

# **The Plasma Speaker:**

## **Construction and Characterization of Both Full- bridge and Single-ended Driving Circuits**

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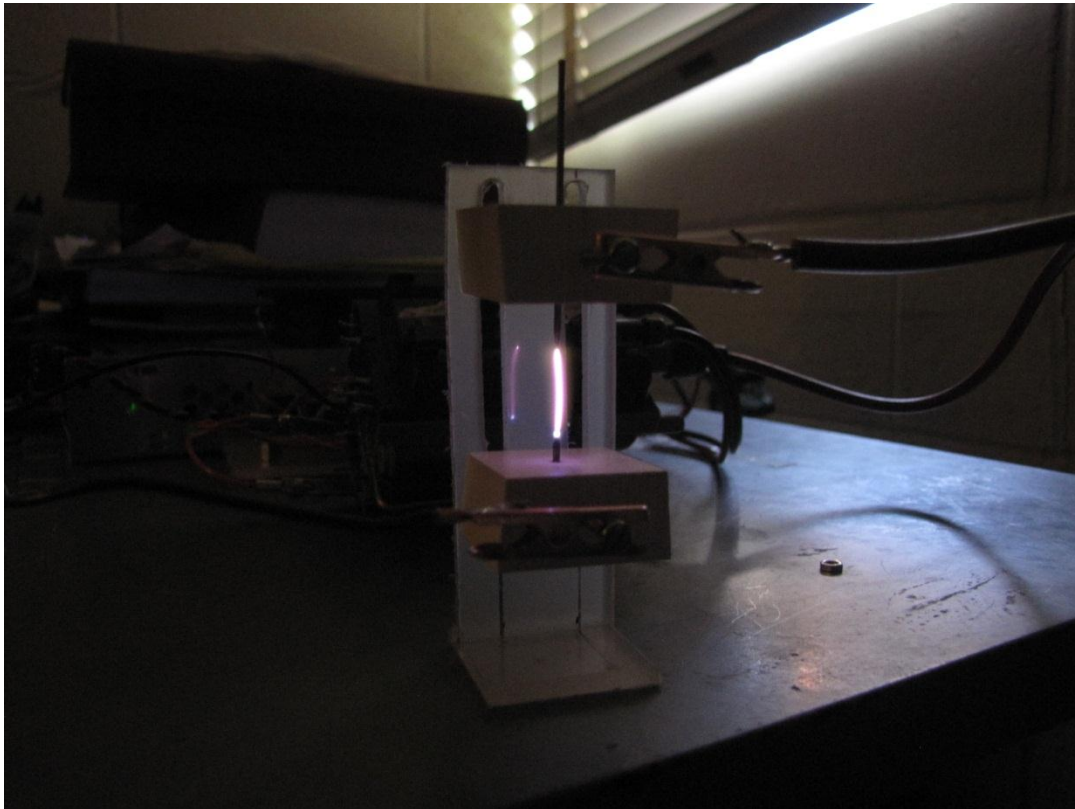
PHYS 406

Class Project – Final Report

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## **Introduction**

A plasma speaker uses a high-voltage-pulse generator to produce a rapidly occurring series of plasma arcs, through which an audio signal can be transduced from an electrical signal into an overpressure wave, capable of being heard by a human. A picture of our working plasma speaker is shown below.



This particular speaker produces arcs triggered at approximately 50 kHz. The energy deposited into the air with each pulse is controlled, such that the series of arcs can amplitude can be modulated with an audio signal to produce sound.

## **Theory of Operation**

A plasma speaker uses one of a variety of methods to produce a series of high-voltage pulses between two electrodes, ionizing the air between them with each pulse. This serves as a mechanism to deposit energy into a thin, cylindrical region of air between the electrodes on a

time-scale that is much faster than the pulse-to-pulse delay. Since the internal energy of a diatomic gas (air, consisting of mostly N<sub>2</sub> and O<sub>2</sub>) is linear in temperature, we can write,

$$\Delta T = \frac{2}{3R} \Delta U, \quad (1)$$

where  $\Delta T$  and  $\Delta U$  are the changes in temperature and internal energy of a diatomic gas, respectively, and  $R$  is the ideal gas constant. Thus, if one the amount of energy deposited into the air is known, so too is it's change in temperature.

Also occurring on a time-scale much faster than the pulse-to-pulse delay of the high-voltage pulses, is the cooling of the air back down to room temperature. As a result of this, the temperature of the air as a function of time is a series of impulses, each occurring when a high-voltage pulse arrives at the electrodes.

