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**HARDWARE DEVELOPMENT FOR THE GENERATION OF LARGE-VOLUME
HIGH PRESSURE PLASMA BY SPATIOTEMPORAL CONTROL OF SPACE
CHARGE**

by

Nikhil Boothpur
B.E. July 2017, Acharya Institute of Technology, VTU, Bangalore

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

ELECTRICAL AND COMPUTER ENGINEERING

OLD DOMINION UNIVERSITY
December 2020

Approved by:

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ABSTRACT

HARDWARE DEVELOPMENT FOR THE GENERATION OF LARGE-VOLUME HIGH PRESSURE PLASMA BY SPATIOTEMPORAL CONTROL OF SPACE CHARGE

Nikhil Boothpur
Old Dominion University, 2020
Director: Dr. Shirshak K. Dhali

While generating a plasma under laboratory conditions, any attempt to scale the pressure and volume leads to instabilities due to the build-up of localized space-charge. This poses a challenge in the design of the discharge chamber, type of excitation field, and the type of gas that is used in the discharge. This work investigates a spatially and temporally varying electric field to control the formation of space-charge in large-volume (greater than 5 mm in the smallest dimension) near atmospheric pressure. The simulations show that in a space-charge dominated transport, the charged species disperse both in azimuthal and radial directions in cylindrical geometries. This leads to stable discharges due to better control over the space charge. In this approach, multiple conformal electrodes along the length of the cylindrical discharge chamber are excited with phase-shifted sinusoidal voltage. This causes a rotating electric field, which disperses the space-charge to prevent instabilities from developing. The phase-shifted waveforms are obtained by programming an FPGA. The digital waveform generated by the FPGA is then converted to an analog signal and is amplified to a voltage above a kV. The phase staggered high voltage is applied to a custom chamber with eight electrodes. The chamber was constructed with 3-D printing to accommodate the subtle feature required for a miniature discharge chamber. This thesis describes the design and implementation of a novel discharge chamber and the associated power system.

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I dedicate this thesis to my parents, siblings, friends, and colleagues whose continuous support kept me motivated throughout this journey.

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I would like to express my acknowledgments to several people for their support and encouragement, without which this process was impossible.

Firstly, I express my whole-hearted gratitude to my M.S. Supervisor, Dr. Shirshak Dhali, for his guidance and motivation throughout my research period. I thank him for offering an opportunity to work under his supervision and conduct research, which concluded in this thesis report. He taught me various methods, discipline, and systematic steps to carry out the research work as clearly as possible. He taught me to work with delicate things such as vacuum and also high voltage power supply. It was a great privilege to work under his guidance.

I am grateful to Dr. Linda Vahala and Dr. Sanjeevi Chitikeshi for their willingness to serve my thesis committee from their timely schedule would also like to thank them for reviewing my thesis.

I would also give a special thanks to Ph.D. student Ankit Baingane as he helped me with the lessons on Autodesk Eagle design software. He also helped me understand the process of PCB etching. I would like to thank Siqin Dong and Juan Cortez for helping me 3D print the electrode assembly numerous times with their 3D printer and material.

I wish to extend my thank you to my parents, Dr. B Vijay and Lalita, for their never-ending support and words of encouragement. Your inspiration always helps me in my personal and professional endeavors. Also, I would like to thank my sister Niharika for her belief and unconditional love towards me from overseas. I am grateful to have you all who support and encourage me at all the stages of my life.

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CHAPTER 1

INTRODUCTION

1.1 LITERATURE SURVEY

There has been a concerted effort to understand the non-equilibrium air plasma at atmospheric pressure through a multi-university research initiative(MURI) entitled "Air Plasma Ramparts" [1]. The progress in this area has only been incremental since that effort. The generation of cold atmospheric pressure plasma is limited by the discharge physics as it tends to form space charge, which leads to instabilities [2]. The main aim of this project is to build the hardware to generate atmospheric pressure plasma as a proof of concept. For a given operating gas composition, the characteristics of plasma can be controlled by the electrode geometry and temporal shape of the voltage pulse. The power source applied to generate plasma to the electrode assembly can be AC, DC, or pulsating. When an alternating field is applied to a neutral gas, the breakdown of the gas is different from a steady field. The field at which the gas breaks down also depends on the frequency of the alternating field. At a critical frequency, the ions in the plasma see a reversal in the electric field before reaching the electrode and start oscillating between the electrodes. The critical frequency is given by [3],

$$f_c = \frac{\mu_+ E_0}{\mu d} \quad (1)$$

In the above equation, μ_+ is the ion mobility, E_0 is the peak electric field, and d is the distance between two opposite electrodes in the electrode assembly. Above this critical field, the voltage required to initiate a plasma is lower than the static breakdown voltage. Simulations and experimental results inform the design of the hardware. If the pressure is increased in the discharge chamber, the cross-section of the discharge is reduced, leading to high power densities, which may

lead to instabilities. The dimensions of the electrode assembly are determined by Paschen's curve. In order for gas to breakdown at atmospheric pressure (760 torr), the discharge gap cannot exceed a few mm [4]. For a glow like discharge operating at voltage-current characteristic, the current density is proportional to the square of the pressure [5]. At larger gap distances, there is a strong space charge domination, which leads to arcing and which is not the desired mode for most technological applications [6, 3].

At atmospheric pressure, dielectric barrier charges, which contain many arcs like micro discharges and also corona discharges, are used widely in industries where the surface treatment of metals and polymers is required for functionality [7]. A stable discharge performs better in applications and can also be used in UV generation due to their uniformity [8]. There are very few stable discharges that are glow-like discharges available and have many limitations [9,10]. These can be used in medical plasma, an emerging field, as the requirements are very different from industrial plasma [11].

