Application Report

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Laser Harp Design and Analysis

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1. Abstract

Electronic circuits have many applications in entertainment devices, such as musical instruments. The laser harp design in this report is an interesting example of a design which demonstrates the fundamental principles of several discrete electronic components. A laser harp is a modern rendition of the classical instrument - the harp. In a classical harp the user plucks strings to produce sound; similarly, in a laser harp the user waves a hand in front of

some sensor to activate sound. Typically laser harps are constructed using microcontrollers, however, the laser harp constructed in this design was built using only discrete electronic components. The laser harp is able to output ten distinct frequencies depending on the activation of specific infrared (IR) emitters and receivers. This report will discuss the design and analysis of the constructed laser harp.

2. Introduction

Many electronic devices in the entertainment industry today such as electric guitars, keyboards, and even some drum sets continue to use discrete components. There is a need to understand how these devices operate, as they may potentially save circuit designers time and money over using single-chip or pre-built board solutions.

In the Spring semester of 2017, students in Dr. Krchnavek's Electronics I course were tasked with designing an interesting device which demonstrated the usefulness of discrete electronic components. This team intended to build a device known as a "laser harp" in which the "strings" of the harp were infrared (IR) beams and the notes created by the strings were produced by a circuit which could individually set and amplify distinct frequency wave outputs. This team believes that this is an interesting and relevant application of discrete electronics and the project was approved for development.

In this report, the design, construction, and analysis of the Laser Harp are given. Texas Instruments Tina-TI (http://www.ti.com/tool/tina-ti) software was used to design the circuit. Several tests and design revisions were made before the final design was confirmed. The main circuit was constructed on a series of breadboards. The IR beam emitters and receivers were laid out on a hand-built surface. The final product was then tested and analyzed.

3. Background

3.1 Infrared Light

Infrared light is a type of electromagnetic radiation, as are radio waves, ultraviolet radiation, X-rays, and microwaves. Infrared spans between 1μm and 100μm on the electromagnetic spectrum. It is not visible to humans, however it can be felt as heat, or radiation. Infrared radiation can be detected using sensing devices.

Two infrared components are used in the Laser Harp: the IR LED emitter and IR receiver module. The devices were chosen because they both operate on the same wavelength of 940nm.

The IR light emitted from the LEDs are reflected onto the surface body. The infrared reflections are propagated in many angles, some of which will angle towards the IR receiver. The IR receiver changes an output signal when IR light is received in the correct modulated frequency.

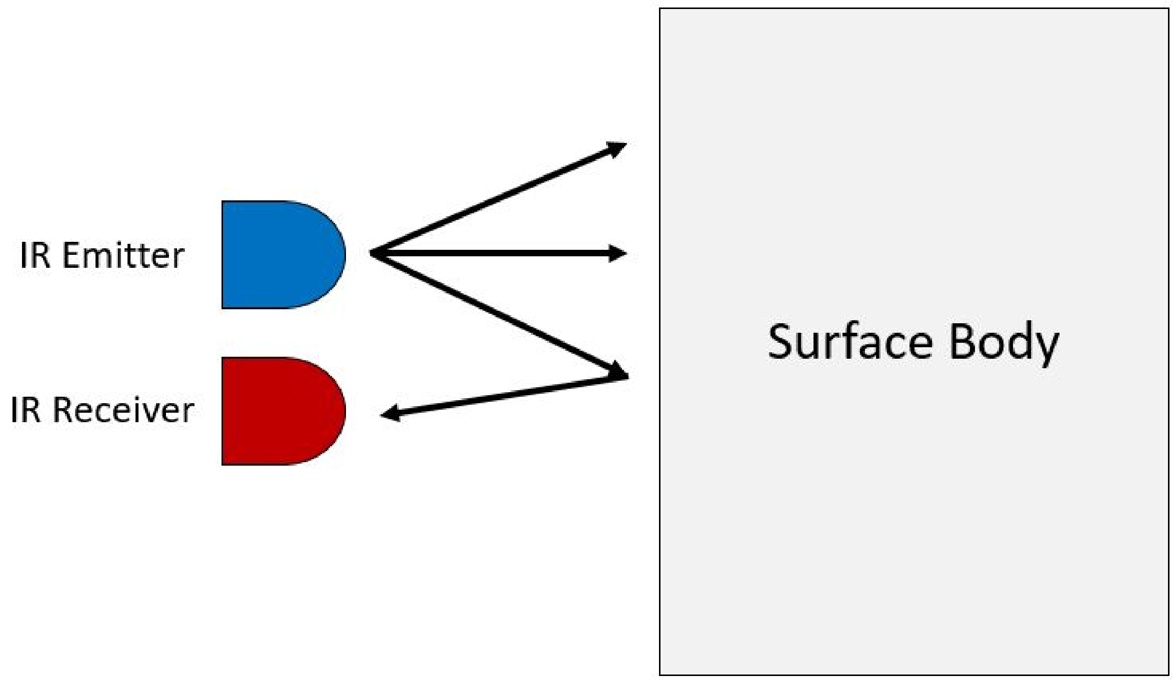

Fig. 1: Example theory of IR light reflecting off a surface body to the receiver

A specialized housing is used to place the IR emitter and receiver in close proximity. The housing must not only provide mechanical support, it must guarantee complete optical isolation between the emitter and receiver.

3.2 Operational Amplifiers

Operational amplifiers, or op amps, are two-terminal devices which amplify the differential input by a factor known as gain. The term operational is used to describe the mathematical nature in which these devices operate. For example, as in the case of this design, the op amp can be used to calculate and output the sum of multiple incoming signals. An example similar to the schematic used in the final design is shown in Fig. 2. The equation used to solve for the output V_{out} is

$$V_{out} = -(R_f/R_{in})(V_1 + V_2 + V_3 + ... + V_{10})$$

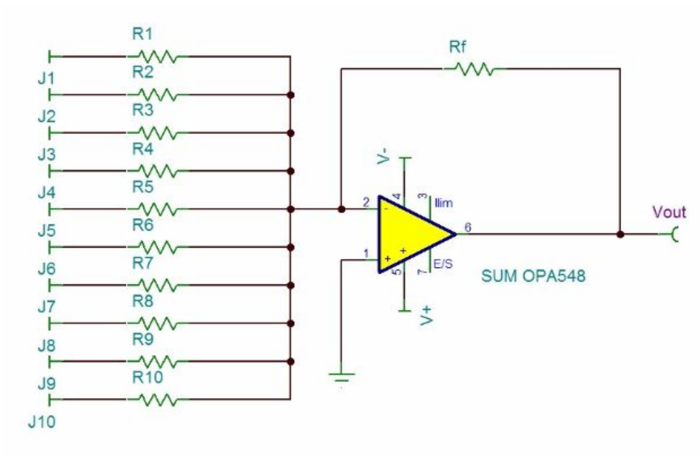

Fig. 2: Summing Amplifer Circuit Diagram

Op amps can also be configured to generate waveforms. One example of an op amp multivibrator that can generate square waves is shown in Fig. 3.