Since the air is heated rapidly and does not have time to expand, it is effectively at a constant volume for the duration of the heating, allowing the use of the well-known ideal gas law to equate a change in temperature to a change in pressure for this thin, cylindrical region of air, which yields,

$$\Delta P = \frac{nR}{V} \Delta T. \quad (2)$$

Combining Equations (1) and (2) gives a relationship between the pulse energy and the change in pressure.

$$\Delta P = \frac{2n}{3V} \Delta U. \quad (3)$$

Thus, if high-voltage pulses arrive with constant pulse-to-pulse timing (of period,  $T$ , and corresponding frequency,  $1/T = f_0$ ), the change in internal energy has the form of an infinite impulse train in time, which is described by,

$$\Delta U(t) = \sum_{n=-\infty}^{\infty} [\delta(t - nT)], \quad (4)$$

where the impulses have been modeled as simple delta functions. The Fourier transform of an infinite impulse train of frequency,  $f_0$ , is itself an infinite impulse train, whose peaks are spaced at intervals of  $f_0$  in the frequency domain. This is mathematically described by,

$$\Delta U(\omega) = \sum_{n=-\infty}^{\infty} [\delta(\omega - 2\pi n f_0)], \quad (5)$$

and shown below, in Figure 1.

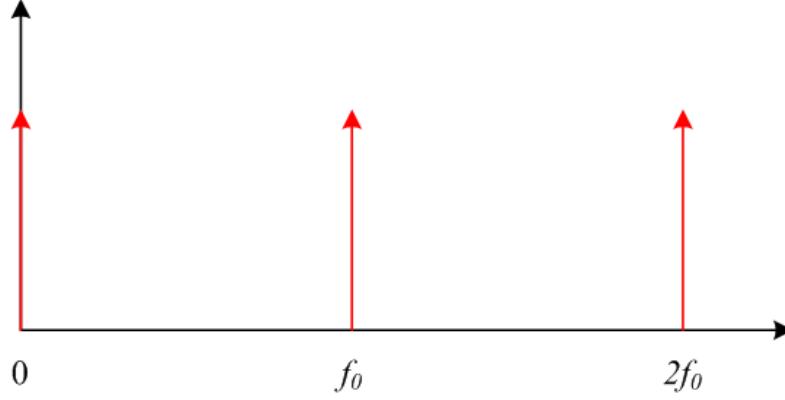


Figure 1: The first three modes of an infinite impulse train, having a pulse repetition frequency,  $f_0$ .

If we then modulate the pulse energies with a sinusoid having a frequency,  $f_1$ , which is less than  $f_0$ , we have,

$$\begin{aligned}
 G(\omega) &\equiv \mathcal{F}\{(1 + \beta\cos(\omega t))f(t)\} \\
 &= \Delta U(\omega) + \Delta U(F(\omega + 2\pi f_1) + \Delta U(\omega - 2\pi f_1)), \quad (6)
 \end{aligned}$$

which can be explicitly written as,

$$G(\omega) = \sum_{n=-\infty}^{\infty} \left[ \delta(\omega - 2\pi n f_0) + \beta \left( \delta(\omega - 2\pi(n f_0 + f_1)) + \delta(\omega - 2\pi(n f_0 - f_1)) \right) \right]. \quad (7)$$

This is shown in Figure 2, below.

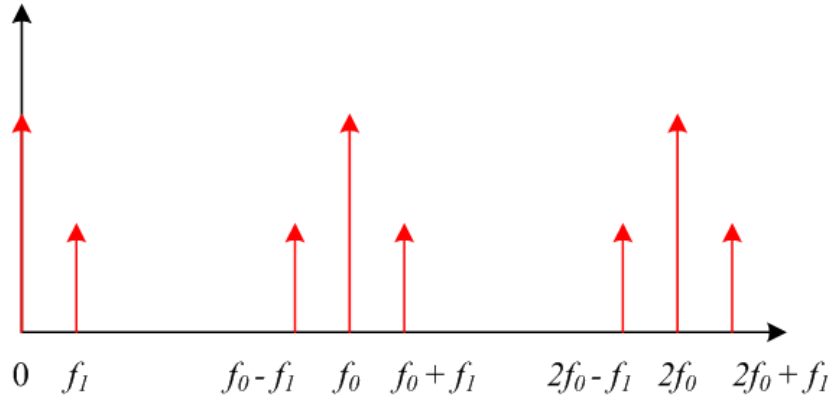


Figure 2: Sidebands occurring as the result of modulating an impulse train, having a pulse repetition frequency  $f_0$ , with a sinusoid of frequency  $f_1$ .

Thus, for carrier frequencies ( $f_0$ )  $\geq$  40 kHz (twice the upper bound of human hearing), the sidebands of the DC peak, located at  $\pm f_1$ , are the only peaks to fall within the range of frequencies able to be heard by humans. Thus, we have that for a given modulation frequency,  $f_1$ , the plasma arc outputs that same frequency (plus others outside the range of human hearing)

as an overpressure wave, as  $\Delta P \propto \Delta U$  (see Eq. (3)). This is depicted in Figure 3, for a 50 kHz carrier frequency.

