Modified Microwave UV-C Sanitizer

Masaya Honda

jp.masaya@gmail.com

Summary

This project is based on the idea of repurposing an old broken Panasonic microwave by converting it into a UV-C sanitizing device to specifically eliminate SARS-CoV-2, the virus that is responsible for the COVID-19 disease. By taking advantage of the safety features that are inherent in a microwave that prevent the user from being exposed to microwave radiation, I was able to create a UV-C sanitizing device that is ultimately safe for the user.

One of the main challenges that I faced was to figure out a way to get the microwave to operate without the high voltage inverter circuit board and the magnetron. After taking measurements and conducting research, I discovered that for a Panasonic microwave to operate correctly, the digital circuit board sends a 220 Hz square waveform to the inverter circuit board, where it would then send back a falling edge triggered 110 Hz square waveform. Consequently, without either of the components, the microwave failed to operate. To fix this issue, I designed a circuit composed of diodes, capacitors, resistors, an inverter, and a D-flip flop that would mimic the function of the inverter circuit board so that the microwave's microcontroller is falsely led to believe that the magnetron and inverter circuit board are both installed and working. With this circuit, the microwave is able to operate without powering the high voltage inverter, which was one of the requirements of making a more efficient and safe UV-C sanitizing device.

Designing this circuit to get the microwave to operate required troubleshooting, which ultimately led to the discovery of two main issues. The combination of the noise that was generated by the turntable motor and possibly the relay switch caused my circuit to falsely trigger the inverter IC leading to a random, non-periodic square waveform. This issue was fixed by adding more decoupling capacitors to the supply pins of the IC's and replacing the normal inverter IC with a schmitt trigger inverter IC. This fix enabled the microwave to operate successfully until the end of the timer with the given condition that the microwave was able to initiate the timer. The second issue was related to the initial condition of the D-flip flop. I discovered that the microwave would only initiate the timer if the output of the D-flip flop was HIGH. To solve this issue, I designed a modification to my circuit and ran simulations on LTspice to confirm that the output of the D-flip flop would remain at HIGH before and after each use. With these two issues fixed, the microwave was able to work successfully.

For the UV-C lights, I installed two 6W UV-C lamps to the ceiling of the microwave's interior. These are connected in parallel with the turntable motor to ensure that the UV-C lamps would turn off in the event the microwave door is opened during operation. I also shielded the interior with aluminium for effectiveness as I learned that it reflects over 90% of light in the 254 nm range. The project deemed itself challenging and rewarding, as I was able to experience and learn through various technical issues while also being able to design a device that is capable of disinfecting items during the pandemic.

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1. Introduction and Objectives

The main objective of this project is to repurpose a microwave that has a broken magnetron to be used as a UV-C sanitizing box. Instead of using the magnetron for heating foods, the microwave will use UV-C lamps to disinfect items. For safety reasons involving high voltages and high frequencies, both the magnetron and the inverter circuit board will need to be removed. The removal of these components poses a challenge, as the microwave has a safety mechanism that checks to see if the key components are working as intended before operation. For example, if the microwave detects that the magnetron is missing, it will not operate. To bypass this mechanism, an external circuit needs to be used to mimic the signal that would have otherwise come from the microwave inverter circuit board. The specific model of microwave used is the NN-SN661S Panasonic microwave. The external circuit used to bypass could technically be used for other Panasonic microwaves, as they most likely use the same safety mechanism across various models. Once the microwave is able to work without the high voltage inverter PCB and the magnetron, two T5 6W rated UV-C lamps will be connected in parallel to the turntable motor located at the bottom of the microwave. This will ensure that the UV-C lamps will turn off if the door is opened during operation. These lamps will be attached to the ceiling of the interior cavity of the microwave.

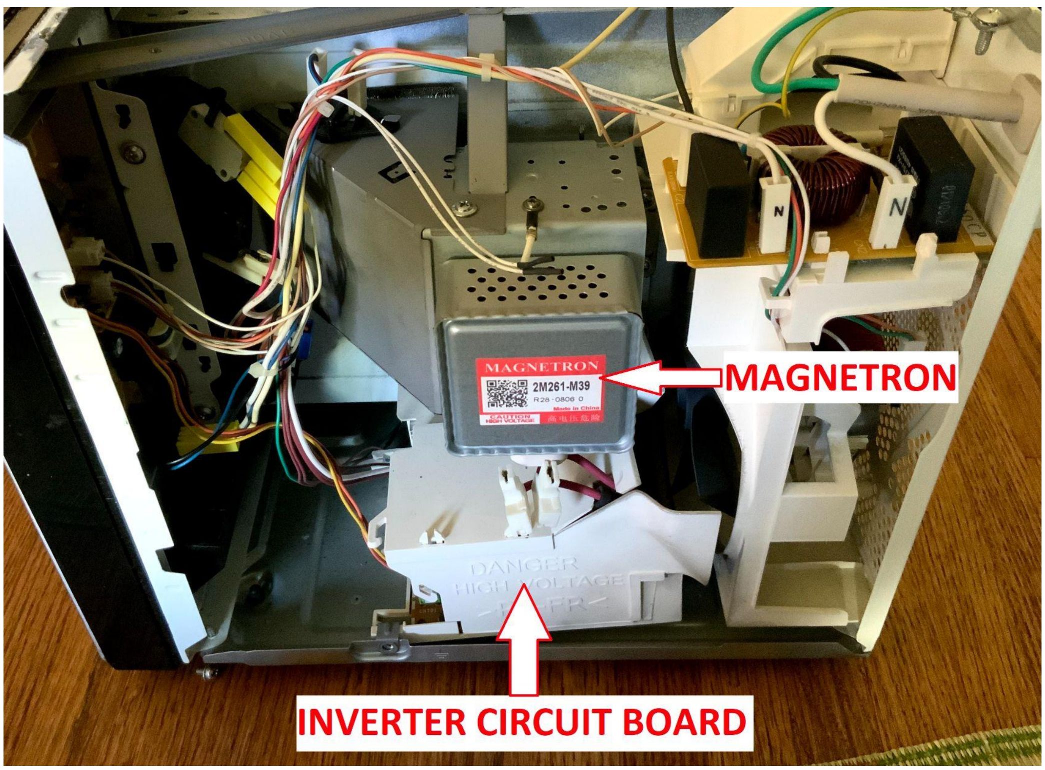

Figure 1: Microwave Default Internals

Using a microwave for a UV-C sanitizing box is safe, as all of the safety features that are implemented in a traditional microwave that prevent the user from being exposed to harmful radiation emitted by the magnetron, such as the magnetron turning off if the door is opened abruptly, apply to the UV-C lamps. This will ensure that the user will not be exposed to UV-C light during use. Furthermore, the built-in motor that spins the microwave plate can be used to help sanitize surfaces from various angles and to improve the UV-C exposure, the use of aluminum foil or tape can be used to cover the interior cavity of the microwave. This will help to scatter the UV-C inside the cavity, as aluminum deflects approximately 92% of the light in the 254 nm range. This modified microwave UV-C sanitizer will allow users to sanitize frequently used items such as their mask without the dangers of being accidentally exposed to harmful UV-C rays.

2. Bypassing the Safety Mechanism

The microwave has a digital circuit board that is separated from the previously removed high voltage inverter circuit board. These two boards communicate with one another through a 3-pin JST connector. The microwave's microcontroller sends a PWM signal to the inverter board through the PWM pin and waits for a return signal at the OSC pin. Using the pins on this 3-pin connector, we can analyze what signals are being sent by the microcontroller to the inverter circuit along with its return signal. Unfortunately, a return signal was not measurable, since the microwave's magnetron was not working. As a result, I was only able to measure the 220 Hz waveform generated by the microcontroller, which is shown in Figure 4.