A fundamentally different approach is proposed here. The traditional method keeps the electrodes spatially fixed and applies a temporally varying electric field [3]. In the proposed plasma source, cylindrical geometry with a set of electrodes placed on the outer surface of the insulator is used, as described in chapter 3. These electrodes are azimuthal electrodes. This configuration does not require an inner concentric electrode to create an electric field inside the discharge chamber. The excitation of the electrodes at a radius R is given by

$$V(\theta, t) = V_0 \cos(\omega t + n\theta) \quad 0 < \theta \leq 2\pi \quad (2)$$

where V_0 is the peak voltage of the sine wave of frequency ω , θ is the anticlockwise angle, and n is the number of cycles. The value of n should be a non-zero integer as $n=0$ would lead to zero electric fields in the discharge chamber. The Laplace equation in polar coordinate is given by,

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \frac{\partial V}{\partial r} + \frac{1}{r^2} \frac{\partial^2 V}{\partial \theta^2} = 0. \quad (3)$$

The above equation (3) is solved for the analytical solution by keeping equation (2) as boundary conditions. The solution on a disk radius R is given by

$$V(r, \theta) = V_0 \left(\frac{r}{R}\right)^n \cos(\omega t + n\theta). \quad (4)$$

The spatial distribution of the charge strongly depends on the value of n . If $n=1$ is considered as a dipole field, the magnitude of the field is constant throughout the cylinder. For $n=2$, it is a quadrupole field, and the electric field shifts to the outer surface. The increasing value of n can be used to enhance the field on the surface to initiate a discharge [12].

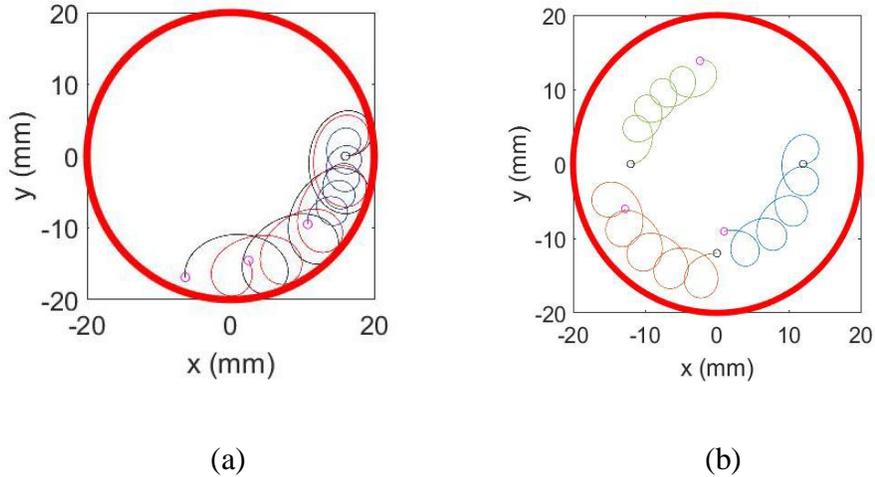


Figure 1(a): Argon ion at 8kHz: (n=1)blue, (n=2)red, (n=3)black. (b) Argon ion at n=1 for different frequencies 8kHz for green, 7kHz for blue, and 6kHz for red.[13]

The electrode assembly has a dielectric where a voltage drop occurs, and the fractional is equal to $\frac{c_g}{c_g+c_d}$ where c_g is gap capacitance and c_d is dielectric capacitance. It is good to have a thin dielectric with a high dielectric constant to reduce this drop. Power dissipation in a dielectric barrier discharge is dependent linearly on applied voltage and frequency [14]. The deposition modeling technique of 3D printing works with plastic to build strong, durable, and dimensionally accurate parts with higher accuracy. It can also be customized to every minute detail. Zwicker et al. of the Princeton Plasma Physics Laboratory characterized printed parts for accuracy, vacuum compatibility, and electrical properties and found them adequate for laboratory use [15]. The 3D printing of electrode assembly helps to have flexibility with the material used and its corresponding dielectric. It also helps to vary the dimensions based on the user. Isakov et al. created alternating layers of low dielectric ($\epsilon_r = 2.65$) material, acrylonitrile butadiene styrene (ABS), followed with high dielectric ($\epsilon_r = 7.0$) formulation of ABS+BaTiO₃ (0.27 volume fraction), for designing a strong anisotropic matching network [16].

1.2 THESIS STATEMENT

This thesis focuses on developing the hardware required for the generation of uniform non-thermal plasma under ambient conditions. The complete hardware from multiphase high voltage generation to the electrode assembly is carried out under this thesis. The power system was tested and characterized. The vacuum system was tested and performed satisfactorily.

1.3 AUTHOR CONTRIBUTION

I have developed the complete hardware for generating the plasma during my one year of research. For the generation of the multiphase voltage system, a Verilog code was written, and various data sets are generated from MATLAB. The digital to analog converters are tried and tested, and then the working circuit is etched on a circuit board. The same thing is done for the high voltage amplifiers. The electrode assembly was also designed and printed using a 3D printer. I have designed two models with different dimensions to test them for plasma discharges. All these processes are carried out under the supervision of Dr. Shirshak K. Dhali.

1.4 THESIS OUTLINE

The following chapters elaborate on building the hardware for generating plasma.

Chapter 2 deals with the steps to build hardware for generating eight phase shifted sine waves. Here the DE-0 nano FPGA is programmed, and then the waves are converted to analog form by building circuits and printed circuit boards. The high voltage amplifier is also built and tested using a power operational amplifier. It includes a step-by-step design procedure for circuit design and hardware construction.

Chapter 3 deals with the design of the electrode assembly. It gives brief information about the design of the electrode assembly in Autodesk Inventor and the material used to 3D print the final design.

In chapter 4, the setup of the hardware and the conditions for obtaining the plasma are discussed, and the results are recorded in detail.

CHAPTER 2

MULTIPHASE SINEWAVE GENERATION USING DE-0 NANO

2.1 INTRODUCTION

The focus here is to generate a rotating electric field that can be used to generate a uniform plasma. In order to create the rotating electric field, we need to create eight sinusoidal waveforms each 45 degrees apart from the preceding one. In order to create these waveforms, we use the DE-0 nano FPGA. This FPGA is programmed using hardware programming language Verilog. The digital waveforms obtained from the FPGA are then converted to analog waveforms using an 8-bit R-2R ladder. These sinusoidal waveforms are used for generating plasma but can also be used for various other applications. We can also generate different types of waveforms, such as sawtooth, square, and triangular, using this method. The whole setup is shown in Figure 2.1 below.