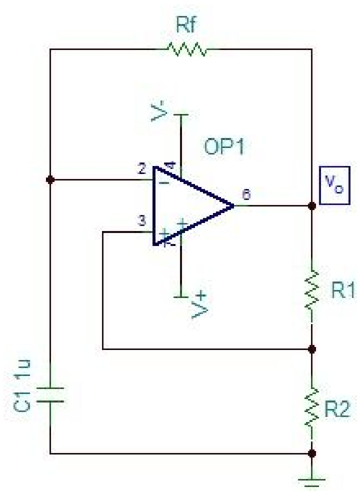

Fig. 3: Op Amp Multivibrator Circuit Diagram

The op amp multivibrator circuit generates a square output waveform using the RC timing network connected to the inverting input of the operational amplifier and a voltage divider network connected to the non-inverting input. The circuit will be analyzed in the discussion sections. In each circuit, a feedback resistor, R_f, creates a negative feedback loop which sets the closed-loop gain and limits the differential input to a point within the device's power specifications. The power specifications of the op amp are controlled by, among other things, the positive and negative voltage rails, V_+ and V_-, respectively.

3.3 Speaker

A loudspeaker, or speaker, is an electroacoustic transducer that is used to produce a sound based on an electrical audio signal. The speaker uses a diaphragm attached to a coil that moves back and forth to produce sound waves. This movement of this coil occurs when an alternating current electrical audio signal is applied to it. Speakers also have a resistance.

A typical 8 Ω speaker is used to output audio generated from the Laser Harp.

3.4 Capacitors

A capacitor is a component created out of two metal plates and an insulating material called a dielectric. The metal plates are placed very close to each other, in parallel, but the dielectric sits between them to make sure they don't touch. The dielectric material can be made out of various insulating materials: paper, glass, rubber, ceramic, or plastic. The plates are made of a conductive material: aluminum, tantalum, silver, or other metals. Capacitor plates with more overlapping surface area provide more capacitance, while more distance between the plates equate to less capacitance. The total capacitance of a capacitor can be calculated with the equation:

$$C = \varepsilon_{\mathrm{r}} \frac{A}{4\pi d}$$

Where ε_r is the dielectric relative permittivity, A is the amount of area the plates overlap each other, and d is the distance between the plates.

When electrical charge flows through the capacitor the positive and negative charges on the plates will attract each other and ultimately store charge. A capacitor can store electrical charge and discharge electrical charge. Capacitors are used in the laser harp for timing frequency generation and for blocking DC current.

3.5 Diodes

Diodes are single-input devices which, when powered, block current flowing into the cathode. On average, a typical pn diode will require a minimum of 700mV to turn on. At this voltage, the diode will enter the active region of operation and assume nearly linear behavior. Therefore, it can be assumed that, in the active region, diodes act much like resistors, although current can only be positive.

Diodes can also be used as switches. When the diode is off, hence there is not enough voltage to power the diode, the device will block all current. In an audio application, this could prevent small residual noise from passing through to any amplification stage. As soon as a high enough voltage is passed through, the diode will turn on and current will flow.

3.6 Bipolar Junction Transistors

Bipolar Junction Transistors (BJTs) are current-controlled devices composed of a “base” terminal, a “collector” terminal, and an “emitter” terminal. Similar to a diode which is a pn device, BJTs may be either npn or pnp material. In an NPN BJT, current flows into the base of the device which sets the collector current. Collector current is dependent on the base current and a factor known as β, which can vary wildly depending on operating conditions.

One configuration can cause the BJT to act as a switch or comparator. Because collector current drawn is directly related to base current, switching base current from a high to low value will also cause the collector current drawn to switch from high to low. Consider the circuit shown in Fig. 4, similar to a design unit found in the final Laser Harp design.

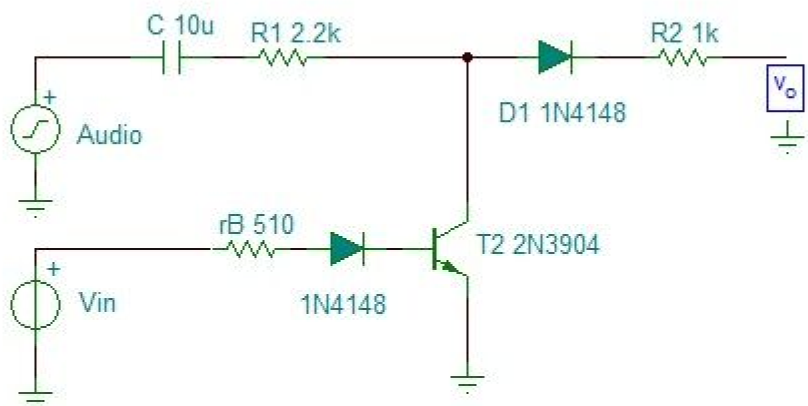

Fig. 4. Circuit Diagram Depicting a BJT Used as a Switch

Because the base of the BJT is biased at a higher voltage and the diode is obviously in the active region, current will flow into the collector, restricting the amount of current flowing out of *VF1*. Now imagine the 5V source is off (or 0V). The diode would be off in this case, creating no base current, and therefore no collector current. All current would flow out of *VF1*. This design principle is used in the Laser Harp for each different signal. For now, the signal is represented by the source *VG*. The capacitor, *C*, is used for DC blocking and AC coupling.

3.7 555-IC Chip

The 555-IC Chip is a timing device which uses multiple RC timing networks to produce time delays and oscillation. A similar concept of using a resistor and capacitor for oscillation can be seen in Section 4.2, which discusses an oscillator circuit using an op amp instead of a 555-IC. Besides the necessary V_+ and GND pins, the chip has several other useful pins, including pins to control threshold voltage and triggering. There is also a pin to set the control voltage and negative-edge synchronous reset. A discharge pin can be used to control the discharge rate of the capacitor.

Another useful function of the chip is pulse width modulation (PWM). In the Laser Harp, the 555-IC is used to demodulate IR signals. The reset pin is connected to V_{CC} to avoid false triggering. The discharging pin is connected to a resistor network through which the capacitor discharges. Connecting the trigger and threshold pins together allows for the chip to act as an oscillator. Refer to the following Section 4.1 for more information on the method in which the circuit was constructed and how it operates.

4. Discussion and Results

4.1 IR Emitter Circuit

The IR receiver used in this design demodulates any infrared signal at a peak frequency of 38kHz. Therefore to get peak responsivity, the infrared emitters should be pulsed at a frequency of 38kHz. A frequency of 38kHz can be generated using a 555-IC as a basic astable oscillator. The circuit of a astable 555 oscillator circuit can be seen in Fig. 5.

