1. LED Star Board and Secondary Optic

Adding the secondary optic focuses the beam to a full width at half maximum (FWHM) intensity beam width of 43°x16°.⁴ This beam is still diverging so a Fresnel lens is added to further collimate the light.

³ **Total Angle** is defined the angle at which 90% of total luminous flux is captured.

⁴ The 43°x16° beam width is asymmetrical because an elliptical optical element was selected. No round spot optics were available at the time of purchase. The addition of a Fresnel lens was expected and an elliptical optic was deemed suitable.

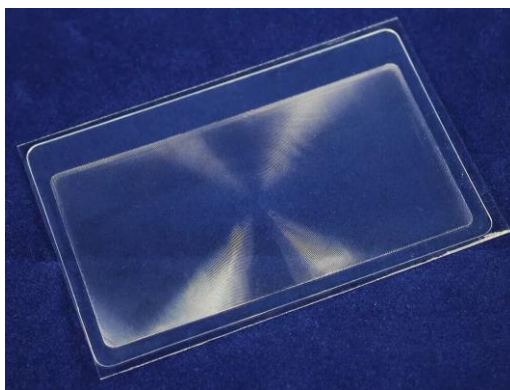


Figure 2. Example Fresnel Lens Sold As A Page Magnifier

The transmitter is comprised of a 3-diode LED emitter board, a Carclo secondary optic which focuses the emitter light to a 43°x16° FWHM arc and a Fresnel lens which collimates and projects an image of the Carclo optic output. The receiver optic uses a Fresnel lens to focus the collimated light received onto the photodiode. A cheap wallet page magnifier lens is used as a collimating Fresnel lens.

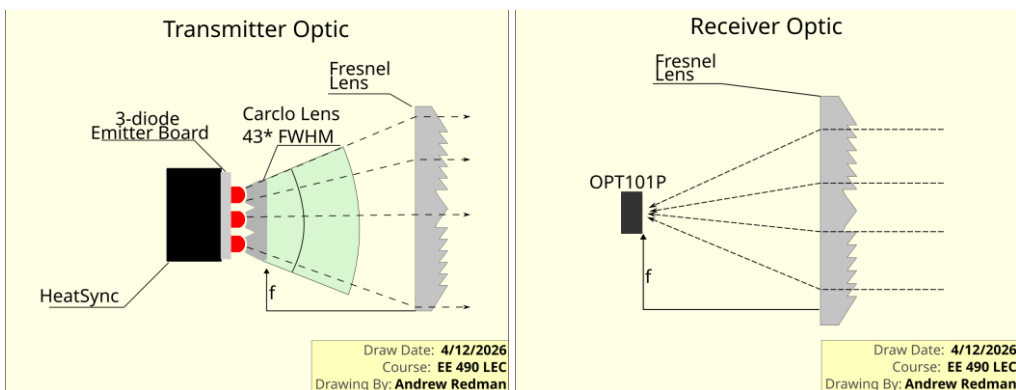


Figure 3. Optical System Lens Diagrams

Experimental testing with the specific Fresnel lenses purchased for this project determined they have a focal distance of 17cm. The receiver diode and the transmitting LEDs are each placed at the focal distance of the Fresnel lenses to efficiently focus the collimated light on the photodiode and collimate the emitted light, respectively.