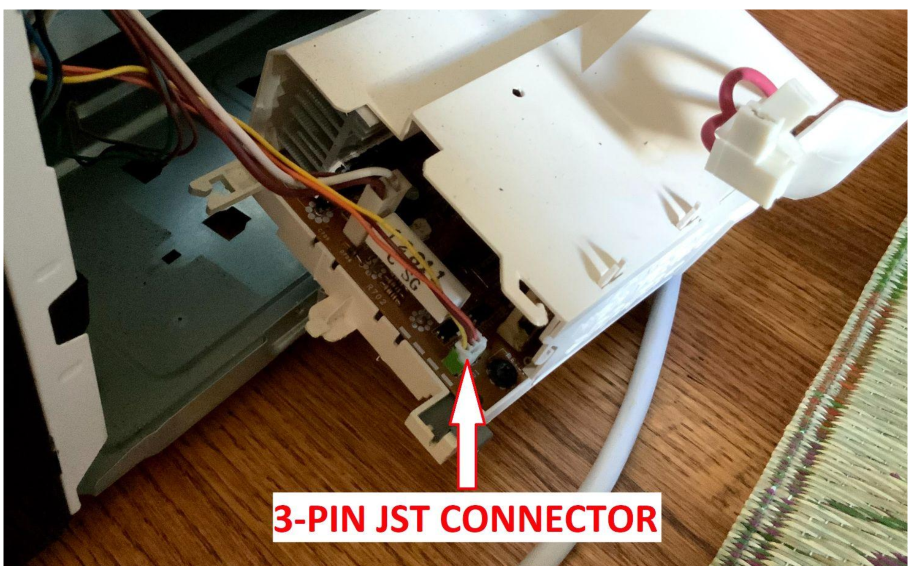

Figure 2: 3-Pin JST connector plugged into Inverter PCB

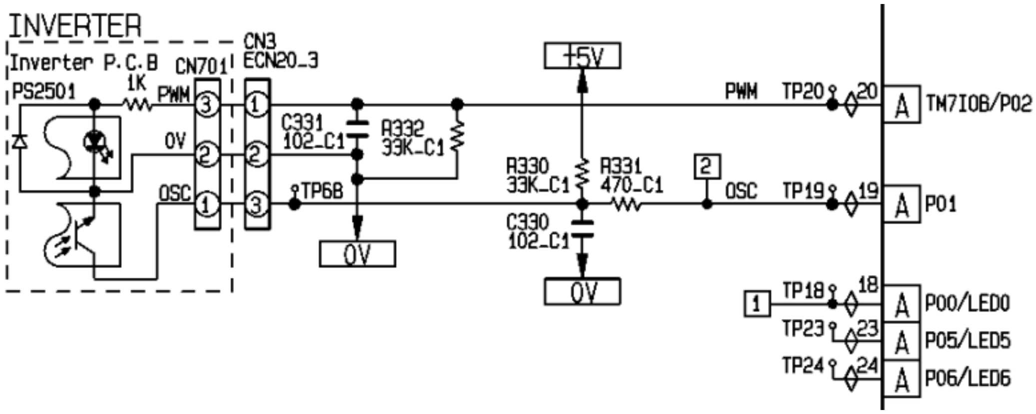

Figure 3: Schematic with the 3-Pin connector

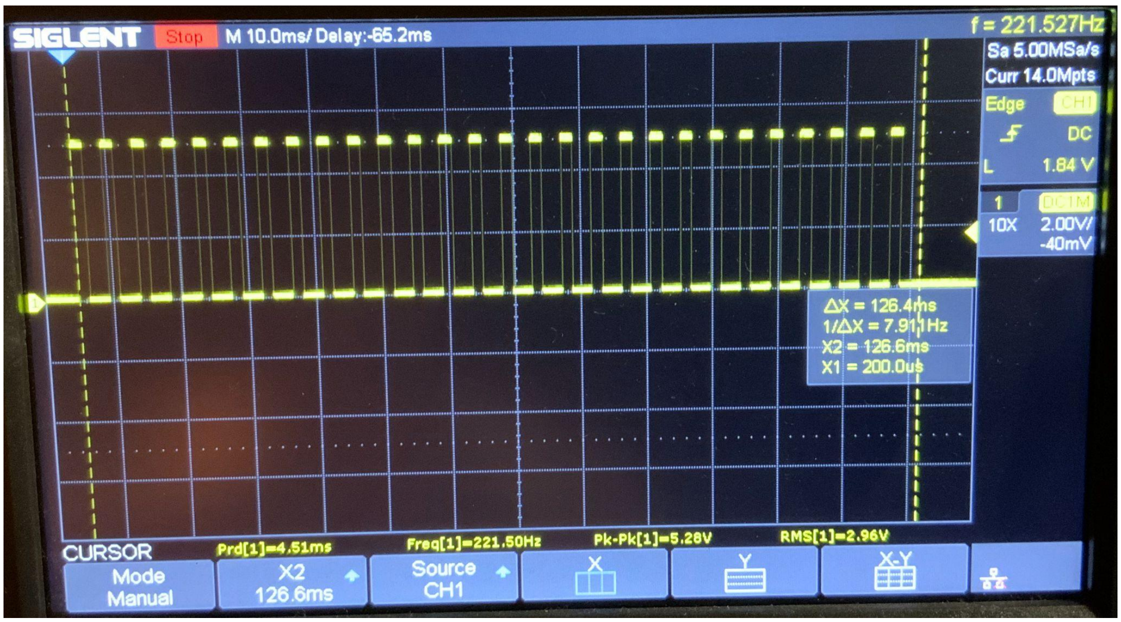

Figure 4: Incoming PWM sent by Microwave's MCU

Figure 5: PWM and OSC signal (Credit to TomTechTod Youtube Channel)

I found a YouTube video that showed both the incoming and returning waveforms of a Panasonic microwave that matched my own measurement of the 220 Hz waveform. If this video didn't exist, I would have taken oscilloscope measurements from the Panasonic microwave that replaced the unused broken microwave.

As shown above in Figure 5, the expected 220 Hz square waveform is generated by the microwave's microcontroller. The return signal is a 110 Hz square waveform with a duty cycle of about 50% and an amplitude of 5V. Now that the characteristics of the return signal are known, it is possible to test whether the microwave is able to start with a 110 Hz square waveform return signal. The easiest way to test this is to use an Arduino to replicate this particular return signal.

3. Return Signal Arduino Prototype

I programmed an Arduino to output a clock divided by 2 by making sure the state of the output changes only at the falling edge of the input clock. The code is shown below.

```
// Masaya Honda: Falling Edge Triggered Clock Divided by 2
const byte int_pin = 2;
const byte OUTPUT_PIN = 12;
volatile byte state = HIGH;

void setup() {
  pinMode(OUTPUT_PIN, OUTPUT);
}

void loop() {
  attachInterrupt(digitalPinToInterrupt(int_pin),pulse_gen,FALLING);

void pulse_gen() {
    digitalWrite(OUTPUT_PIN, state);
    state = !state;
}
```