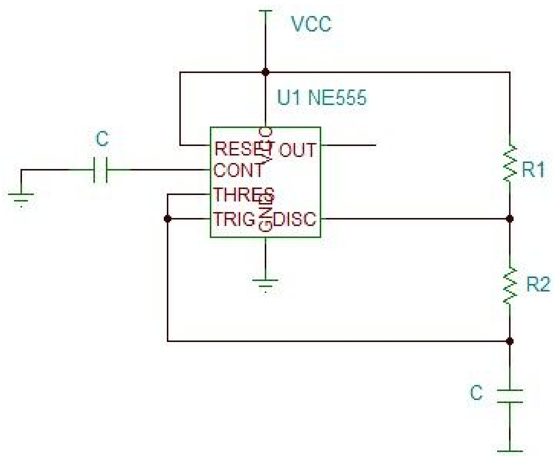

Fig. 5: Astable 555 Oscillator Circuit Diagram

The trigger (TRIG) and threshold (THRES) pins are connected together allowing the circuit to re-trigger itself on each cycle allowing it to operate as an oscillator. During each cycle, the capacitor (C) charges up through the timing resistors R1 and R2. The cycle discharges through R2 as it is connected to the discharge (DISC) pin.

The equation for calculating the charging time is

$$t_1 = 0.693(R_1 + R_2) \cdot C$$

and the equation for calculating the discharging time is

$$t_2 = 0.693 \cdot R_2 \cdot C\,.$$

The duration of one full timing cycle is equal to the sum of the two individual times that the capacitor charges and discharges.

$$T = t_1 + t_2 = 0.693(R_1 + 2R_2) \cdot C$$

The frequency of the the astable timer is the inverse of the calculated time,

$$f = \frac{1}{T}$$

We can find values for the resistors and capacitor that provide us with about a 38kHz frequency output.

$$T = 0.693(18k\Omega + 2(180k\Omega)) \cdot 100pF$$

$$T = 0.0000262s$$

$$f = \frac{1}{T} = \frac{1}{0.0000262s} = 38174Hz$$

The duty cycle of the oscillator can be calculated as,

$$Duty\ Cycle\ \% = \frac{t_1}{t_1 + t_2}$$

$$Duty\ Cycle\ \% = \frac{0.00001372s}{0.00001372s + 0.00001247s} = 0.52386$$

$$Duty\ Cycle\ \approx 52\%$$

Fig. 6 shows the simulation of the square output waveform. The frequency of the waveform is approximately 38kHz with a duty cycle of about 52% as per calculations.

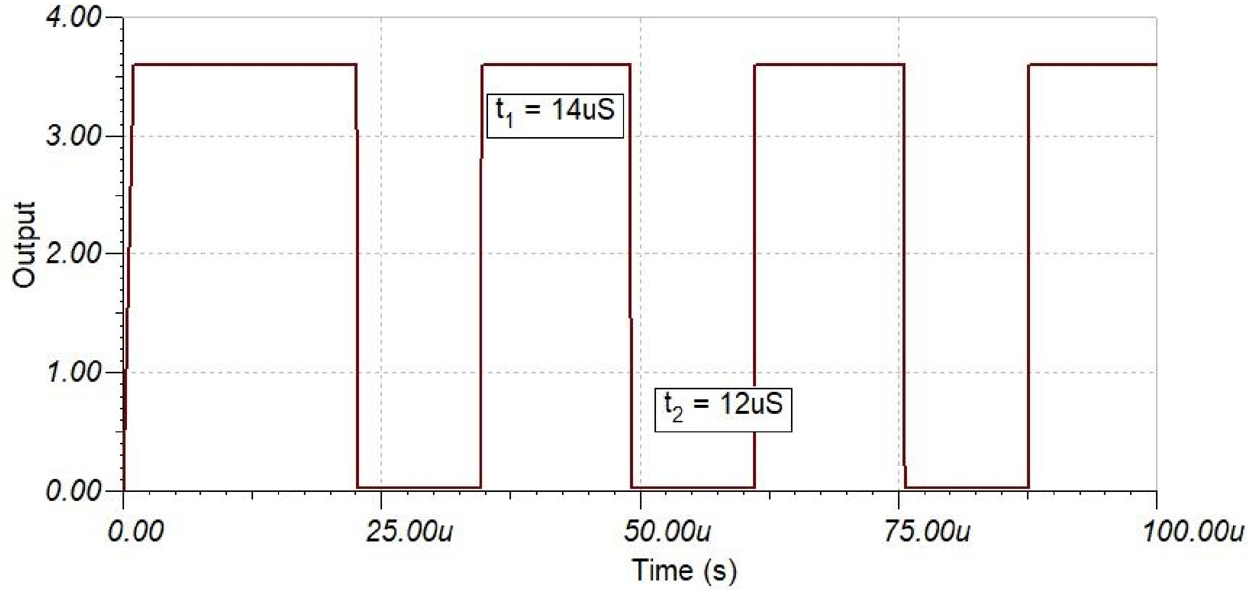

Fig. 6: Simulated Square Wave with 52% Duty Cycle

The 38kHz output waveform can be connected to a BJT to switch on the infrared emitters as a load whenever the timing waveform is high. A example of the circuit that satisfies these specifications can be seen in Fig. 7.

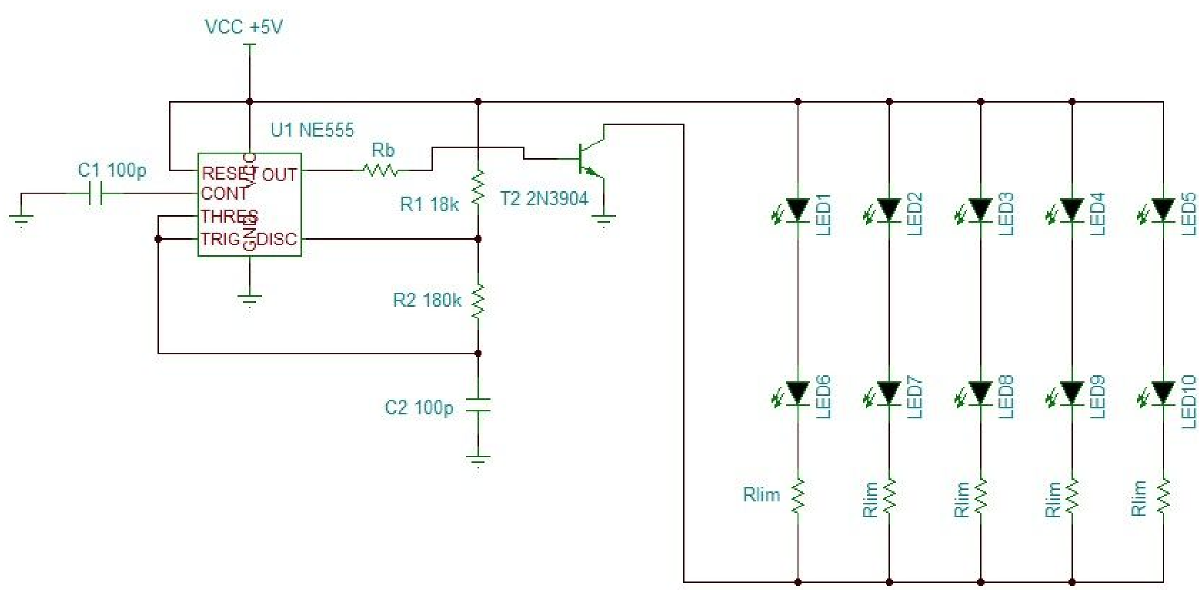

Fig. 7: IR Emitter Circuit Diagram

Current into the IR emitters should be optimized because the greater the current to the emitters, the brighter they will be, and therefore provide maximum detection range. However, the emitters should not receive too much current as to destroy the internals.