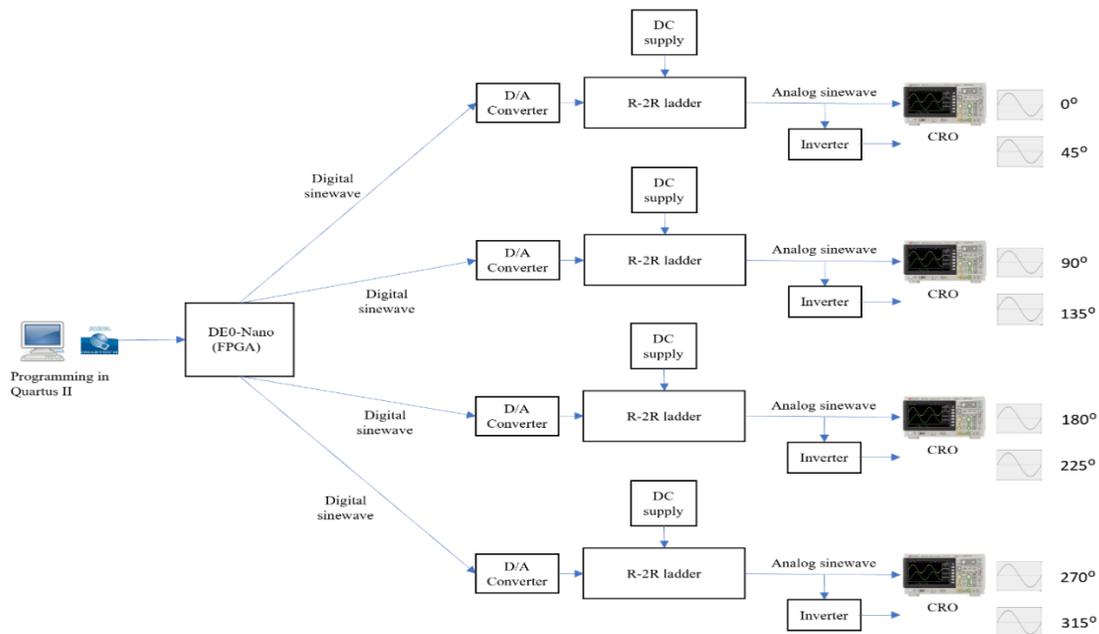


Figure 2.1: Block diagram of the FPGA and R-2R ladder setup

The ion mobility μ_+ for argon gas is $1.54 \text{ cm}^2 (\text{V}\cdot\text{sec})^{-1}$, the peak electric field E_0 generated from the amplifier stage is $1600 \text{ V}_{\text{p-p}}$, and the distance between the electrodes d is 0.5cm from the design of model 2. Thus, by using equation (1), we get the critical frequency as 1568 Hz , so this is the critical frequency where the ions are released from their atoms. If a frequency higher than this is given, the ions start to oscillate between two opposite electrodes, leading to the breakdown of the gas. Therefore, the power supply will need to generate frequencies above this critical frequency.

2.2 DE-0 NANO

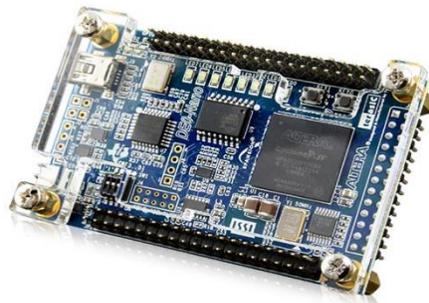


Figure 2.2: Cyclone IV DE0-nano Evaluation Board [17]

The DE-0 nano board introduces a compact-sized FPGA development platform that suits a wide range of portable design projects, such as robots and mobile projects [18].

It is ideal for embedded soft processors. It features powerful Altera cyclone IV FPGA. The DE-0 nano has a built-in USB blaster for programming. The USB blaster itself can power the board, or it can be powered by an external power source. The inputs and outputs include two push

buttons, four switches, and 8 LED lights. It consists of 2 digital input or output ports called DPIO-0 and DPIO-1 on either side, as shown in Figure 2.2.

The salient features of the board are listed below:

- The board has 32 MB of SDRAM, 2 kb EEPROM, and a 64 Mb serial configuration memory device.
- It uses an 8-channel 12-bit A/D converter.
- It has a 3-axis accelerometer device.
- The GPIOs provides 72 I/O pins. It has 5V power pins, two 3.3V power pins, and 4 ground pins[19].

The FPGA is programmed initially to get four sinusoidal outputs. The generated sinusoidal waveforms have a frequency varying from 10kHz to 100kHz. By writing a simple Verilog program, we can develop specific points of sine waves using MATLAB. The points for the 45° phase shift between the four waveforms are generated using the following formulae in MATLAB.

$$sine_{value1} = 127 * (\text{sine}(\text{angle}) + 1);$$

$$sine_{value2} = 127 * (\text{sine}\left(\text{angle} + \frac{\pi}{2}\right) + 1)$$

$$sine_{value3} = 127 * (\text{sine}\left(\text{angle} + \frac{\pi}{4}\right) + 1)$$

$$sine_{value4} = 127 * (\text{sine}\left(\text{angle} + \left(3 * \frac{\pi}{4}\right)\right) + 1)$$

The angle is given by a formula: $angle = \frac{address * 2 * \pi}{depth}$.

The depth and width are specified at the beginning as 256 and 10. The file name is also defined, and all the generated values are printed out to that file.

The waves obtained from the FPGA are in digital form. These waves are converted to analog format for our application.

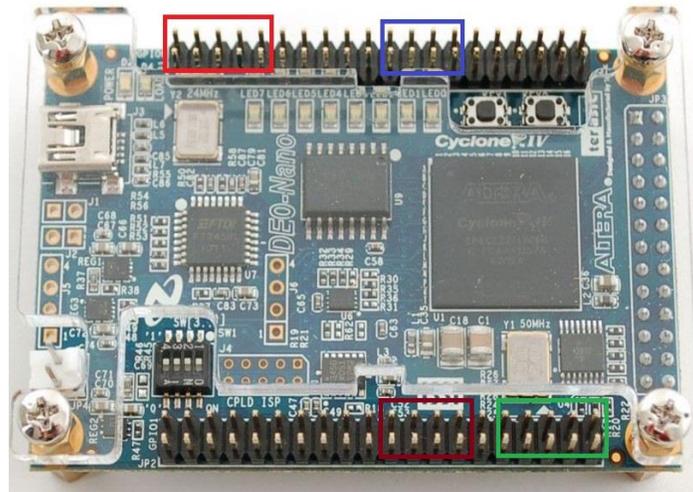


Figure 2.3: DE-0 Nano with port markings

As we can see from the DE-0 Nano in Figure 2.3, we use four ports to get four digital waveforms. We use two sets of pins from GPIO-0 and GPIO-1, respectively. These pins can be programmed as input and output pins as required. The outputs from the pins are highlighted and recorded in Table 1 below.