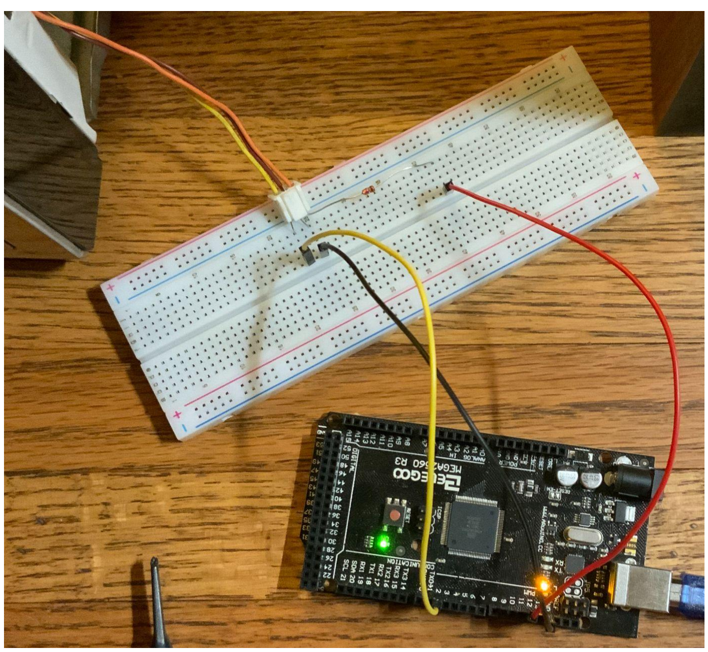

Figure 6: Arduino Prototype Setup

The 3-pin connector consists of yellow, brown, and an orange wire. The yellow is the PWM, brown is 0V, and the orange is OSC as shown below in the schematic given in the microwave's service manual. The yellow wire connected to the arduino reads the 220 Hz waveform sent by the microwave through the yellow wire on the 3-pin connector. The arduino outputs a falling edge triggered clock divided by 2 waveform to the orange wire through a diode in series. As shown in Figure 6 above, the diode is connected in series as a quick way to ensure that the microwave's microcontroller sees an open-drain pin from the arduino instead of a push-pull pin. This was done to prevent possible damage by using the microwave's internal circuit to pull the pin up since the phototransistor in the optocoupler is only able to pull down as shown below in the schematic. Consequently, the forward voltage drop of the diode will cause the output to be a voltage V_F above 0V. Since it is less than around the approximate $V_{DD}/2$ threshold voltage, it is safe to be used for this application.

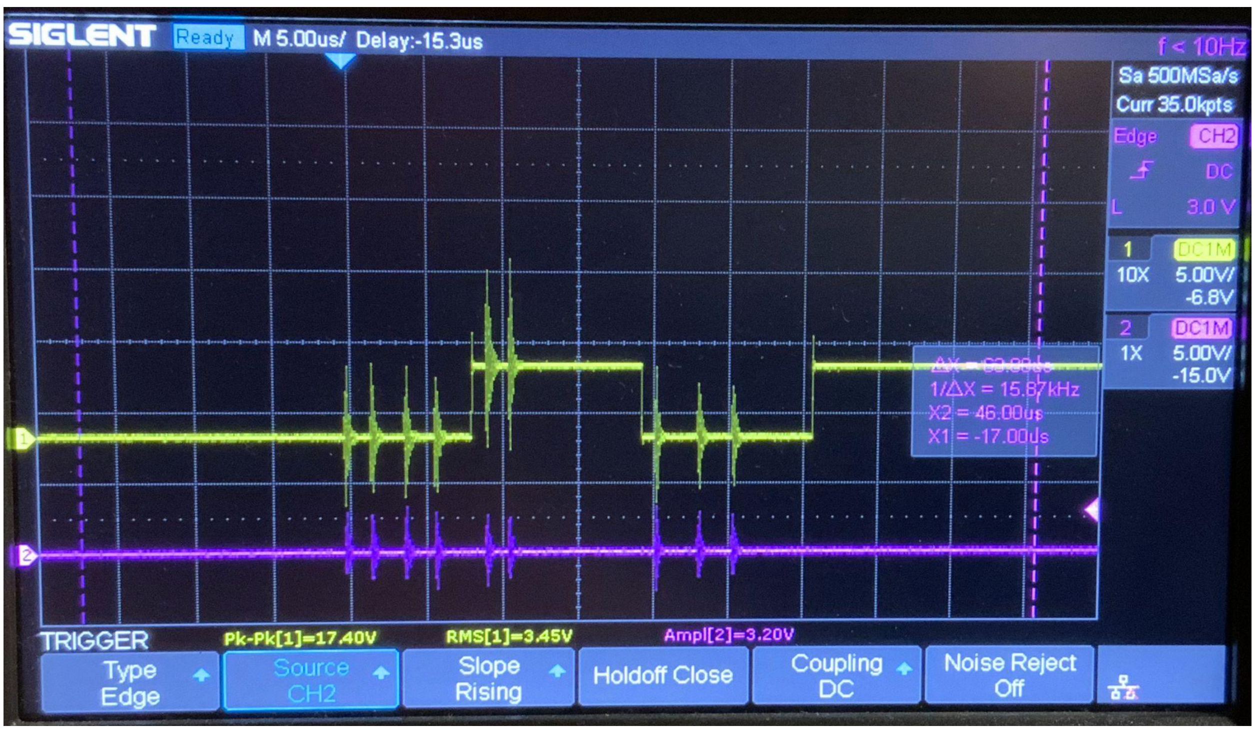

Figure 7: False triggering from noise resulting in the microwave failing

4. Transitioning from Prototype to Circuit

The circuit consists of a schmitt trigger inverter and a conventional D-Flip Flop. As shown below in Figure 8, this outputs a falling edge triggered clock divided by 2, the same as the Arduino prototype.