As per the datasheet for the TSAL4400, the maximum forward current with a duty cycle of 100% is 100mA (Refer to Fig. 8).

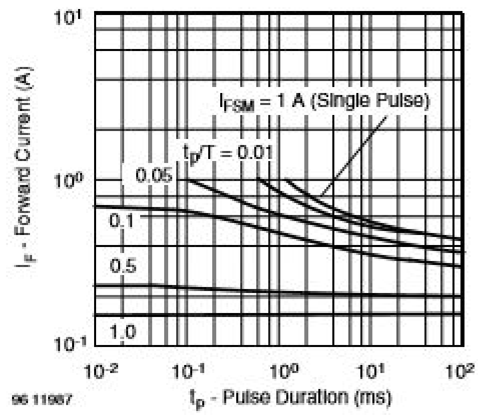

Fig. 8: Pulse Forward Current vs. Pulse Duration

In this application the duty cycle (t_p/T) is approximately 52% (0.5). Therefore, more forward current can be pushed into the emitter. This is because the silicon dye within the LEDs have time to cool down between cycles. While as many as 210mA can safely be fed into the emitter, only 180mA will be used for the purposes of this design.

Fig. 9 contains information on the forward voltage as forward current changes.

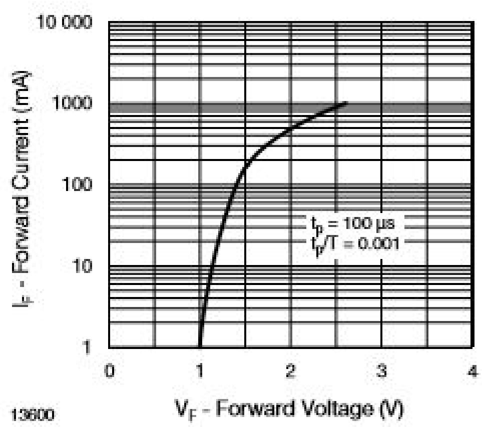

Fig. 9: Forward Current vs. Forward Voltage

The emitter was tested using lab equipment to have an approximate forward voltage of 1.09V.

For load switching applications, it is recommended that a BJT is run in the saturation region (V_{CE} of ~0.2V). In order to solve for the base resistor R_b which is needed to bias the BJT in this region, the base current must be known. Base current, I_b in this circuit is

$$I_b = \frac{I_c}{\beta} = \frac{0.180A}{100} = 0.0018A$$

where β = 100 is assumed to be the worst case value for the 2n3904 BJT transistor. Then,

$$R_b = \frac{V_i - V_{BE}}{I_b}$$

where V_i is the input from the 555-IC output (approximately 3.57V) and V_{BE} is approximately 0.7V. Therefore,

$$R_b = \frac{3.57V - 0.7V}{0.0018A} = 1.5k\Omega$$

To solve for the current limiting resistors for the IR emitters, the following expression was derived:

$$I_c = \frac{V_{cc} - V_f - V_f - V_{CE}}{R_{lim}}$$

where V_{CC} = 5V, V_f (emitter forward voltage) = 1.09V, V_{CE} = 0.2V, and I_C = 0.180A. Solving for R_{lim}, it was found that

$$0.180A = \frac{5V - 1.09V - 1.09V - 0.2V}{R_{lim}}$$

$$R_{lim} = 15\Omega$$

Therefore, to provide the emitters with maximum forward current the limiting resistor should be approximately 15 Ω. Changing this rtesistance slightly will change the strength of the emitted beam. During design, the limiting resistor was arbitrarily changed to create a weaker infrared beam. By increasing the resistance value and testing the range of the beam, interference between adjacent beams was reduced. The design now uses R_{lim}=150Ω.

Fig. 10 shows a simulation of the IR emitters pulsing approximately 180mA at a frequency of 38kHz as originally designed.

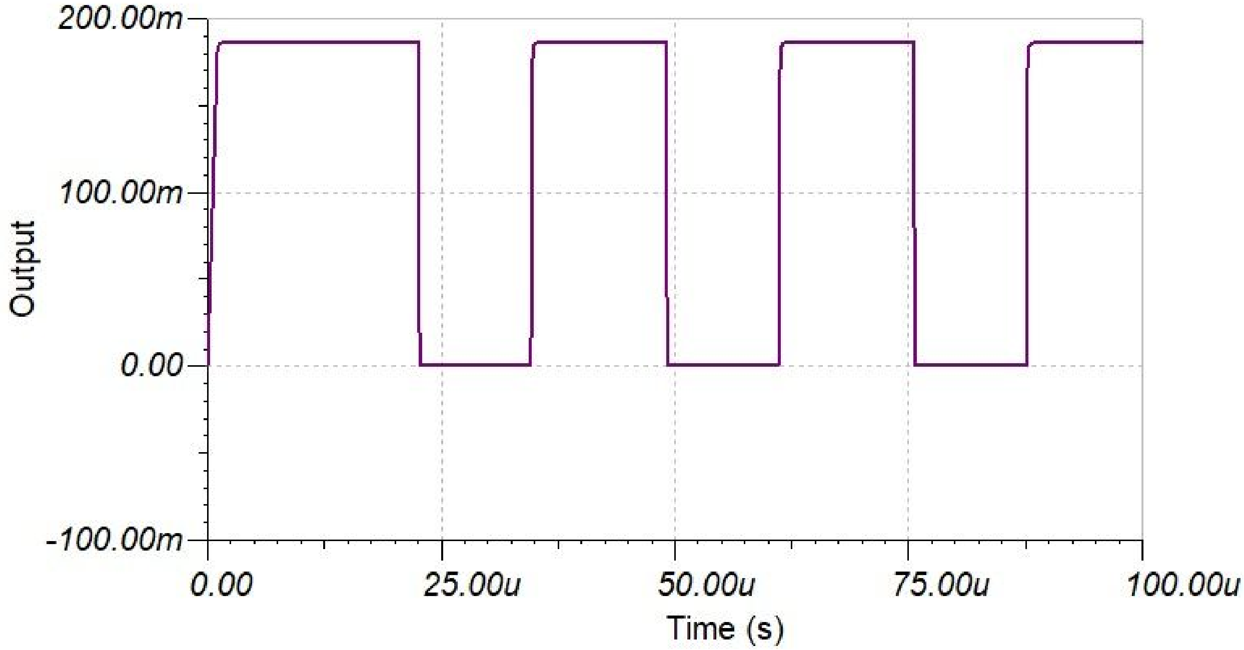

Fig. 10: Simulated IR Emitter Pulsation

Source: http://www.electronics-tutorials.ws/waveforms/555_oscillator.html

4.2 Opamp Multivibrator (Frequency Generation)

An opamp is configured as an astable multivibrator to generate a square wave with a desired frequency. The output square wave is used as a singular musical note in the laser harp. The multivibrator is an astable oscillator circuit that uses a RC timing network and voltage divider network to generate a frequency dependant on a calculated feedback resistor.