Highlighted set of pins on FPGA	The phase shifted digital sine wave
Red color	0 degree
Green color	45 degree
Blue color	90 degree
Brown color	135 degree

Table1: I/O pin sets used in the experiment

2.3 DIGITAL TO ANALOG CONVERTER USING R-2R LADDER CIRCUIT

The digital to analog converter is used to convert the digital wave to an analog wave. A digital waveform is a collection of binary information at a definite time interval. An analog signal varies in step or some other physical phenomenon, acting as an analog to model. For example, a microphone's electrical signal is an analog of the sound waves impinging on the mike [20].

The design for this R-2R ladder is a combination of $10k\Omega$ and $20k\Omega$ resistors. The IC741 is a better option for an operational amplifier because of its various salient features such as high gain and high input impedance. A split DC supply of +15V and -15V is used. We can use this IC in various configurations, such as inverting and non-inverting amplifiers. The pin diagram of IC 741 is in Figure 2.4 below.

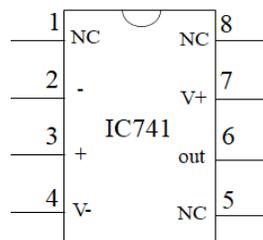


Figure 2.4: Pin diagram of IC741

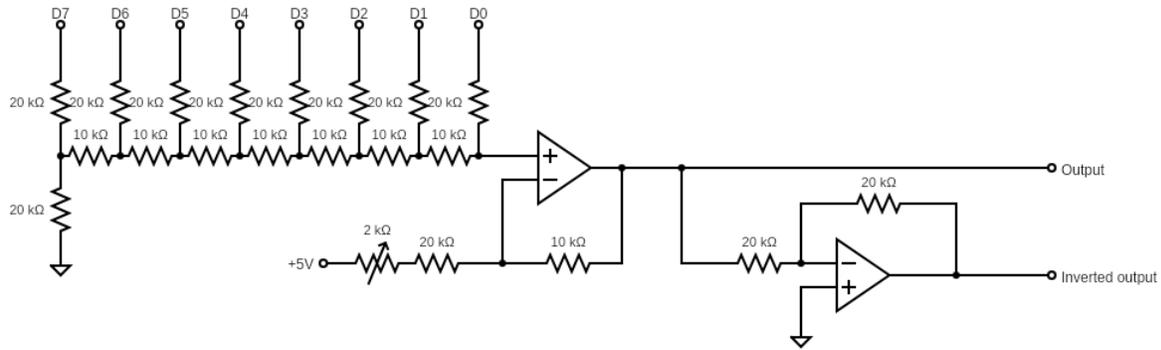


Figure 2.5: Schematic circuit of the R-2R ladder

The schematic representation in Figure 2.4 consists of IC 741 used as a unity gain buffer and an inverter. The 8-bit inputs D0-D7 to the R-2R ladder are the digital output from the FPGA. A 5V DC is provided to the circuit, and using a 2k Ω potentiometer, the output sinusoidal wave is adjusted. Then, we use another IC 741 as a basic inverter circuit. The obtained sinusoidal waveform is given to the inverter to get an inverted output. The acquired waveforms have a voltage of 5V_{pp}.

The schematic diagram in Figure 2.5 was designed using Autodesk EAGLE for manufacturing the printed circuit boards. The free version of Autodesk EAGLE is available online and is a simple design software for designing circuits.

2.4 DESIGNING WITH AUTODESK EAGLE

Autodesk EAGLE:

EAGLE is scriptable electronic design automation. EAGLE stands for Easily Applicable Graphical Layout Editor. It has various schematic capture applications, printed circuit board (PCB) layout, auto-router, and computer-aided (CAM) manufacturing features.

EAGLE contains a schematic editor with files having .sch extensions where we draw a schematic diagram. It has many built-in libraries with file extension .lbr, which we use for various resistors, ICs, capacitors, and many more components used in the circuit.

The PCB layout editor stores the board files with the extension .brd. It allows back-annotation to the schematic and auto-routing to automatically connect traces based to the connections defined in the schematic [21].

In the low voltage R-2R digital to analog converter circuit, we have all the necessary components available in the eagle libraries. These components are used, and a schematic diagram is created first. This schematic diagram consists of the whole circuit where connections are drawn, and this file is saved in a .sch extension.