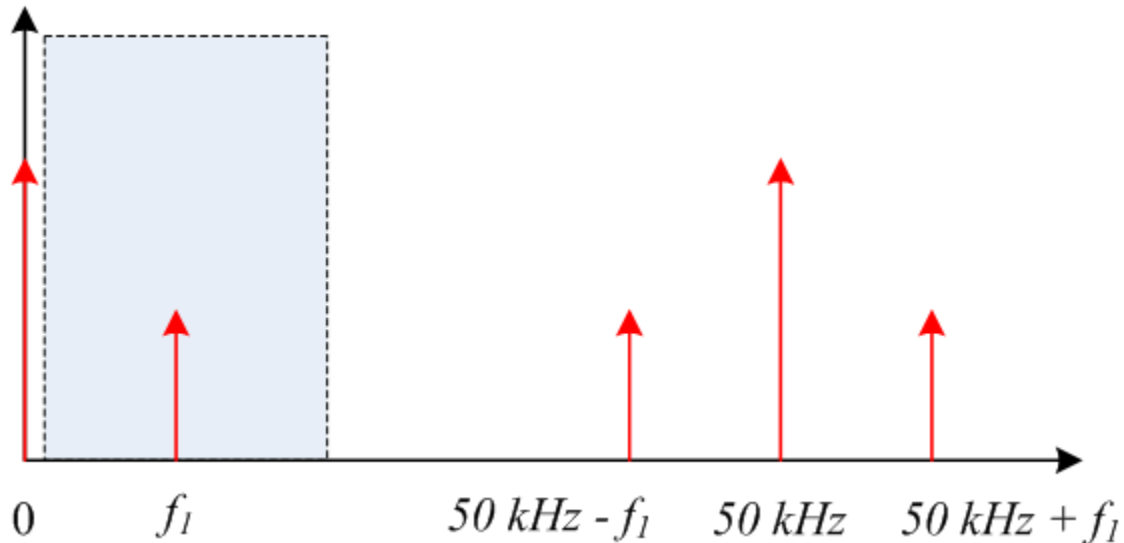


Figure 3: Sidebands occurring as the result of modulating an impulse train, having a pulse repetition frequency of 50 kHz, with a sinusoid of frequency  $f_1 < 50\text{kHz}$ . The shaded area roughly denotes the region, throughout which humans can hear (exaggerated to simply illustrate that we cannot hear the DC peak).

## **Circuit Designs**

Two different types of circuits were used to drive a flyback transformer and accomplish the modulated arc that makes up the plasma speaker. One circuit employs a push-pull method that involves a full-bridge circuit while the other is a single-ended driver. The differences between these methods will be discussed later in more detail, though it is important to note that the signal-processing center of the two circuits is common to both. Both circuits use a TL494 pulse-width-modulator (PWM) to mix the audio signal with the internally generated driving signal, as well as the TC4429/4420 MOSFET drivers.

### **Pulse Width Modulator: TL494**

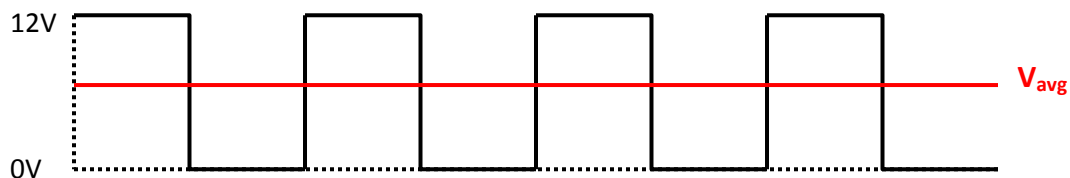
This chip is most important part of the circuit. It is what turns the audio signal into something that can be fed into the primary winding of the flyback transformer, creating sound. It does this through two of its features; it sets the oscillation frequency of the signal that will be used to drive the flyback transformer and then modulates the pulse width of the individual pulses that make up that signal to gradually vary the energy stored in the flyback transformer with each pulse.

The frequency that is output by the TL494 is controlled by pins 5 and 6, labeled  $C_T$  and  $R_T$  respectively.  $C_T$  is the total capacitance, in Farads, input into pin 5 and  $R_T$  is the total resistance, in Ohms, input into pin 6. The output frequency,  $F_{osc}$ , can be calculated with the following equation:

$$F_{osc} = \frac{1}{2\pi R_T C_T}$$

The output frequency can then be controlled by using a potentiometer as  $R_T$ . The idea here is to set  $F_{osc}$  well above the audible range for humans (20 Hz to 20 KHz) so that all that is heard from the arc is the audio signal, created by the pulse width modulation of this signal.

For the sake of explanation, let's assume the output wave looks like a pure square wave that varies between 0V and 12V (in reality, there are transient phenomena that distort the edges of the square wave, but we'll ignore that here):



The duty cycle of the wave is the amount of time the wave is on, at 12V, versus the amount of time it is off, at 0V. In the wave above the duty cycle is 50%.

For a given voltage and frequency, as the duty cycle is increased, the flyback transformer spends more time building up energy to release into each arc. The audio input is connected to the TL494 to slightly vary the duty cycle, such that—over the course of many arcs—the energy released with each arc is gradually changing. It is in this way that the audio signal is modulated into the arc.

Also connected to the duty cycle pin is a potentiometer, which is used to set the neutral pulse width, around which the audio signal modulates.