The general schematic for the opamp multivibrator is seen in Figure 11.

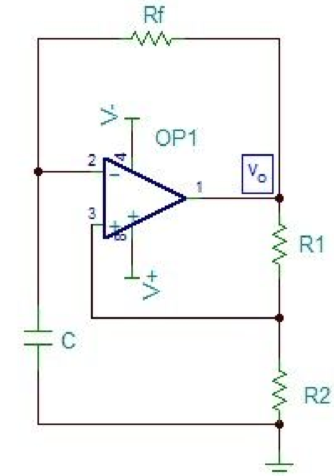

Fig. 11: Op Amp Multivibrator Circuit

Resistors R1 and R2 in the circuit are used a voltage divider network as to bias the circuit to provide a simple equation to calculate for a feedback resistor. The divider network is connected to the non-inverting input of the opamp which causes the output to switch positive or negative cycles depending on the charging state of the capacitor.

The voltage connected to the inverting input is determined by the voltage divider network,

$$\beta = \frac{R2}{R1 + R2} = \frac{30k\Omega}{35k\Omega + 30k\Omega} = 0.462$$

The period of the output waveform is determined by the RC time constant of the two timing components (resistors) and the feedback established by the divider network which set the reference voltage level.

$$T = 2R_f C ln(\frac{1+\beta}{1-\beta}) = 2RCln(\frac{1+0.462}{1-0.462})$$

$$T = 2 \cdot R_f \cdot 0.01\mu F \cdot ln(2.717)$$

$$f = \frac{1}{T} = \frac{1}{2 \cdot R_f \cdot 0.01\mu F}$$

Therefore to determine the feedback resistor to generate a 500Hz waveform,

$$500Hz = \frac{1}{T} = \frac{1}{2 \cdot R_f \cdot 0.01\mu F}$$

$$R_f = 100k\Omega$$

Figure 12 shows a simulated 1kHZ square wave generated by the op amp multivibrator.

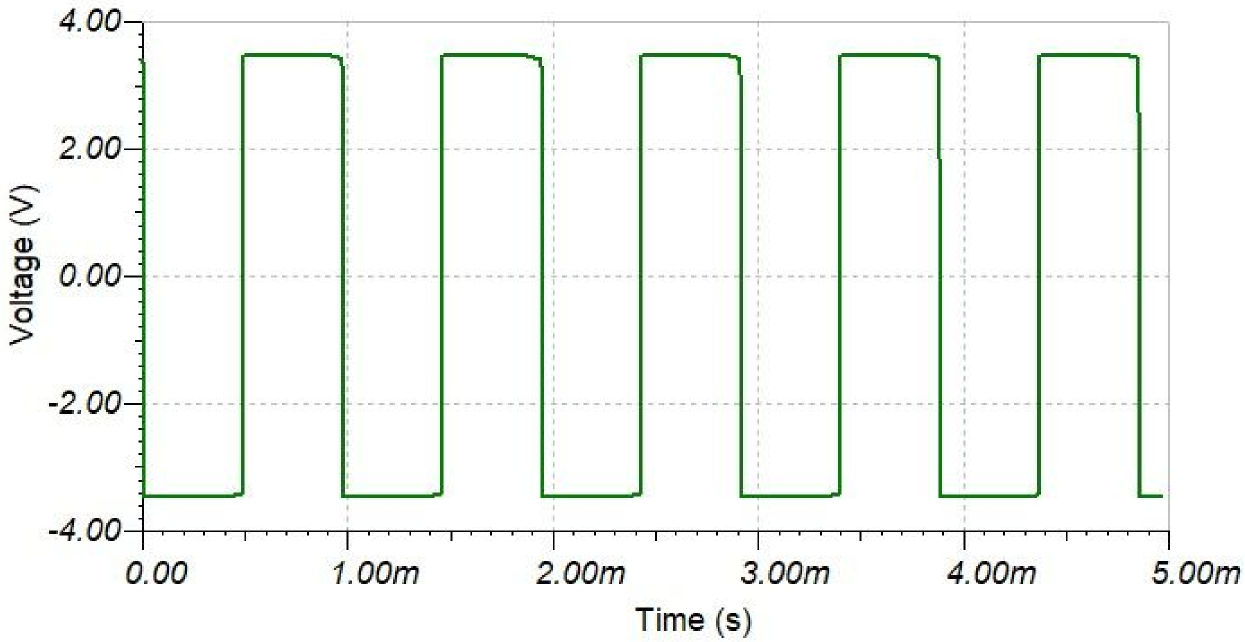

Fig. 12: Simulation of 1kHz square wave generated by op amp multivibrator

The opamp multivibrator was constructed ten times (for ten unique frequencies, or notes) in the following configuration shown in Figure 13.

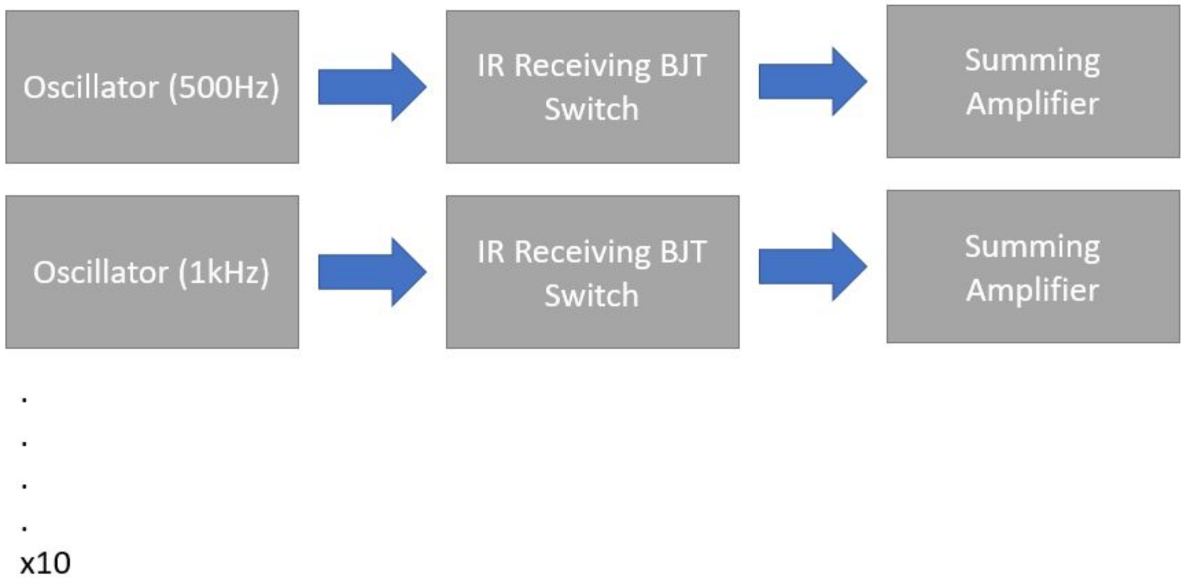

Fig. 13: Relation of opamp multivibrators to the IR receiving switch and summing amplifier portions discussed in the next sections