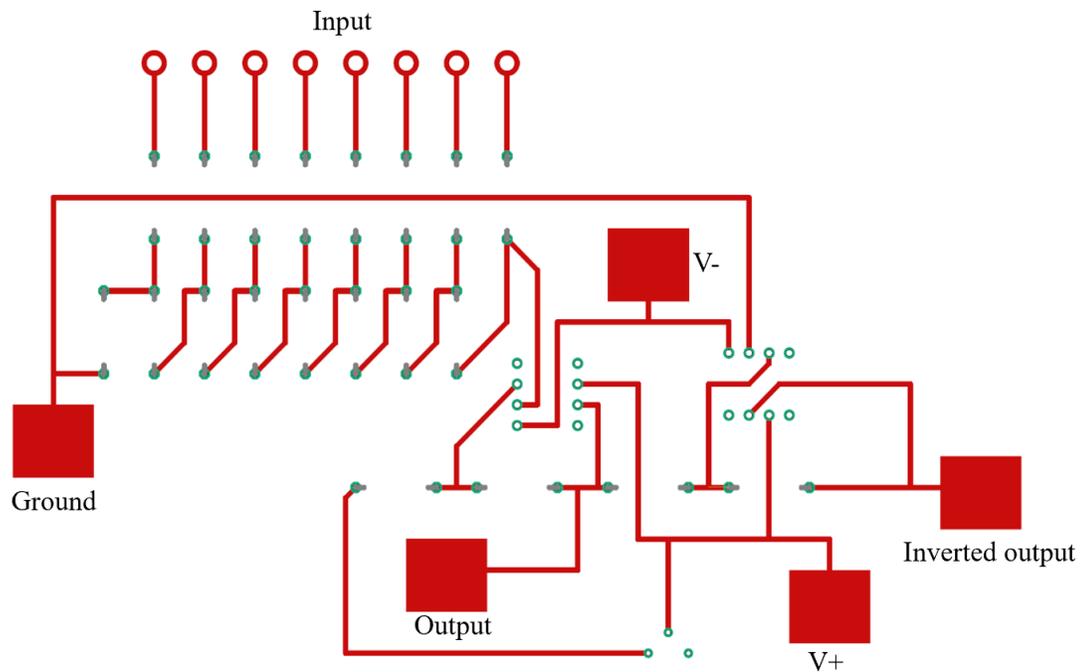


Figure 2.6: Low voltage circuit designed for PCB etching

The schematic diagram is drawn in the Eagle software with the resistors and ICs available from the library. This circuit is saved in .sch and then converted to an etchable circuit on the board shown in Figure 2.6.

Figure 2.6 shows the inputs to the circuit from the FPGA. It shows the R-2R ladder and two ICs. There are the +5V and -5V inputs given to the circuit and also a ground pin. It has two outputs with a standard and inverted sine wave. There are four such similar circuits etched and assembled. The packaged circuit with all eight outputs is shown in Figure 2.7 below.

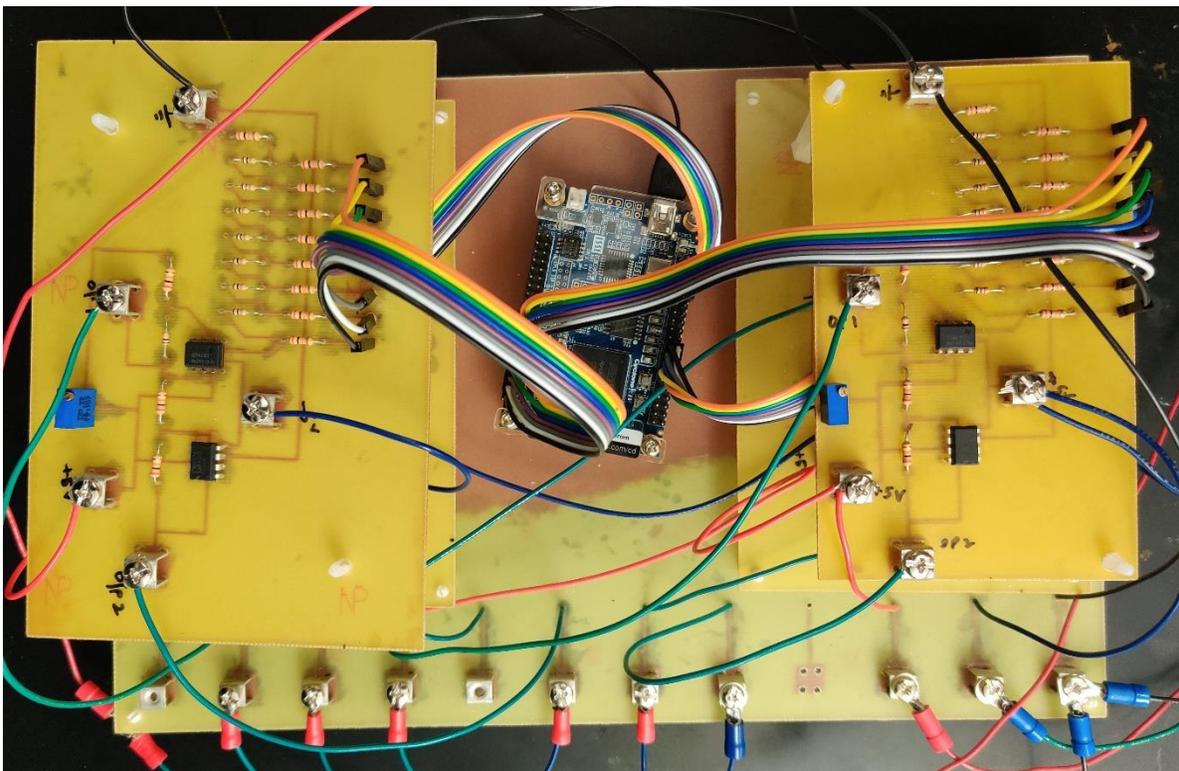


Figure 2.7: Complete low voltage etched circuit with 8 outputs

2.5 DESIGNING THE HIGH-VOLTAGE AMPLIFIER

This section includes a detailed design and fabrication of the high voltage amplifier using the high voltage power operational amplifier.

2.6 INTRODUCTION

The high voltage amplifier is designed using a power operational amplifier called PA99. A circuit is created using the PA99 with a gain of 100. The input given to this circuit is the output from the previous low voltage circuit. The high voltage circuit is designed to work as an amplifier using various resistors and capacitors and tested.



Figure 2.8: PA99 op-amp[22]

2.7 PA99 POWER OPERATIONAL AMPLIFIER

The PA99 is an ultra-high 2,500V power operational amplifier designed for output currents up to 50mA to target high voltage applications, including piezoelectric positioning,

instrumentation, semiconductor production testing, and electric deflection [23]. APEX manufactures it. The output voltages can swing up to 2400 Vp-p.