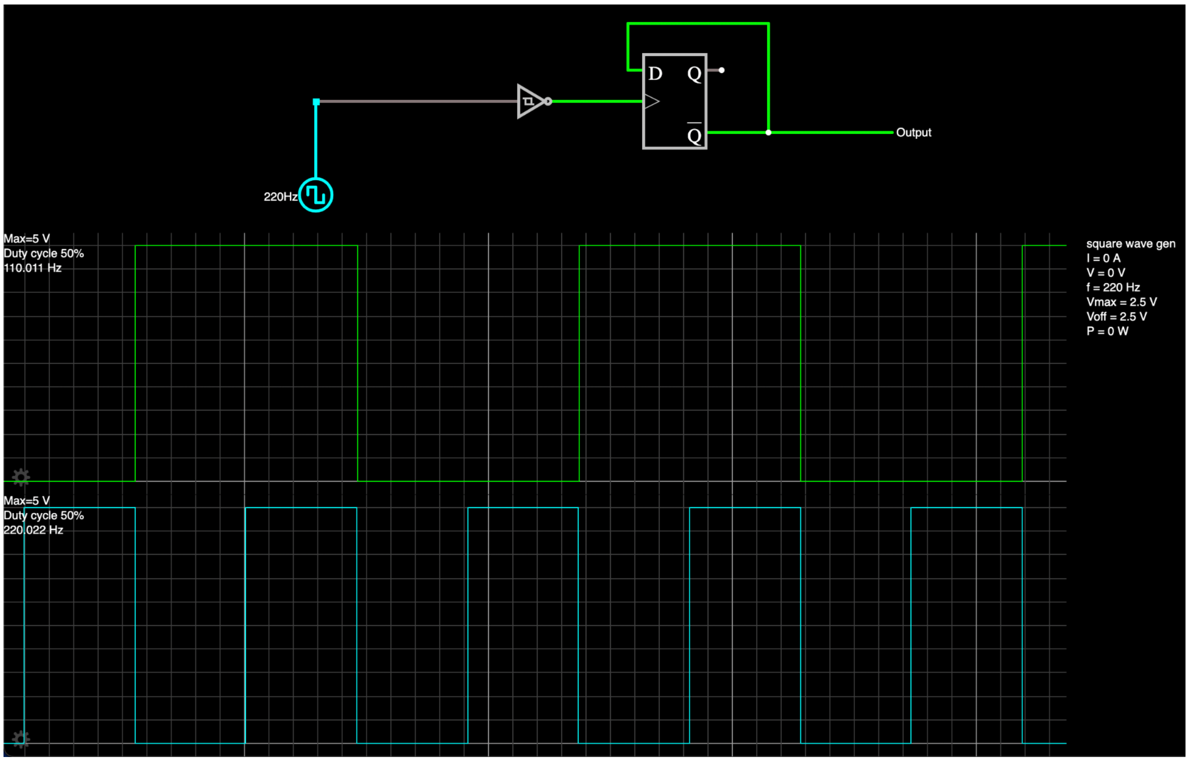

Figure 8: Proof of Concept using CircuitJS1

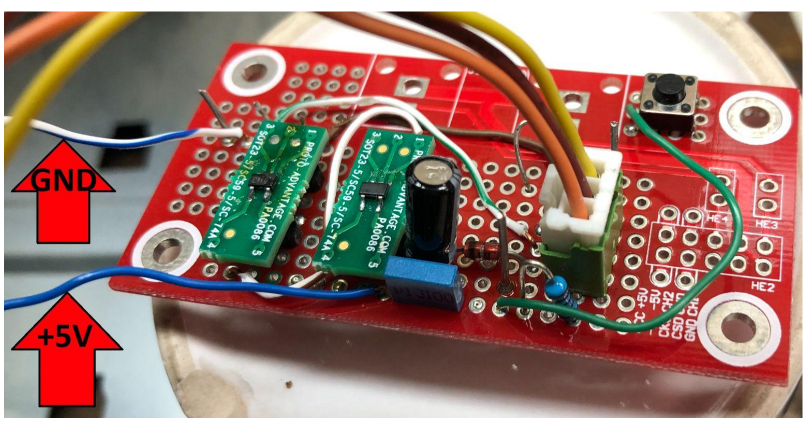

Figure 9: First Version of the Circuit

Shown in Figure 9 is my first attempt consisting of an SN74LVC1G80BV for the D-Flip Flop and a SN74LVC1G04 for the inverter (non-schmitt trigger). I added decoupling capacitors to the supply pin of the D-Flip Flop and the inverter, and a 100Ω resistor in series with the pin (orange wire in the JST 3-pin connector) that sends the 110 Hz square wave back to the microwave. These were added as a way to minimize the noise that was seen earlier in the arduino prototype. The GND and +5V wires that are coming out of the circuit board are soldered directly to the exposed wires on the digital circuit board labeled 0V and +5V respectively as shown below in Figure 10.

Figure 10: 0V and +5V Connection on Digital Circuit Board

5. Noise and D-Flip Flop Initial Condition Issue

The use of a non-schmitt trigger inverter resulted in the noise that was coming from the motor or relay to falsely trigger, resulting in an incorrect waveform at the output of the circuit. Instead of seeing a clean 110 Hz square waveform at the output, it was showing a nonperiodic square waveform with random counts of HIGHs and LOWs. Initially, I tried connecting a capacitor across the terminals of the turntable motor and also twisted the motor wires to reduce noise, but the noise was still problematic. After switching the inverter for a schmitt trigger inverter, the problem was resolved and allowed the microwave to execute successfully for as long as the timer ran.

The last issue remaining was that the microwave either starts and executes successfully, or it abruptly fails to start in the beginning. After analyzing the oscilloscope readings, it was determined that the state of the output feeding back to the microwave directly affected whether the microwave would start or fail. When the output of the designed circuit is LOW before pressing start, the microwave fails every time. Conversely, when the state was HIGH, the microwave was able to start without any issues. Without setting the initial condition for the output pin, the output would sometimes start at LOW and other times at HIGH. This meant that a modification needed to be made to the current circuit that would define the state of the output to HIGH, before and after running the microwave.

6. First Version of the Initial Condition Circuit

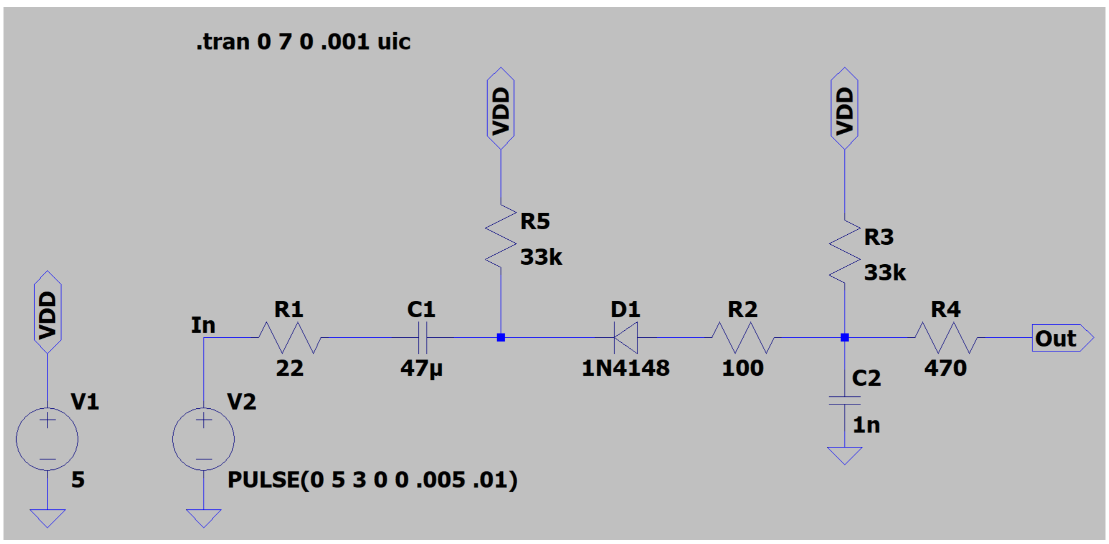

Figure 11: LTspice Schematic of First Version of the Initial Condition Circuit

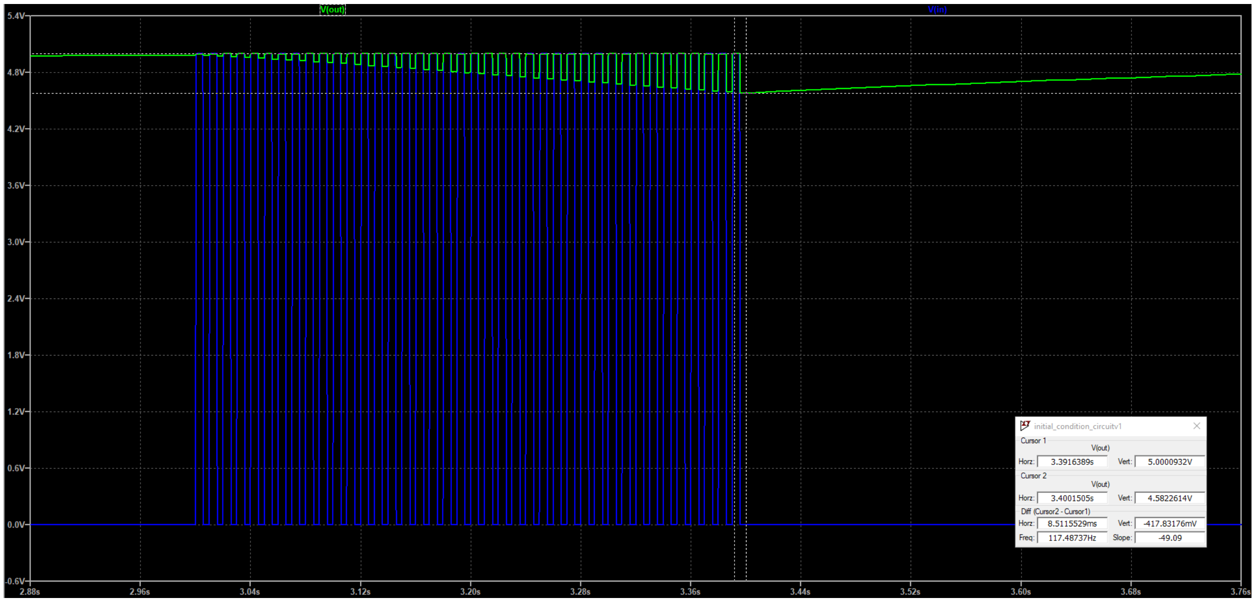

Figure 12: LTspice Simulation Result (Green = Output and Blue = Input)

The square waveform source at "In" is the equivalent output signal of Q Bar from the D-Flip Flop. R1 is its approximate impedance looking into the Q Bar pin. This version has an issue of the output waveform not swinging low enough due to the effect of R5, R2, and R3. As shown below, the output waveform lower swing tapers off at around 3.5V, which is not enough to meet the threshold.