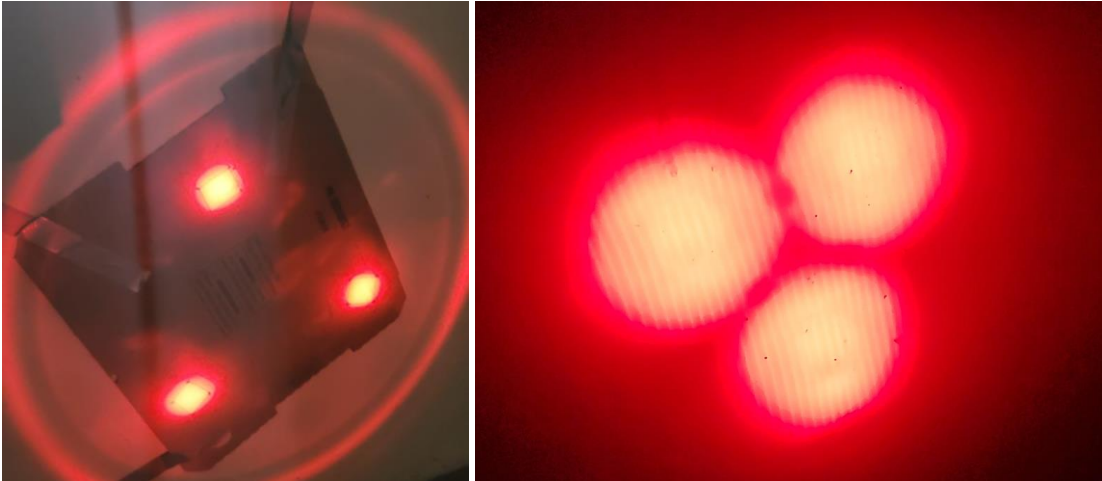


Figure 4. Optical System Lab Testing

Photographs from lab testing show the difference between the output of the Fresnel lens without (left) and with (right) the secondary optic attached to the LED board. This also demonstrates that the output of the Fresnel lens is not well collimated and is continuing to diverge which reduces the power at long distances and will not pose a regulatory risk when operating in the field.

6. Software Design

Ideally, this device will be used in the field without the use of an additional device such as a phone or laptop. Any processing necessary should be constrained to a low-cost microcontroller such as an Arduino Nano ATMEGA 328p. Currently the microcontroller is only used to generate an oscillating PWM signal which generates a fixed audio tone for morse code use. Sample Arduino source used for simple morse code operation is provided in **Appendix 4**. To play simple musical runs, this code is extended to play multiple frequencies in series. In the future, programming could be extended to add simple audio processing to convert an input audio signal to an AM signal output using PWM.

7. Mechanical Design

The current mechanical design is primarily focused on being portable enough for brief tests and keeping the optical system roughly aligned. Going forward, the cardboard housing should be replaced by either wood, PVC, or a 3D printed material like PETG. When travelling the lens system should be capped in order to protect the Fresnel lens from being accidentally exposed to sunlight which could pose a fire hazard or cause damage to the optical system. Currently an extended baffle is used to reduce noise and minimize the risk of excess light being focused on the sensitive components.

The current design is intended to be hand-held for ease of portability and use in a classroom setting. Being able to move the device around quickly allows for repositioning and pointing the receiver at various light sources to see the effect of the additional noise floor and hear the variability of a light source. For field use, this device should be mounted to a stable tripod system which can be pointed at a long-distance receiver.

8. Future Work

Currently an ATMEGA 328p is used to generate a PWM audio signal, however the LM386 can itself be used to generate a square wave which could generate the tone needed to send a morse code CW signal. For a single-purpose, morse code device, this could be an attractive way to simplify setup by eliminating the need to configure and provision software while reducing the BOM cost.

The main updates for long-term work will be to reduce materials cost and finalize a schematic design. The use of the OPT101 and Arduino Nano ATMEGA 328p breakout board represent the main costs of the electrical BOM at a total cost of \$14. For morse code use,

these two components could be replaced by two LM386 op-amps, a BPW34 photodiode, and supporting passive components for a total cost of \$4.

Preliminary work was done to create a layout for each of these schematics in an effort to become familiar with the layout capabilities of KiCad. Additional work is needed to finalize the schematic design, check symbol creation and footprint selection, and determine the final board dimensions before placing an order with a board fabrication house.