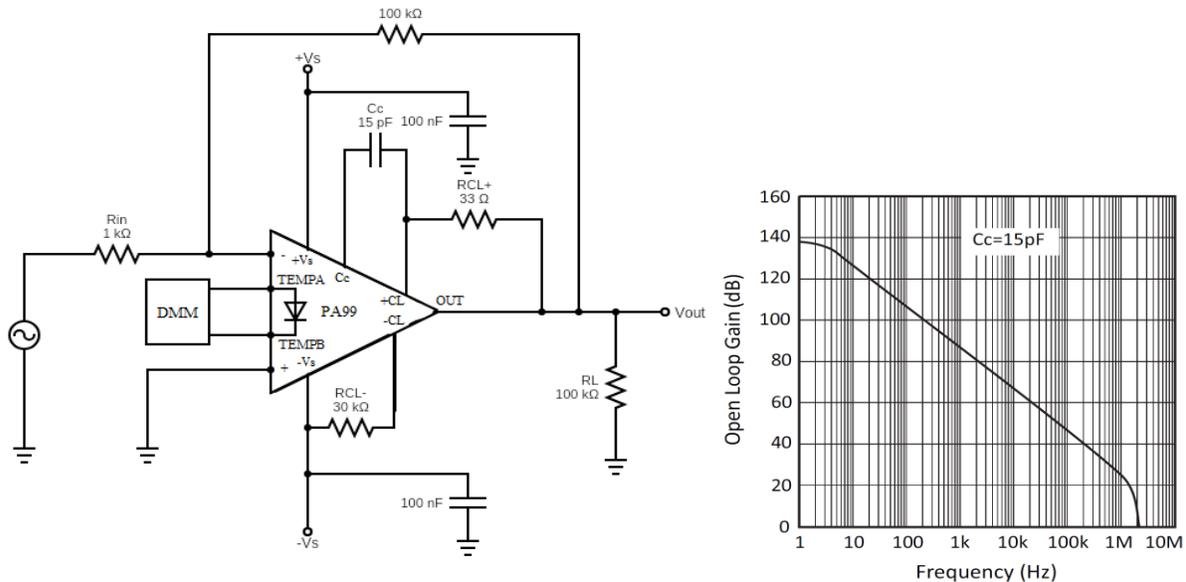


Figure 2.9: Circuit diagram of a high voltage amplifier and a graph of bandwidth selection.

We can use this power op-amp for various applications. In one of its typical applications, we can configure it as an inverting amplifier.

PA99 can handle output currents of 50mA, but careful considerations are taken to keep the device cool; otherwise, it may be damaged due to overheating. We can calculate the power dissipated in the device by using the formula $P_{\text{DEVICE}} = (V_i - V_o) * I$. Based on this equation if we consider the input voltage to be 1000V, the output voltage to be 500V, and the output current to be 50mA, the power loss in the device can be calculated as 25W. This shows that the device will

dissipate 25W of heat. If we increase the input voltage, then more heat is dissipated. Thus, we use a proper cooling system or a heat sink based on our application.

I designed the circuit in Autodesk EAGLE. The schematic diagram requires components such as PA99 and some surface mount and pin mount resistors and capacitors. The PA99 is not available in the built-in libraries, so a new library is created in Autodesk EAGLE.

2.8 DESIGN OF AMPLIFIER CIRCUIT

The amplifier circuit is designed by considering the gain, which we impart to the output wave.

- The input and feedback resistors are chosen so that the gain is 100 for this circuit. The R_{in} is selected as $1k\Omega$, and the R_f is selected from as $100k\Omega$ which gives the gain as 100.
- The bypass capacitors of $100nF$ each are used at $+V_s$, and $-V_s$. They are used to attenuate the high-frequency noise, which is formed on power supply lines given to the op-amp.
- The compensating capacitor $C_c=15pF$ is used. The graph in Figure 2.9 shows that for a $15pF$ compensating capacitor we get a bandwidth of $200kHz$ for a gain of $40dB(100)$. This is adequate for our application.
- The R_{CL+} and R_{CL-} are used as 33Ω and $30k\Omega$, respectively for a current of $20mA$. The positive and negative current limiting resistors are provided by the manufacturer for various current values.

The schematic representation of the amplifier in the eagle software and the completed board design is shown in Figure 2.10 below.

Slew rate calculation:

The slew rate for PA99 is in a range of 10 V/ μ s to 30 V/ μ s. To avoid the slew rate limitation, the sinusoidal signal ωV_p should be less than the slew rate.

$$\omega V_p < SR$$

At 800V_p (see Fig. 5.4),

$$\omega < \frac{10 \cdot 10^6}{800} \text{ for } 10 \text{ V}/\mu\text{s} \text{ slew rate}$$

$$f = \frac{10 \cdot 10^6}{2\pi \cdot 800} = 2 \text{ kHz.}$$

For the slew rate of range, 10V/ μ s to 30V/ μ s, the frequency varies from 2kHz to 6kHz. It represents that at peak voltages greater than 800 volts, the output starts to slew or becomes a triangular wave at frequencies higher than 6 kHz.

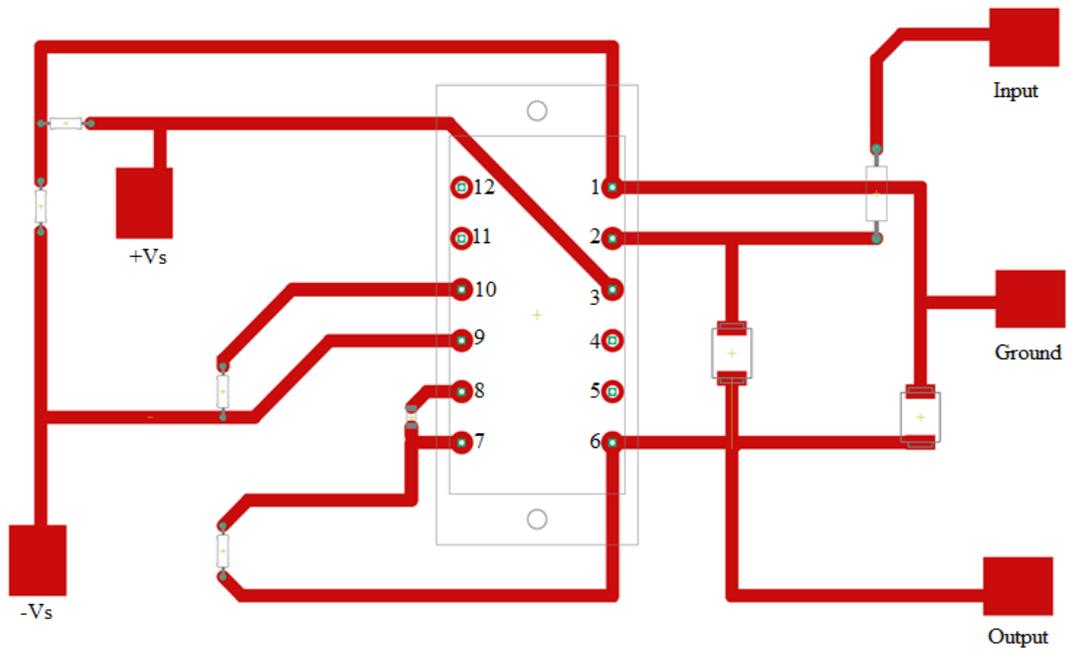


Figure 2.10: Amplifier circuit designed for PCB etching

The printed circuit board is fabricated using the designed circuit. All the components are soldered on the board, and then the continuity is tested with the help of a digital multimeter. For the power op-amp, a heat sink is used to keep it cool during the operation. The components used on this board are both pin mount and surface mount. The complete circuit with mounted components is shown in Figure 2.11.