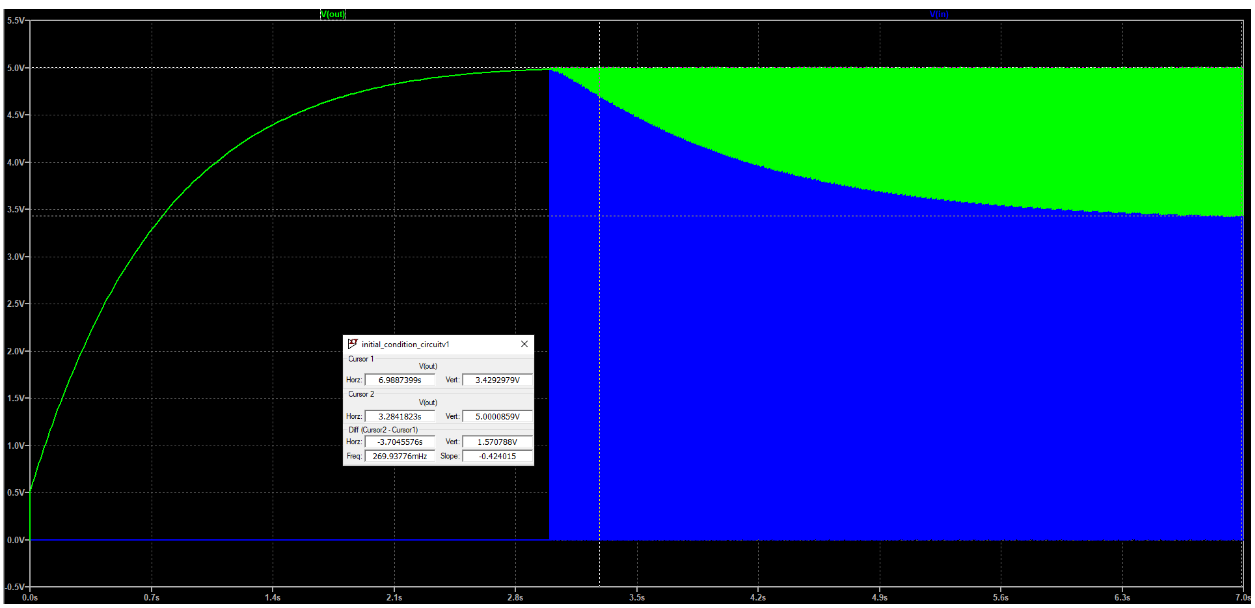

Figure 13: LTspice Simulation Result (Green = Output and Blue = Input)

7. Final Version of the Initial Condition Circuit

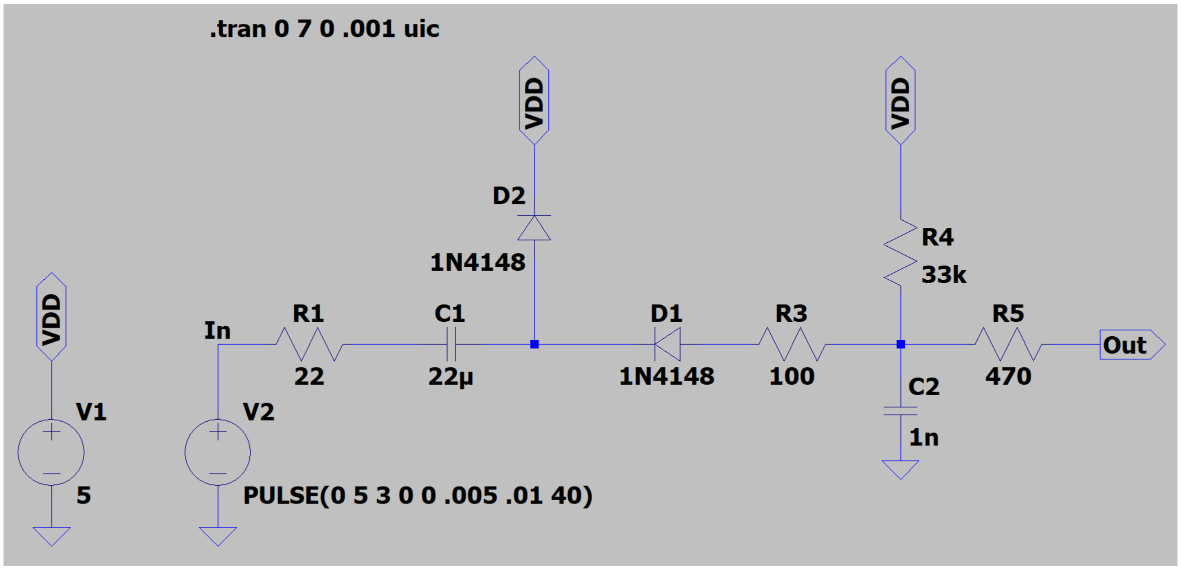

Figure 14: LTspice Schematic of Final Version of the Initial Condition Circuit

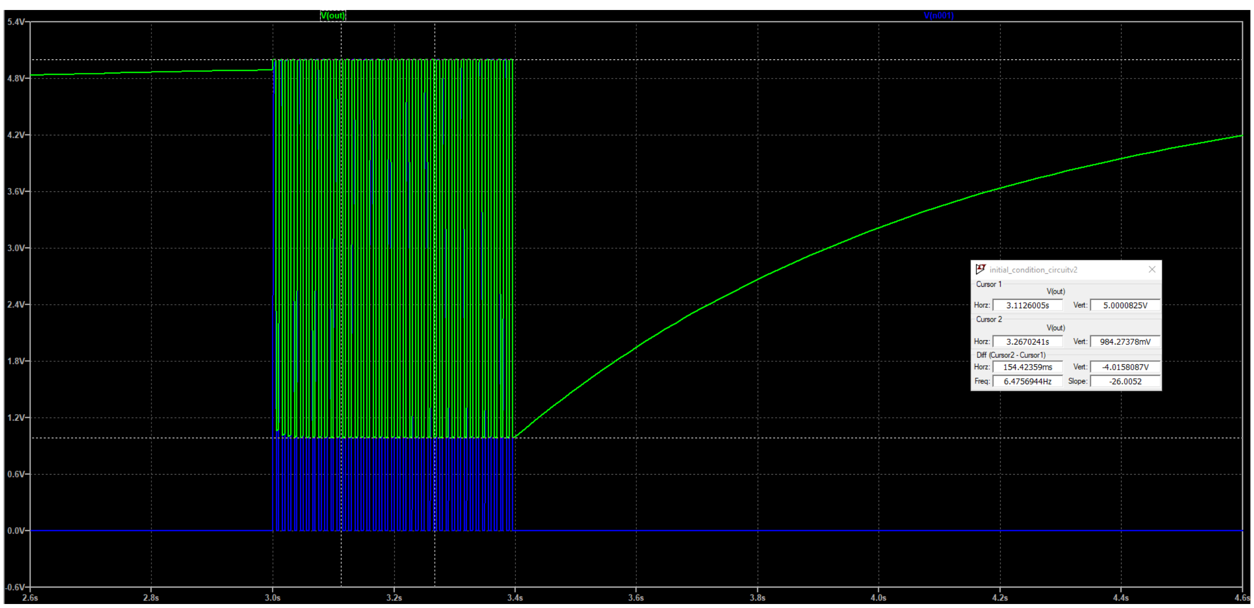

Figure 15: LTspice Simulation Result (Green = Output and Blue = Input)

R5 was removed entirely and was replaced by a switching diode (non-switching diode should work fine here since we are only dealing with low frequency signals ~100 Hz). C1 is a polarized capacitor with the positive pin sharing the node with the anode of D2. C1 is charged when D1 conducts and is discharged when D2 conducts. The clamping circuit that is formed with

C1 and D2 clamps the peak of the waveform to 5V. With this modification, the waveform swings down to roughly 1V, which is enough for this application.