### **MOSFET Drivers: TC4429/4420**

The TC4420 and TC 4429 are both MOSFET drivers. Their purpose is to quickly overcome the gate capacitance of the MOSFETs, quickly turning them on or off. This leads to cleaner turn-on/turn-off transitions in the MOSFETs and results a signal with less jitter. They also help to cut down on switching losses, which can add to the problem of overheating in the MOSFETs. The

MOSFET drivers are connected directly to the output of the TL494 chip. The TC4429 takes the signal fed to it from the TL494 and inverts it whereas the TC4420 just passes the input signal.

### High-Voltage Pulse Generator: Flyback Transformer

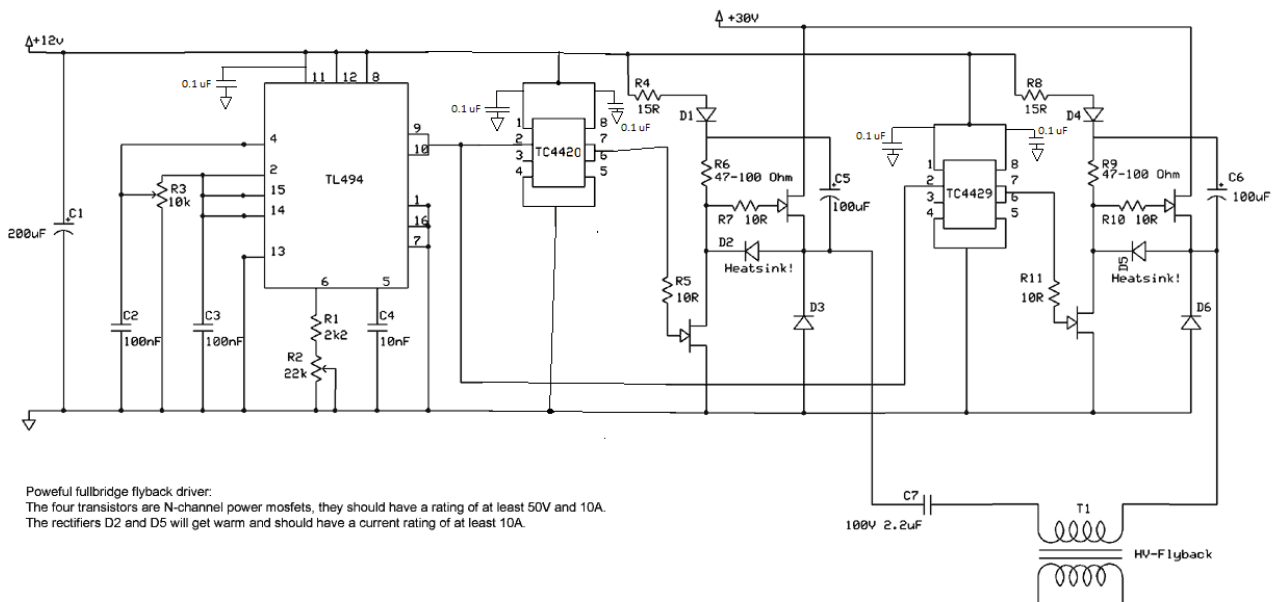
The output of the TL494 is passed through the MOSFET drivers, and then to the MOSFETs themselves, which are used to switch the voltage across the primary windings of the flyback transformer. What the transformer then does is takes the voltage put into the primary windings and increases it drastically on the secondary coil through induction. Theoretically it should follow this equation:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

Where  $V_s$  and  $V_p$  represent the voltage at the secondary and primary, respectively, and  $N_s$  and  $N_p$  represent the number of turns of wire on the secondary and primary coils, respectively. The two ends of the secondary coil are then where the high voltage arc that makes up the plasma speaker is created.

### Full-Bridge Circuit

Here is a schematic of the full-bridge circuit used.