4.2 Bipolar Junction Transistor Switch

To create a switch using analog components, a bipolar junction transistor (BJT) is used in conjunction with the output of the infrared receiver. The output of the IR receiver is placed in series with a signal diode and a 510Ω resistor to the base of a 2N3904 small-signal, NPN transistor. The emitter of the transistor is grounded. The audio signal, V_{audio}, is connected in series with a 0.01µF. This capacitor is used for AC coupling and DC blocking, preventing any current from flowing into the aforementioned multivibrator circuit. Following the capacitor is a 1kΩ resistor connected to the collector of the BJT. The collector is then connected to a signal diode in series with a 2.2kΩ resistor. This leads to the summing node of each signal. The switch configuration is replicated ten times, once for each audio signal, and the outputs go to one node before the summing amplifier.

4.2.1 IR Receiver

The IR receiver's pinout is shown in Figure 14.

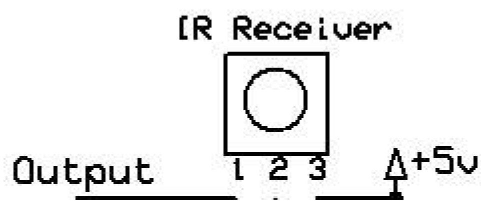

Fig. 14: Pinout diagram for the infrared receiver integrated circuit

The +5V terminal of the IR receiver is connected to a 100Ω resistor, which is then connected to a 5V source. The +5V terminal is also connected to the anode of a 0.1μF capacitor. The GND terminal of the IR receiver is connected to the cathode of this capacitor. This configuration is shown in Figure 15. The design creates a low-pass filter, resisting rapid variations to the input terminal of the IR receiver. This reduces noise and eliminates the effects that spikes to the input of the receiver typically have on its operation.

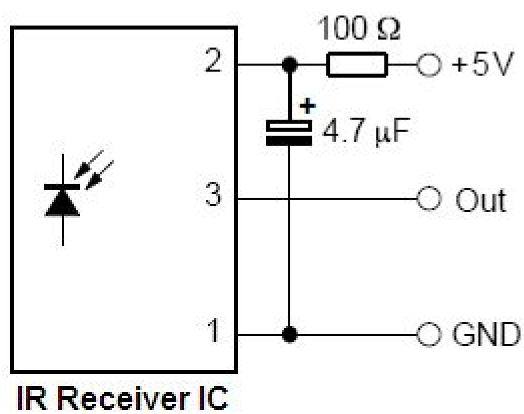

Fig. 15: Infrared receiver pinout diagram demonstrating additional low pass filter

The output of the IR receiver varies, theoretically, from 0V to 5V. However, experimentally, the output varies from 23mV to 4.87V. When the IR beam is broken and reflected onto the receiver, the output is approximately 23mV. If the beam is not reflected onto the receiver, the output is approximately 4.87V. This is an example of an active-low device.

The processes the receiver integrated circuit undergoes is as shown in Figure 16 below:

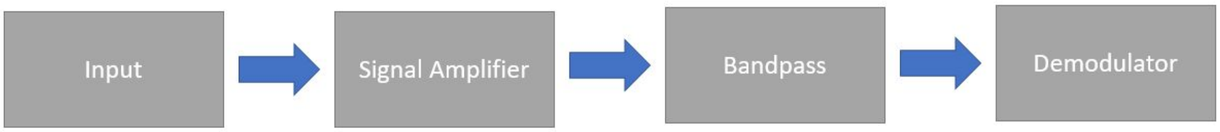

Fig. 16: Internal process of the receiver IC

The receiver takes the input signal, amplifies the signal, and puts it through a bandpass filter to eliminate low and high frequencies. The receiver demodulates the signal at a 38kHz frequency; this is why the emitter LEDs were modulated at a 38kHz frequency previously.

4.2.2 BJT Switching

The output of the infrared receiver is connected to a BJT-switch configuration. The circuit is shown in Figure 17.

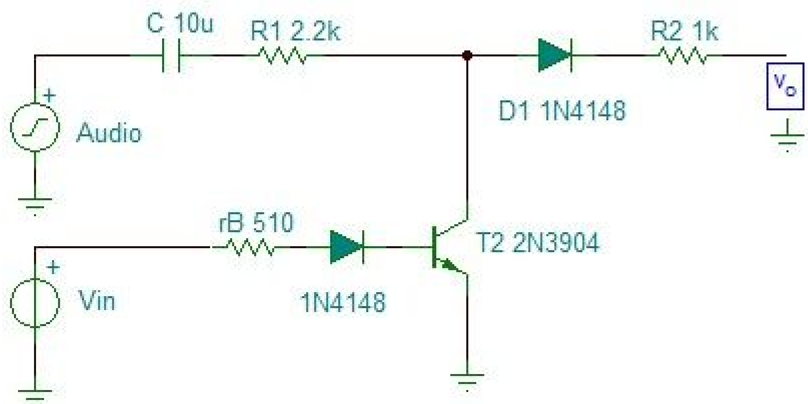

Fig. 17: BJT audio switching circuit

When the IR beam is broken, the output is 23mV and the signal diode is turned off. This can be modeled with an open circuit -- eliminating any base current. By eliminating the base current, the collector current is also set to 0A.

$$i_C = \beta i_B$$

$$i_C = (100)(0A) = 0A$$

Because of this and Kirchhoff's Current Laws, it can be said that the current through the 2.2kΩ resistor is approximately equal to the current through the signal diode as no current is flowing through the i_C branch. Thus, when the IR beam is broken the signal diode is turned on, allowing the audio signal to pass to the speaker.

When the IR beam is not broken, the output is 4.87V and the base signal diode is turned on. This can be modeled with a 0.7V drop, creating about 7mA of base current.

$$-4.87V + 0.7V + 510\Omega(i_B) + 0.7V = 0$$

$$i_B = \frac{(4.87V - 0.7V - 0.7V)}{510\Omega}$$

Designed for a worst-case of β=100 (max 400), this results in a collector current, i_C=0.7A. With a collector current large with respect to the current created by the audio signal, very little current is passed to the signal diode. Thus, the signal diode can be modeled with an open circuit, as the current through it is less than the threshold current. With this open circuit model in place, the audio signal is not passed through the signal diode to the summing node.

The 510Ω resistor was chosen in the design to limit the base current enough that the transistor would not be burned by continuous use. Research revealed that the BJT can be exposed to continuous use in the active region for base currents up to 20mA without damage. The laser harp was designed to use a base current much less than this value. It is important that there is still enough base current to create the current sink needed to drain the current away from the speaker when the IR beam is not broken.

When the beam is not broken the output of the IR receiver is high (5V). Therefore, when the beam is not broken it should mute the note attached to the circuit portion.