Furthermore, the simulation result in Figure 15 shows that the output (green) starts at HIGH and returns to the HIGH state after the input signal (blue) ends. This ensures that the HIGH state is maintained before and after operation, which allows the microwave to start correctly every time. Before and after the pulse, C1 is open and the output is pulled to V_{DD}. During the pulse, V2 either starts at V_{DD} or 0, which creates two scenarios for what happens to C1. If V2 starts at 0V, then C1 is charged through D1 and when V2 changes to V_{DD}, D2 conducts and C1 is discharged to around V_F (where V_F is the forward bias voltage of the diode). On the other hand, when V2 starts at V_{DD}, C1 is not charged since both sides of C1 are V_{DD}. When V2 changes to 0V, then C1 is charged through D1 when it conducts and C1 is discharged through D2 to around V_F.

8. Completed Circuit with an added Initial Condition Circuit

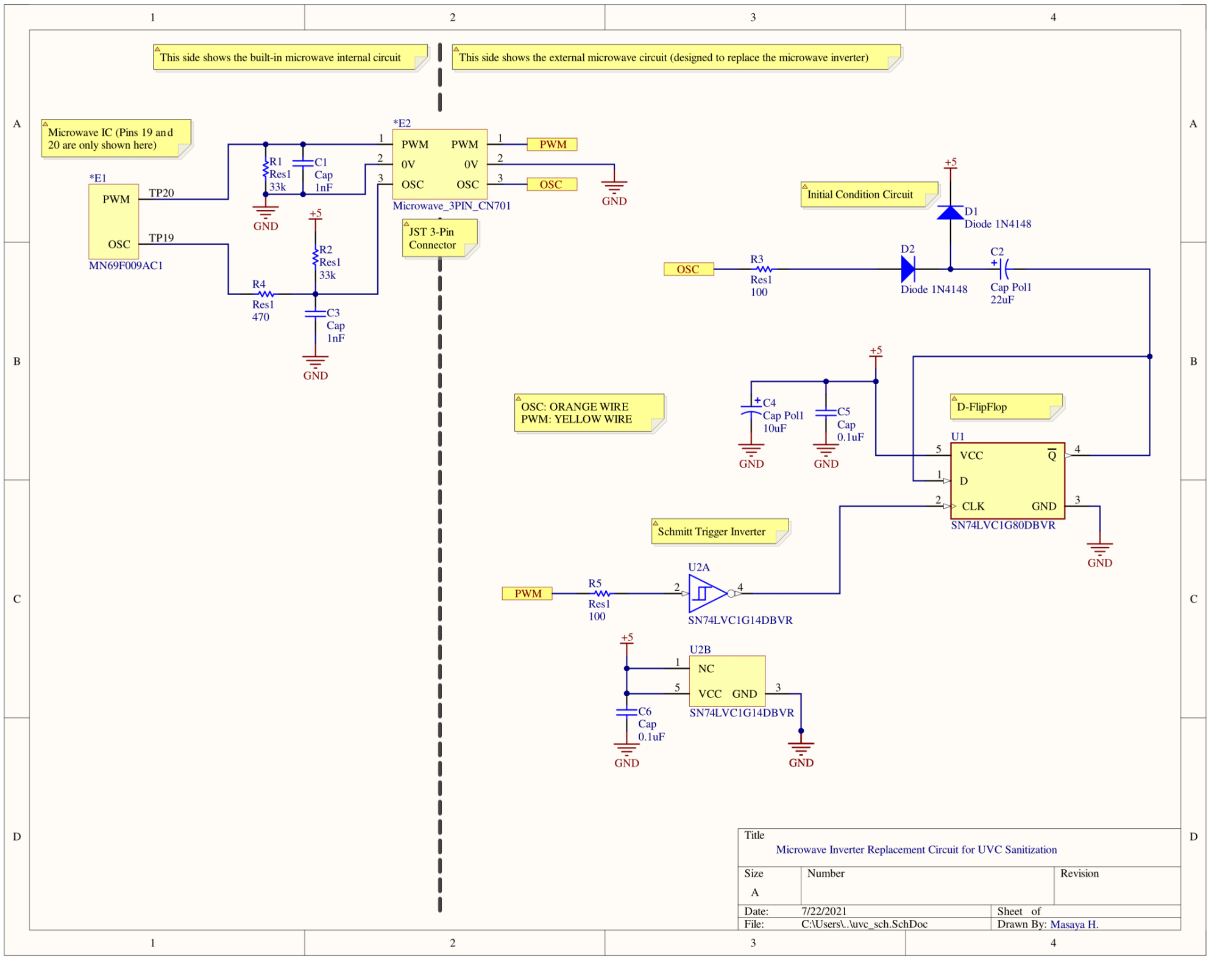

Figure 16: Schematic created in Altium Designer

The finalized circuit used to bypass the safety mechanism is shown to the right of the dashed line. The circuit to the left side of the dashed line is the internal circuit that is in the microwave's digital circuit board. These are connected together by a JST 3-pin connector as shown above.

9. Analysis of the Fixed Initial Condition Issue

The following analysis is done on the final circuit shown in the previous page. As a reference, probing the PWM pin will show the incoming 220 Hz waveform and the OSC pin will show the 110 Hz waveform.

Figure 17: Input Pin (PWM) in Magenta and Output Pin (OSC) in Cyan

Figure 17 shows that the circuit outputs a waveform at half the frequency of the input. The output also shows that each rising edge of the output waveform occurs at the falling edge of the input waveform.