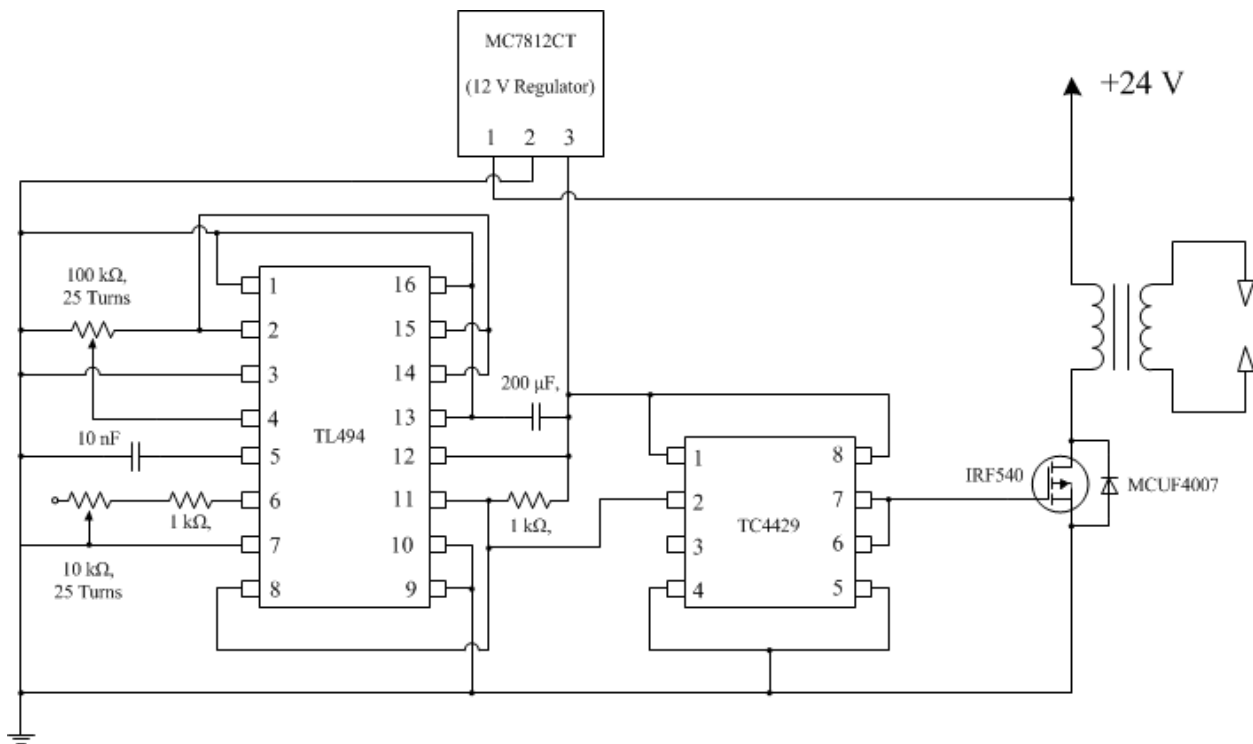
### Important Parts List:

- IRFZ46NPBF – N Channel MOSFET
- MBR1645G Diode (for D2 and D5)
- UF4002 Diode (for all other diodes)

This circuit has a signal coming in from both ends of the flyback primary. One side goes through the TC4429 MOSFET driver while the other goes through the TC4420 MOSFET driver. Therefore, when they reach the primary they are exactly  $180^\circ$  out of phase. This phase difference results in the push-pull operation that characterizes the full-bridge driver. During the first half-cycle, the driver is holding one end of the flyback transformer's primary winding high, while grounding the other end. During the second half-cycle, this is reversed.

### Single-ended Circuit

The single-ended circuit is slightly less complex in comparison to the full-bridge circuit. The single ended circuit is shown below.