Figure 18 below demonstrates a simulation when the beam is not broken and no audio is played in the output.

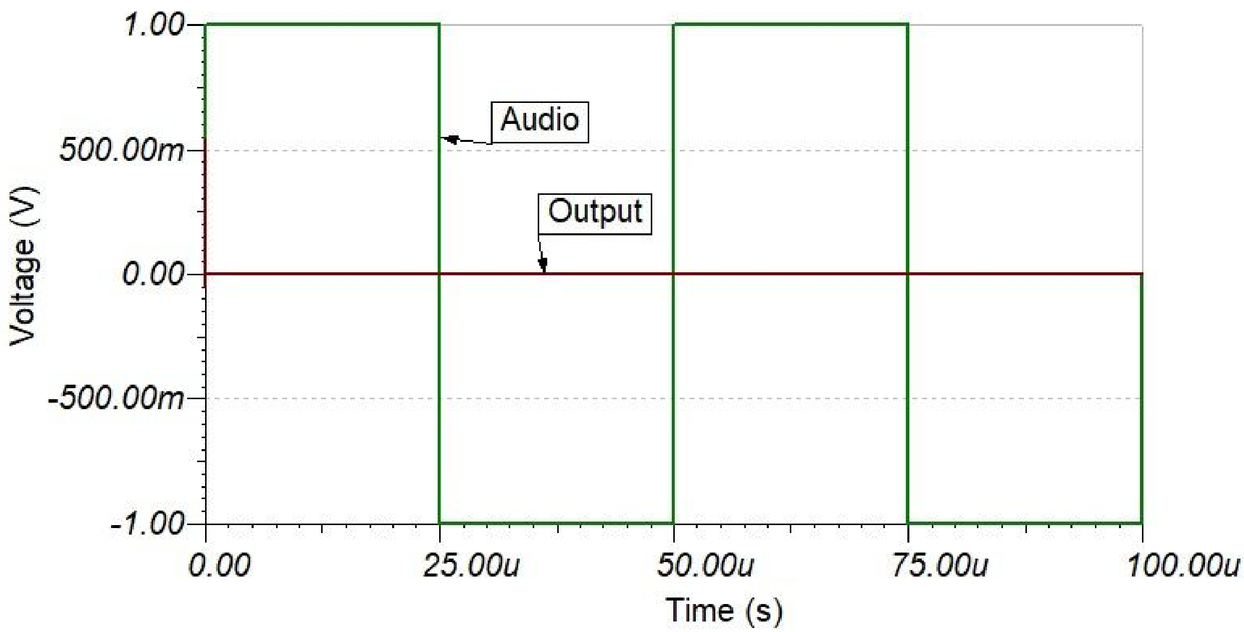

Fig. 18: Simulation of the switching output when the IR receiver is high [non-broken] (5V)

When the beam is broken the output of the IR output is low (0V). Therefore, when the beam is broken it plays the note attached to the circuit portion.

Figure 19 below demonstrates a simulation when the beam is broken and the input audio is switched on to the output.

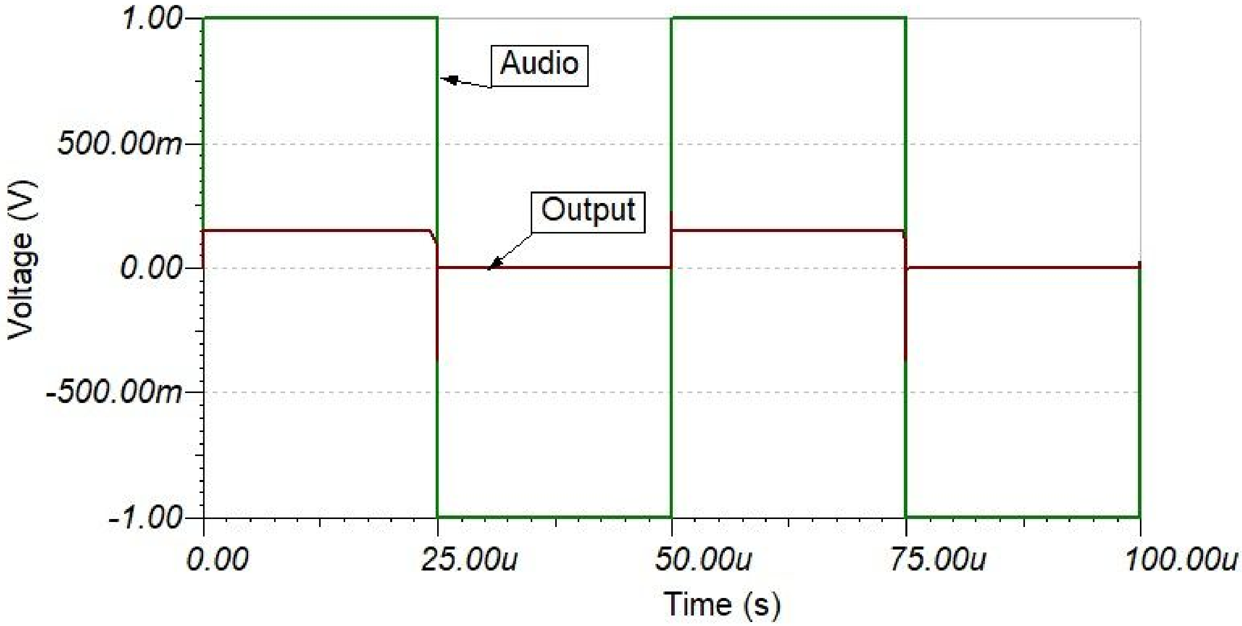

Fig. 19: Simulation of the switching output when the IR receiver is low [broken] (0V)

4.3 Summing Amplifier

The output of the switch configuration, v_O in Figure (Insert number here), is connected to a summing node. The summing node is connected to the inverting terminal of an TL072 operational amplifier configured as a summing amplifier. With R_{IN}=1kΩ, as shown in Figure (Insert number here), the output of the amplifier is calculated with the formula shown below.

$$V_{out} = -(R_f/R_{in})(V_1 + V_2 + V_3 + ... + V_{10})$$

With R_f = 2.2kΩ, the summing amp is set for a gain of 2.2V/V. The audio signals are square waves of varying frequencies with amplitudes approximately equal to 5V. After the switch, the signals are, in simulation, square waves with amplitudes of 904mV. This leads to square wave outputs from the summing amplifier with amplitudes approximately equal to 9.04V. This was purposely designed to avoid clipping the operational amplifier output, which uses +/- 12V supplies. Without saturating the amplifier, noise is reduced, which is of importance in a musical application.

4.4 Visual Design

The Laser Harp was constructed from a series of IR emitter and receiver modules connected to an external breadboard with the aforementioned circuits. Figure 20 displays the final working version of the Laser Harp.