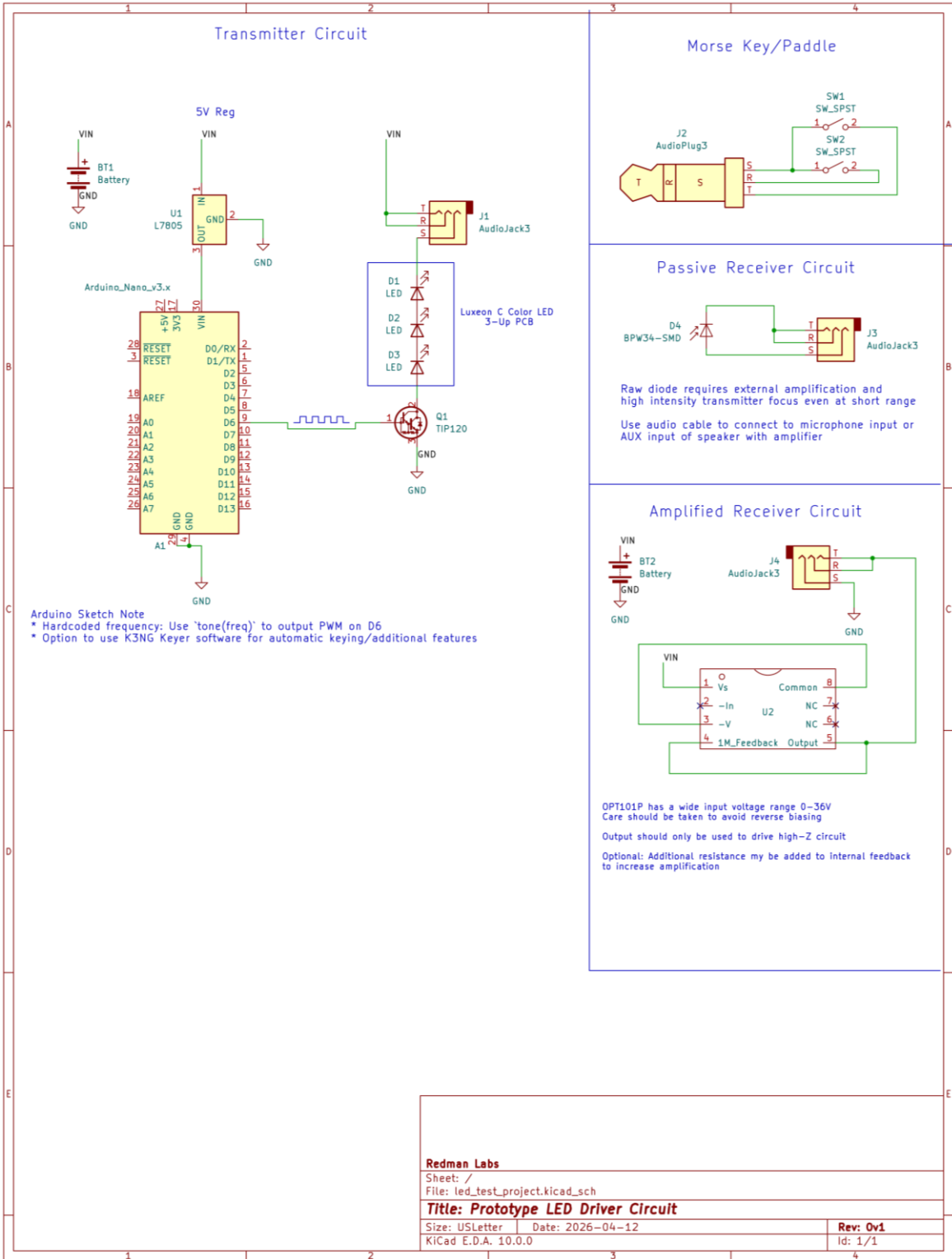
9. Conclusions

During field testing a usable signal was detected at a range of 250 meters at dusk. Better performance would likely be achievable in nighttime conditions and with a higher gain receiver. Increasing the transmit power is unlikely to increase performance until the receiver has been optimized. The main design has been validated and additional work should be undertaken to improve receiver gain and test longer range communication.