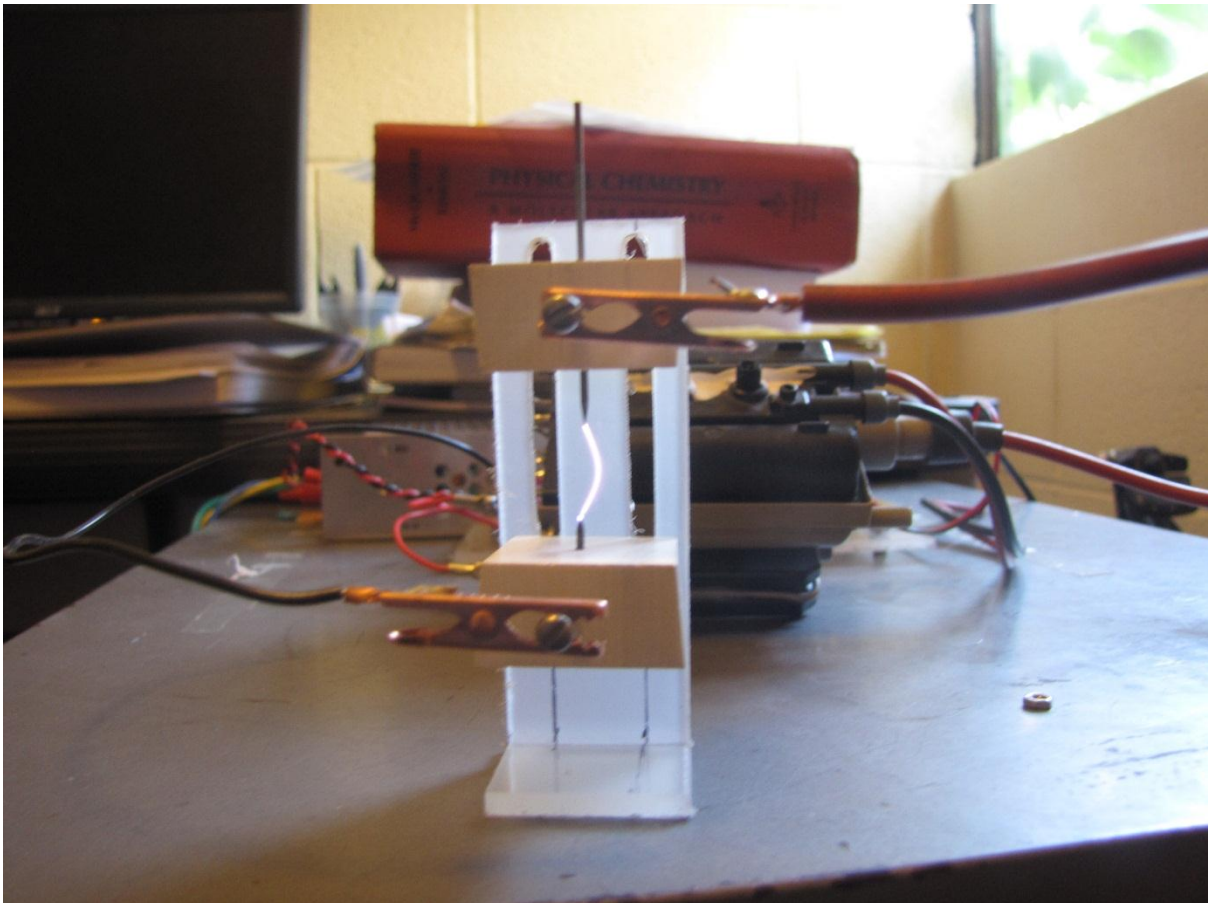




Succinctly put, the single ended driver alternates between pulling one end of the flyback transformer's primary winding to ground (closed circuit), and letting it float (open circuit). The arc occurs when as the circuit switches from closed (current flowing through the primary winding) to open (no current flowing through the primary winding).

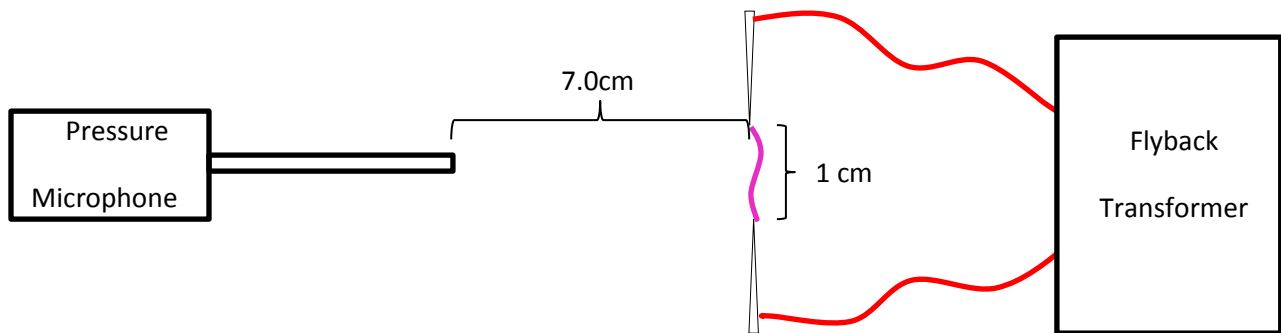
### **Electrode Assembly:**

Due to the similarities between a plasma speaker and a TIG welder, we chose to use TIG welder electrode rods (thoriated tungsten; 2% Th, 98% W). They were held by set screws embedded in a machinable glass-ceramic (known as MACOR), which was then mounted to a plastic slide-rail, constructed using machinable variant of polyethylene terephthalate (known as PETG). This assembly is shown below, actively generating an arc triggered at 50 kHz.



## Experimental Setup

Tests were run on the two circuits so that comparisons could be made. A function generator was hooked into the audio input of the circuit so the audio frequency and amplitude could be controlled. A pressure microphone was then placed close to the plasma arc to pick up the fundamental and harmonic frequencies that the speaker put out. The microphone was then connected to a spectrum analyzer which sent the data to a program in LabVIEW to be stored onto a computer. A schematic of the setup is shown below. It should be noted that each circuit used a different flyback transformer but everything else was identical for each circuit.



## Results

Both circuits were tested throughout the entire audible range using the experimental setup described above. Figures 4 and 5 show the spectral response of the two circuits for inputs ranging from 100 Hz to 1 kHz, and at an input voltage of 700 mV (line-level).