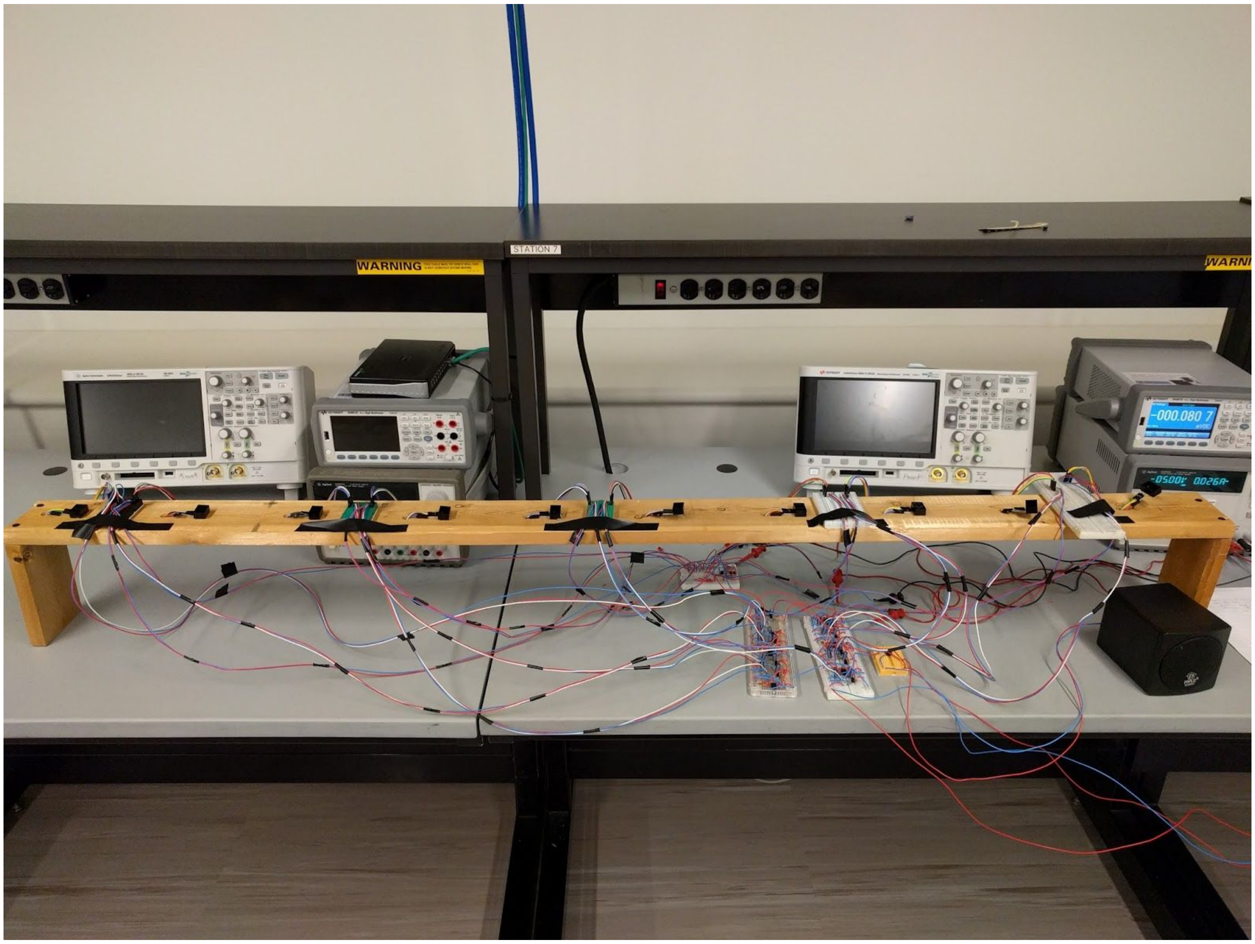

Figure 20: Final Design of the Laser Harp

The Harp is laid out on a hand-built wooden platform that is self-supporting. The IR emitter and receiver modules are cased in small black plastic molds. Hot glue was used to secure the molds to the surface of the top wooden board. The ten modules are evenly spaced on the board with 6” horizontal clearance. Wire access holes were drilled about an inch away from the modules so that the IR emitter and receiver leads could be fed through the underside of the board. The wires are then wrapped around the wooden platform and terminated in small breadboards mounted on the platform’s top surface. From there, longer wires connect the IR emitter and receiver pairs to the main breadboards, which are positioned below the Harp, but not mounted. The above-mentioned circuits were constructed on the main breadboards. There are four breadboards: (1) the 555-timer circuit; (2) the op amp multivibrators; (3) the BJT switches, and (4) the summing amplifier circuit. The output of breadboard (4) is connected to a loudspeaker.

5. Bill of Materials

Table 1: Bill of Materials

Part (#)	**Quantity**	**Description**
Laser diodes	10	Visual laser beams for effect
TI TL072	6	Opamp multivibrator and summing amplifier
2kΩ resistor	1	Feedback resistor for summing amplifier
0.01uF capacitor	20	Timing for multivibrators, DC blocking for audio
35kΩ resistor	10	Reference voltage for multivibrator
30kΩ resistor	10	Reference voltage for multivibrator
16kΩ - 500kΩ resistor	10	Feedback resistor for multivibrator
Vishay TSAL4400	10	IR LED (940nm wavelength)
TSSP-HA	10	Housing for the emitter and receiver
555 IC	1	Timing for the 38kHz pulses
R2: 180kΩ Resistor	1	Can replace the Potentiometer for an accurate 38kHz frequency generation
R1: 18kΩ Resistor	1	Part of the timing module
0.0001uF = 100pF Capacitor	1	Timing capacitor
0.1nF = 100pF Capacitor	1	Stabilization for control voltage of 555 IC
2N3904 Transistor	1	Switches on load when 555 output is active
15Ω-580Ω Resistor	5	Current limiting resistors to emitters
1.5kΩ Resistor	1	Limiting resistor to the base of transistor
Vishay TSSP038	10	IR Receiver (38kHz bursts, 940nm peak wavelength)
100Ω Resistor	10	Current limiting and LPF to voltage source of IR receiver
2N3904	10	Switches audio when IR receiver is low
1N4148 Signal Diode	20	Biasing the BJT
2.2kΩ resistor	10	Biasing the BJT
1kΩ resistor	10	Summing amplifier load

6. Conclusion

Many electronic devices today are designed with microcontrollers, which are usually space-efficient and cost-effective. However, this does not necessarily make discrete components such as BJTs and op amps irrelevant in the discussion of electronics. Although this application could have certainly been developed using a microcontroller, this experiment has proved the ability of discrete components to produce an interesting device. The Laser Harp was constructed using only discrete components and demonstrates relevant electronics topics, such as transistor biasing, signal amplification, and even waveform generation.

The laser harp was able to output ten distinct frequencies simultaneously with very little audio distortion and clean amplification. The design saw many revisions since the device's initial conception. Photoresistors and pulsating LEDs were intended to be used instead of IR emitters and receivers. This method was not favorable, as it was very difficult to fully shield the photoresistor from excess light other than the flashing LED. The IR emitter and receiver combination is much more conducive to play. A 5V voltage regulator was planned for use, but later deemed unnecessary.