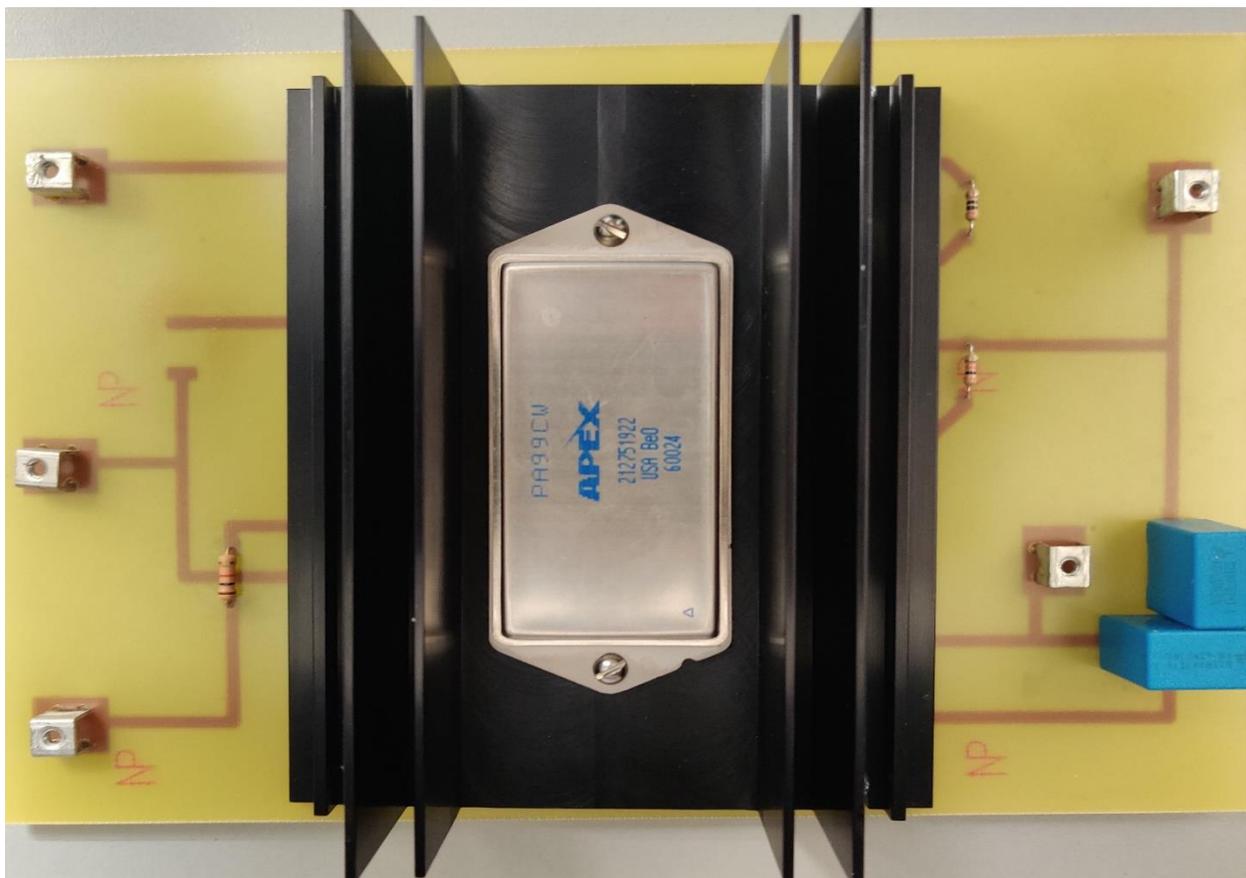


Figure 2.11: Single high voltage board with all the components intact

A simple model is created, and all the circuits are slid into it for better accessibility and cleaner design. All the ground pins, $+V_s$, and $-V_s$ pins, are shorted between all the circuits and

connected to a common point. The eight outputs from the low voltage circuits are given to the eight inputs of the amplifier circuit. The outputs are further connected to the designed discharge chamber.

The circuit is tested with various frequencies. For the same frequency, I have tried various input voltages. The values are shown in Table 2 below. The graph in Figure 2.12 shows that for increasing input values, the output starts to slew for higher frequencies, and to fix this, we can improve the amplifier's gain to get the desired output voltage level.

Frequency(kHz)	Output voltage at 2V input	Output voltage at 4V input	Output voltage at 6V input	Output voltage at 8V input
1	200	400	600	800
5	200	400	600	800
10	200	400	590	790
15	200	400	590	780
20	200	400	580	780

Table 2: Variation of the output voltage by varying input voltage and frequencies