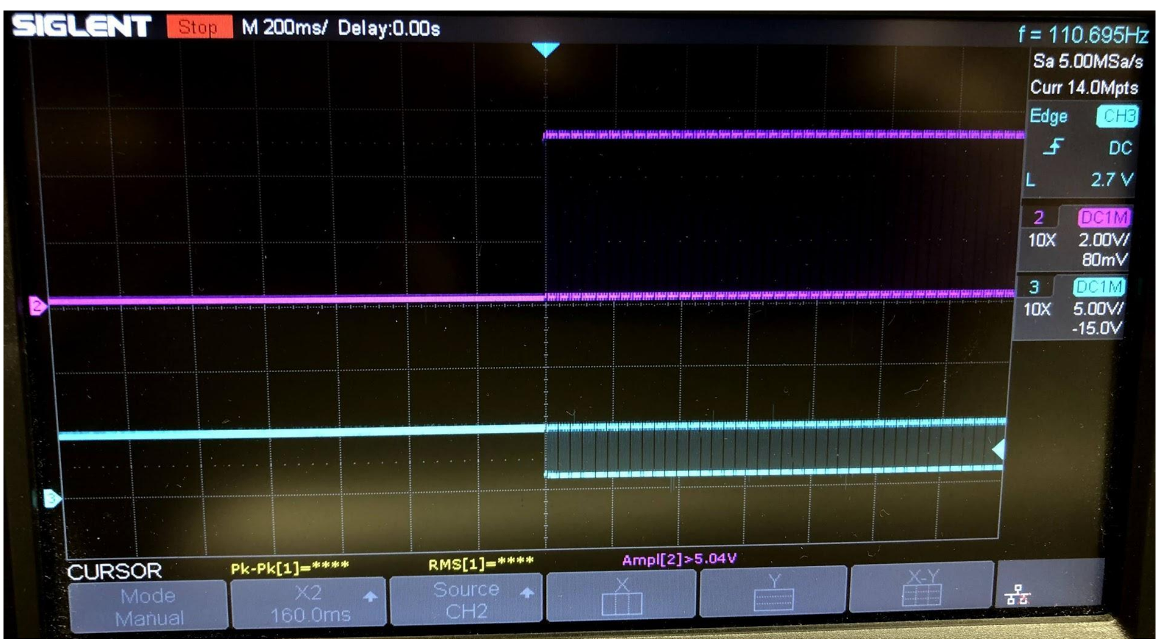

Figure 18: Output Pin of D-Flip Flop in Magenta and Output Pin (OSC) in Cyan

Figure 18 shows that even if Q Bar is LOW, the output pin will always be HIGH. Having the output pin at HIGH is a necessary condition for the microwave to start successfully.

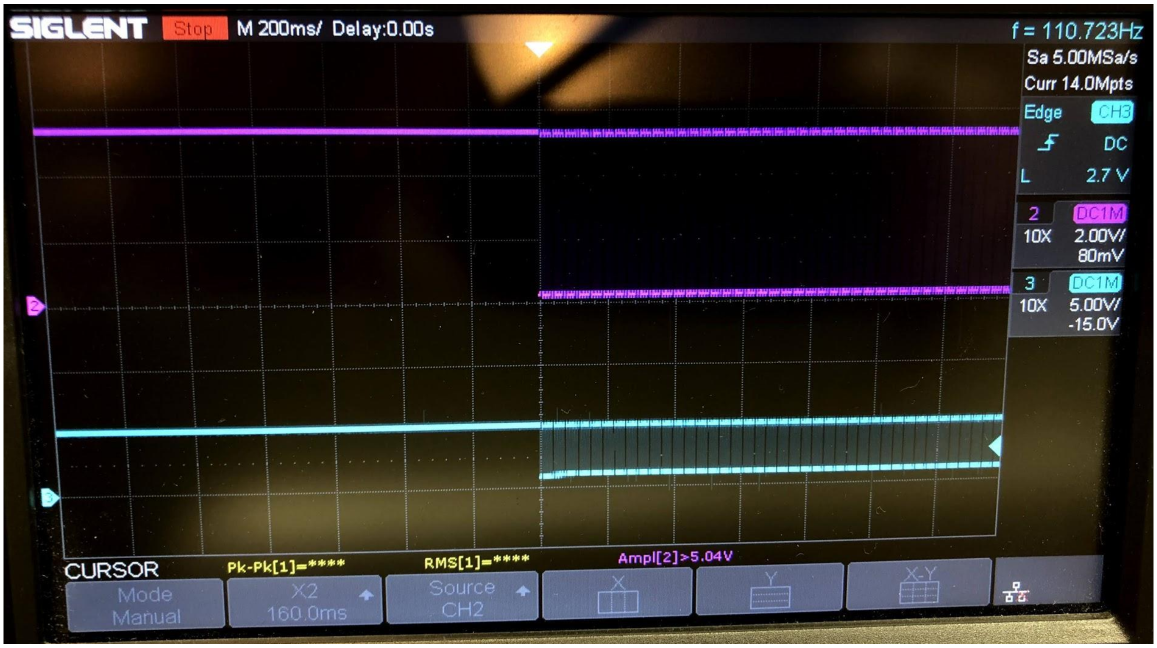

Figure 19: Output Pin of D-Flip Flop in Magenta and Output Pin (OSC) in Cyan

In Figure 19, we can see that the Q bar pin and the OSC pin are both at HIGH. Before using the circuit that solved the initial condition issue of the D-Flip Flop, the microwave would work in an indeterministic way such that it would work fine at certain times and other times the microwave would fail to start entirely. This was actually due to the state of the output pin being either HIGH or LOW (indeterministic state). When the output pin was HIGH before pressing start on the microwave, it would work as intended. However, when the pin was LOW, the microwave would fail to start. This was a significant discovery which led to the design of the circuit that ensured the output pin remained at HIGH before and after each operation.

10. Final Assembly with UV-C Lamp Installment

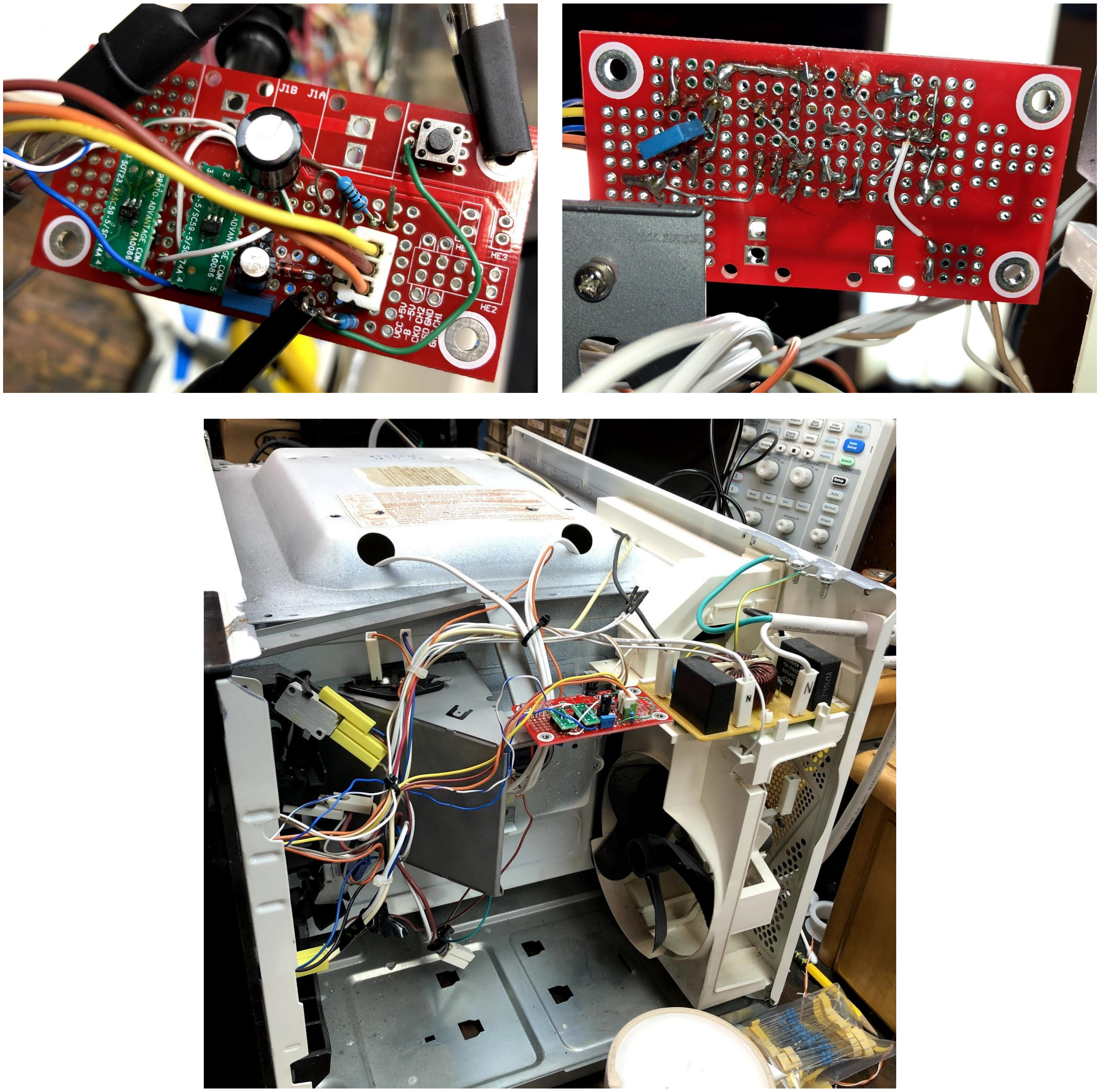

Figure 20: Completion of circuit and assembly

To attach the UV-C lamps, eight holes were drilled into the cavity to allow for the lamps to be secured to the ceiling with zip ties. An additional two holes were drilled for the power cables to be connected to the lamps as shown above. Then, aluminium tape was used to cover the interior surfaces to improve the UV-C reflectivity. This is shown in Figure 21 and 22.