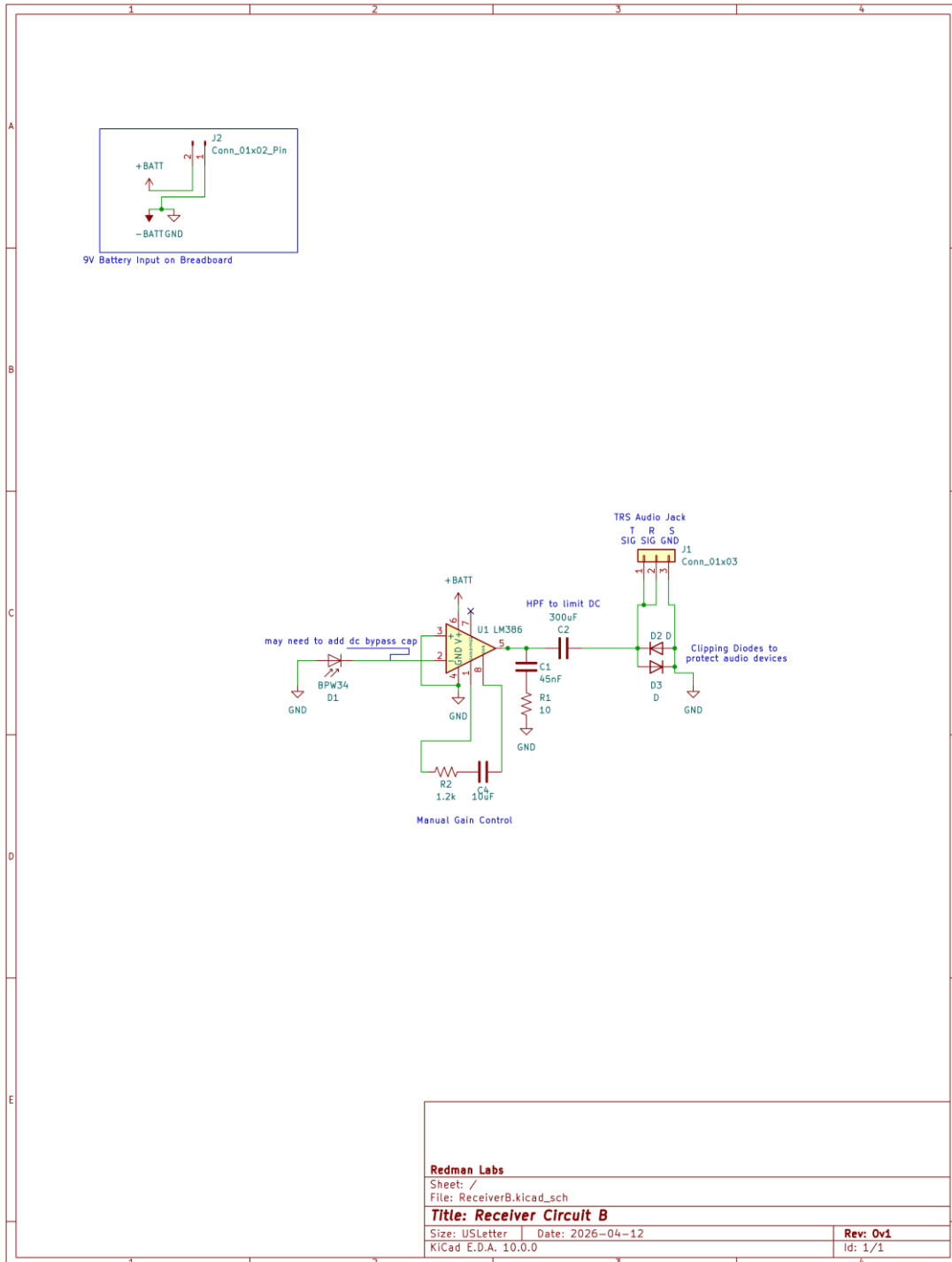


Figure 5. Field Testing Location Map

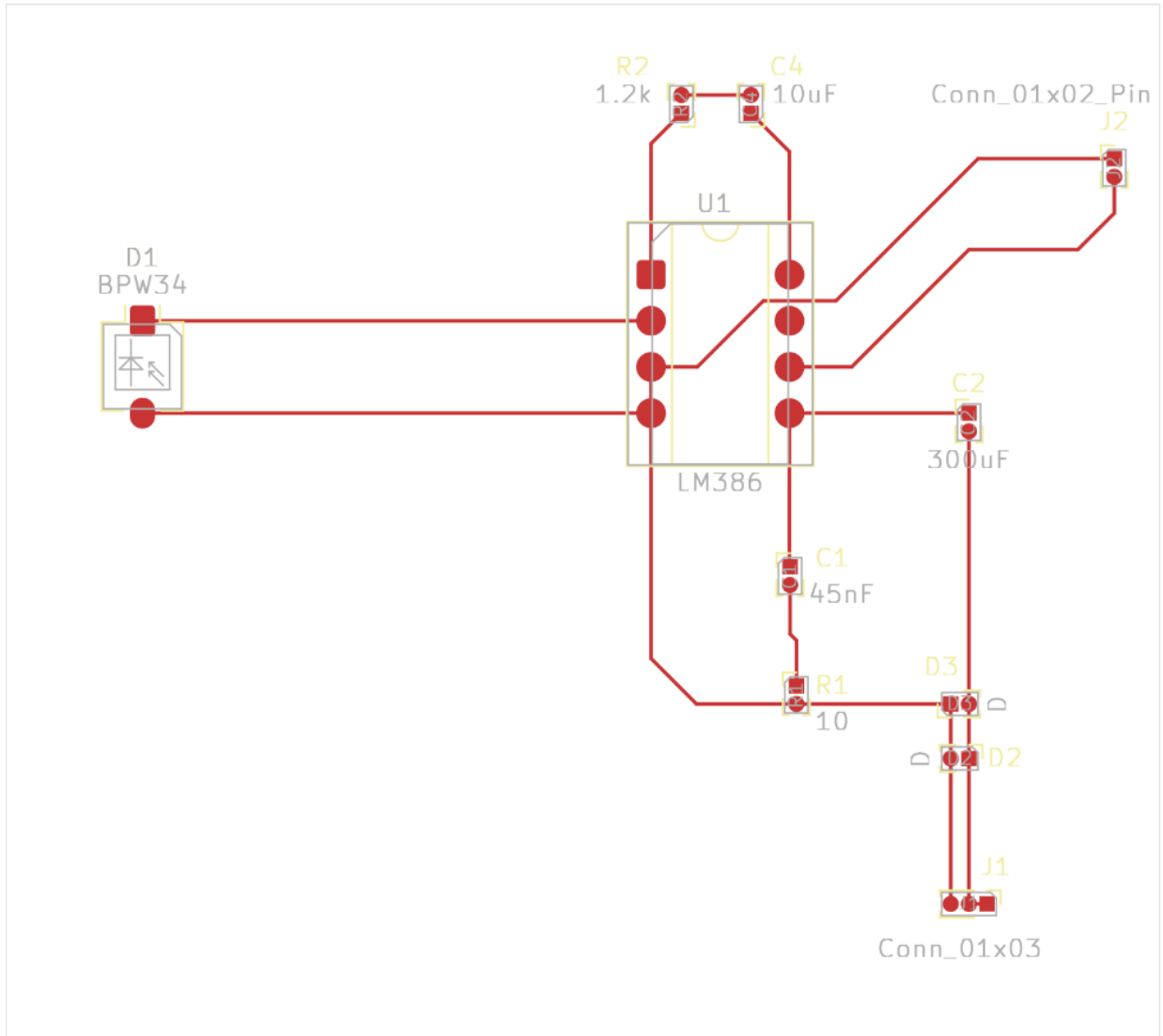
Appendix 1



Appendix 2



Appendix 3. Receiver B Layout



Receiver B Layout viewed from TOP side. Showing Copper, Silkscreen, and Assembly layers for the TOP side.

Appendix 4. Sample Arduino Source Code

```
#define TONE_PIN 6
#define TONE_FREQ 800

void setup(){
    pinMode(TONE_PIN, OUTPUT);
    tone(TONE_PIN, TONE_FREQ);
}

void loop(){
    // No changes needed
}
```