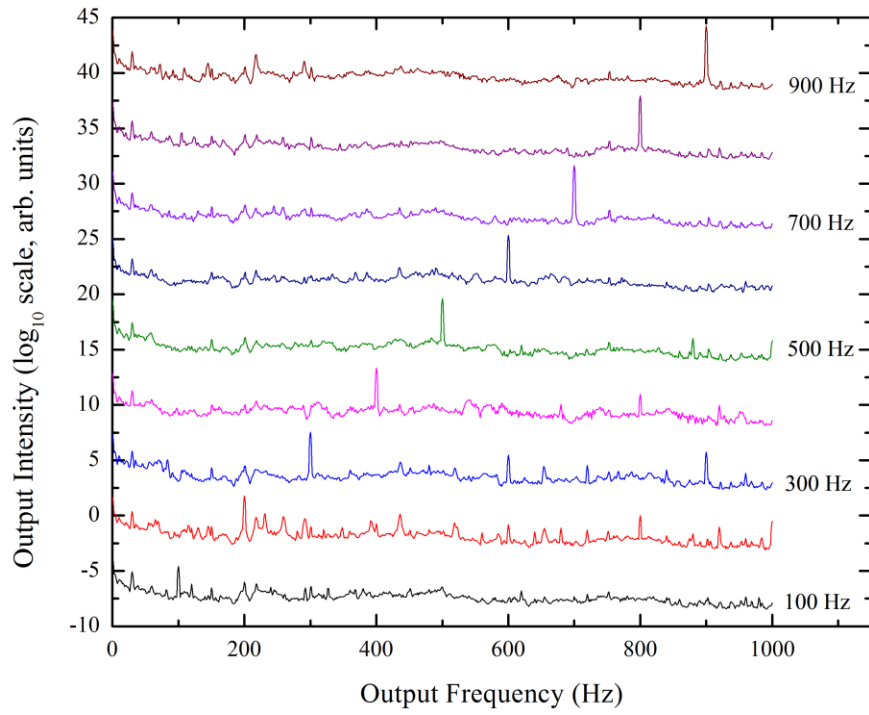


Figure 4: Frequency response of the full-bridge driver.

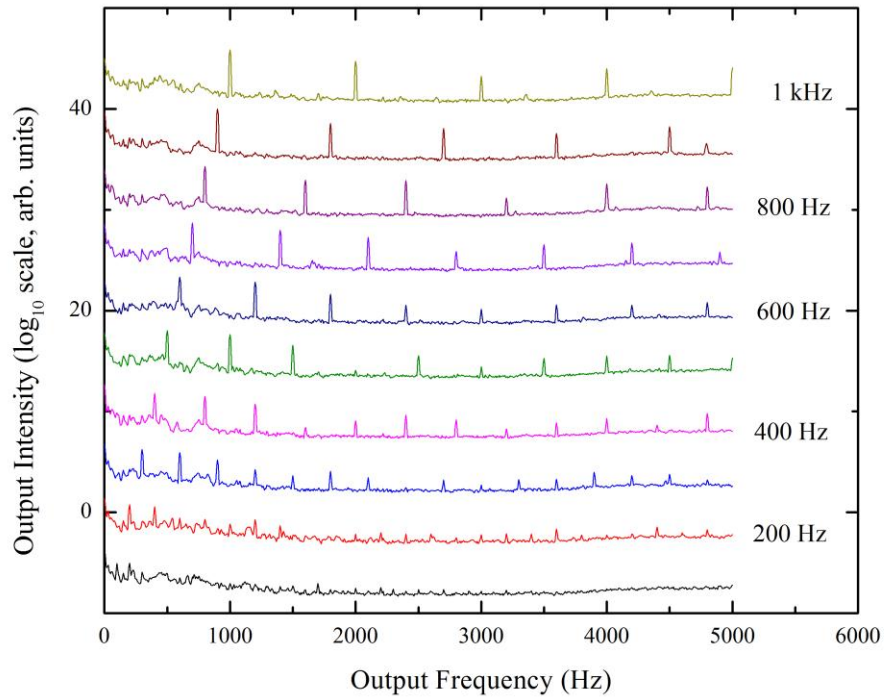


Figure 5: Frequency response of the single-ended driver.

As is shown in Figures 4 and 5, the full-bridge driver produces less intense overtones than the single-ended driver. This is seemingly analogous to the differences in the frequency response of push-pull amplifiers vs. single-ended amplifiers. At the time of this writing, however, the specific cause of this difference in plasma-speaker performance has yet to be conclusively determined.

Figure 6 shows the response of the single-ended driver (chosen because of its more pronounced overtones) as a function of the amplitude of a 1 kHz, input signal.