Figure 21: UV-C Lamps and Aluminium Tape Interior

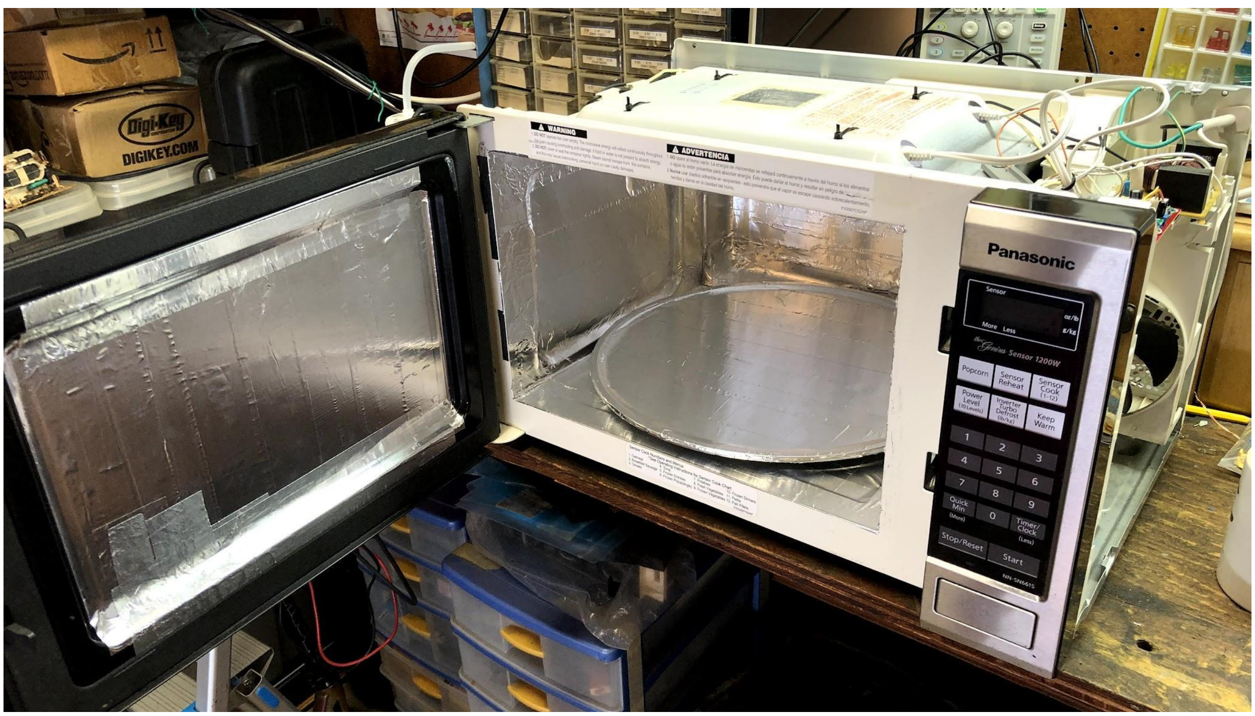

Figure 22: Aluminium Interior used to Reflect UV-C.

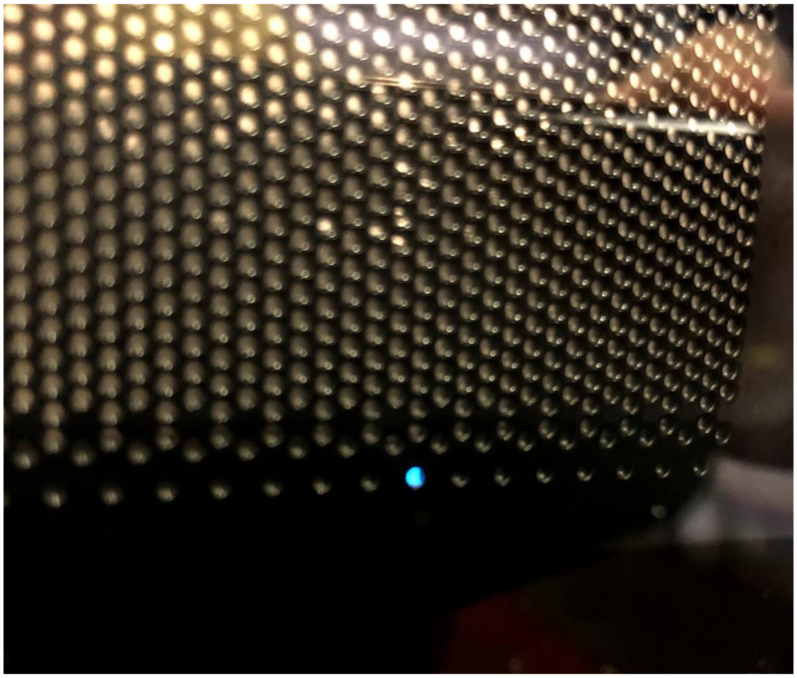

Figure 23: UV-C Indicator on the Microwave Window

Since it is necessary for the user to know whether the UV-C lamps are working as intended, I left a small area uncovered by the aluminium tape as shown in Figure 23.

11. UV-C Information and Calculation

According to this research paper, the target UV-C dose to eliminate COVID-19 is 16.9 mJ/cm^2. Since the UV-C lamps that I used are rated at 0.257 mW/cm^2 at a distance of 25.4 cm in an open environment, the required exposure in seconds can be calculated by dividing 16.9 mJ/cm^2 by 0.257 mW/cm^2. This equates to an exposure time of about 66 seconds. Since the worst-case distance in the microwave is calculated to be approximately 19 cm and the UV-C lamps are installed in a confined space with aluminium surfaces, it is viable to run the microwave for 1 minute to disinfect items. It is also recommended to use a small aluminium grill stand that would allow for items to be held above the bottom surface, to ensure that more surfaces are exposed to UV-C.

12. Conclusion

This UV-C microwave sanitizer is implemented in a way that allows the user to avoid UV-C exposure while disinfecting items. This particular method of modification is specifically for Panasonic microwaves meaning that with the designed circuit, it is possible to convert other similar Panasonic microwaves into a UV-C sanitizing device. The issues that I faced with noise and the D-flipflop's initial condition were both great learning experiences. The design process of turning an old broken microwave into a useful sanitizing device that can be used during the pandemic was challenging, fun, and rewarding.

13. Component List

Component	**Part Number or Manufacturer**	**Quantity**
Schmitt Trigger Inverter (SOT23-5 Package)	SN74LVC1G14DBV	1
D-Flip Flop (SOT23-5 Package)	SN74LVC1G80BV	1
SOT23-5 to DIP-6 Adapter	PA0086	2
Switching-Diode	1N4148	2
0.1 pF Ceramic	N/A	2
22 µF Electrolytic	N/A	1
100 Ω Resistor	N/A	2
6W UV-C Lamp	Coospider	2