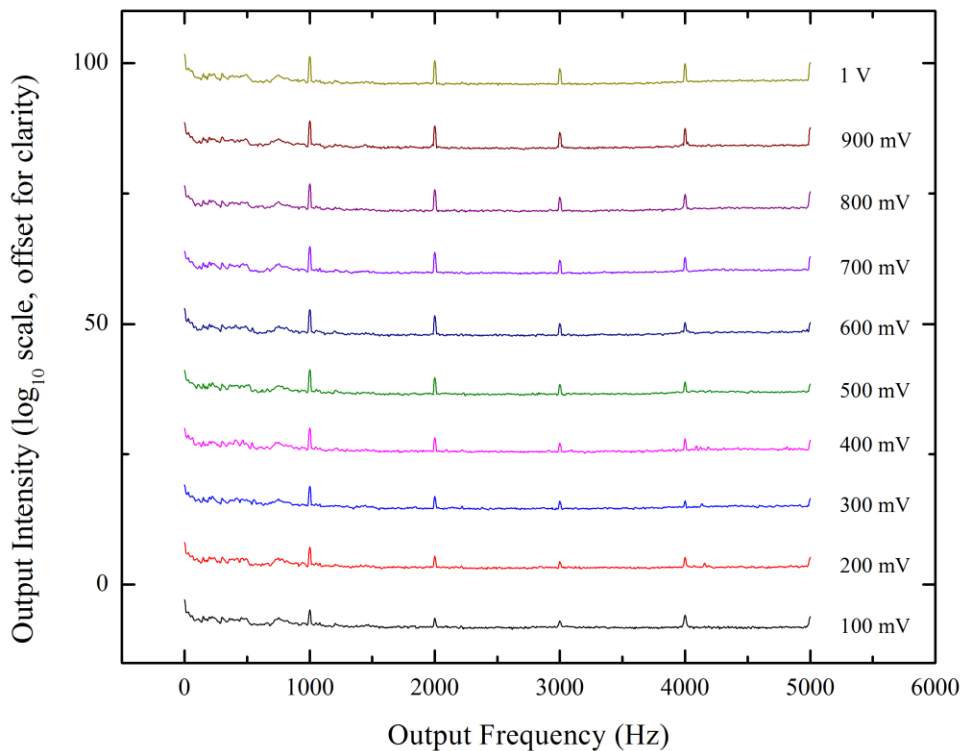


Figure 6: Frequency response of the single-ended driver as a function of

As the input voltage is increased, the overtones become even more pronounced, with the non-linear effects of converting the PWM signal into amplitude-modulated, high-voltage pulses becoming stronger as the small-signal approximation breaks down. Figure 7 shows the ratio of the intensity of second, third and fourth harmonics to the intensity of the fundamental, as a function of input voltage.

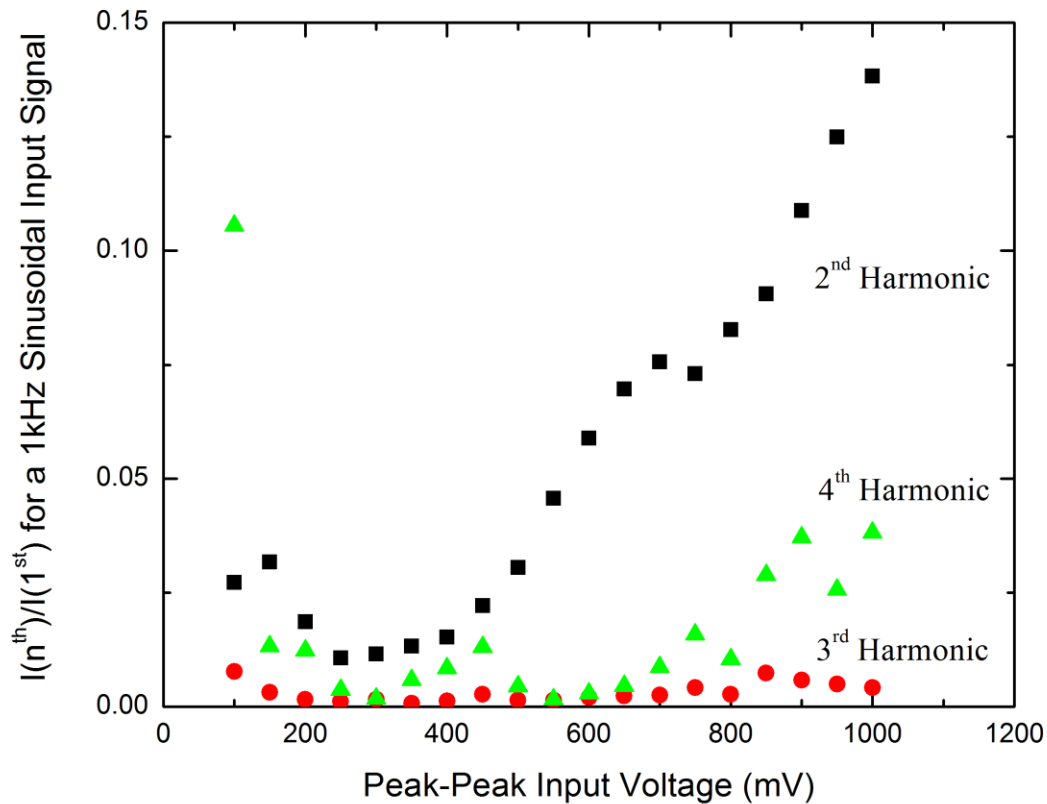


Figure 7: Frequency response of the single-ended driver as a function of

From Figure 7, one we can see that the second and fourth harmonics are considerably stronger than the third, with all three gaining in intensity (relative to the fundamental) as the input voltage is increased. By the time the input amplitude reaches 1 V, the sum of the intensities of the first three overtones reaches ~20% of the intensity of the fundamental. For a 1 kHz input signal, the ratio of the intensity of the fundamental to the sum of the intensities of the overtones appears to be minimized for inputs having an amplitude of 250 mV.

### **Conclusion:**

Two different circuits for driving a plasma speaker were tested. Both circuits were capable of amplitude-modulating a high-voltage impulse train, though they accomplished this task in slightly different ways. The full-bridge driver was found to have lower-intensity overtones, especially in the vicinity of 100 Hz to 1 kHz. Additionally, the spectral response of the single-ended driver was measured while varying the amplitude of the input signal. It was found that for

a 1 kHz input signal, the ratio of the intensity of the fundamental to the sum of the intensities of the overtones was minimized for an input amplitude of approximately 250 mV.