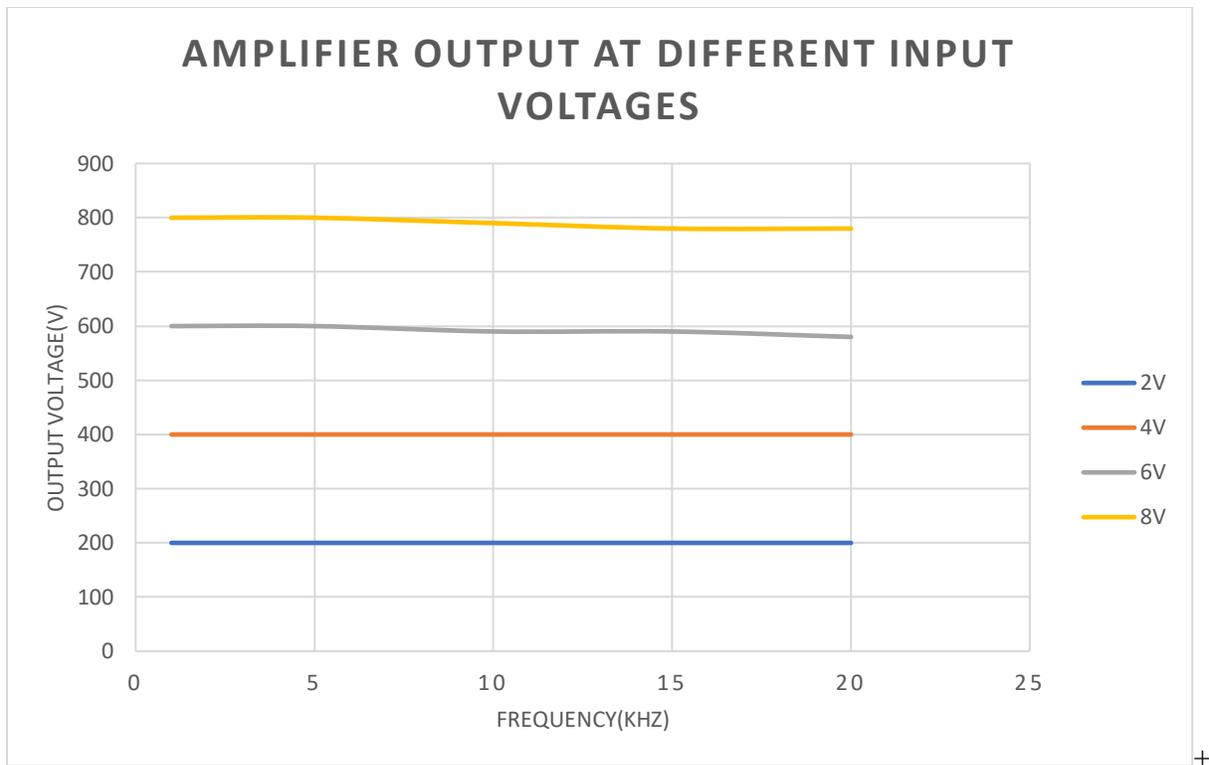


Figure 2.12: Amplifier behavior for different inputs

The circuit is powered with high voltage power supplies. The $+V_s$ and $-V_s$ are given as +1000 and -1000, respectively. Then, the input sine wave is provided, and we record the output using 1000:1 probes. The above tabular column is obtained by varying frequencies and input voltages and recording the circuit's output voltage. The graph of output voltage and frequency is plotted for different input voltages and is depicted in Figure 2.12. Such testing is done for all the etched circuits.

Eight such circuits are created and then tested individually by plying a sine-wave input and checking the output. The above circuit shows the multiple outputs which are connected to the cylindrical model through single-stranded wires.

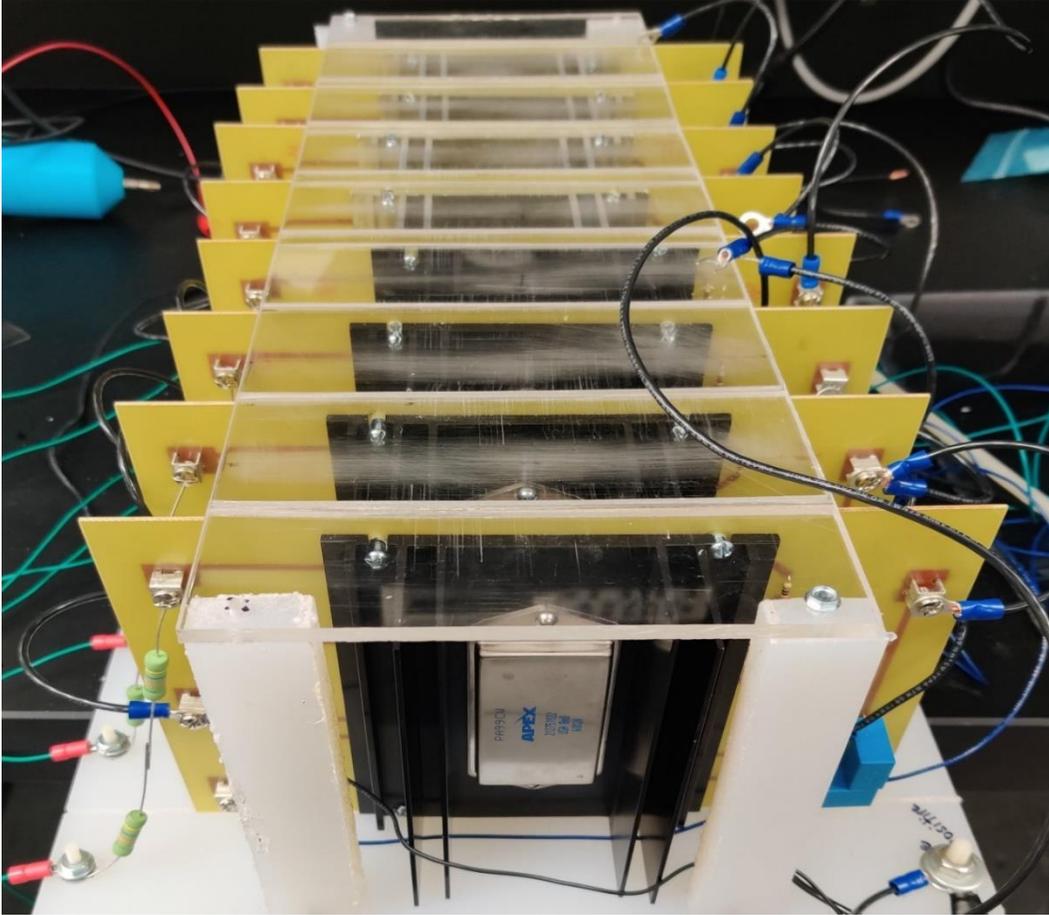


Figure 2.13: A combined model of all eight circuits connected

CHAPTER 3

DESIGNING THE DISCHARGE CHAMBER AND ELECTRODE ASSEMBLY IN AUTODESK INVENTOR

3.1 INTRODUCTION

The voltage to break down the gap and create plasma is in the several tens of kilovolts range at atmospheric pressure. Therefore, the initial proof of concept will be done at higher pressures. There is also a limit as to how small the discharge chamber can be with eight concentric electrodes. Also, the gases that require the least amount of voltage to breakdown are the noble monatomic gases. The Paschen's minimum will be used to design the diameter of the discharge chamber. For Helium gas, the minimum breakdown voltage is 150 volts for a pressure times spacing (pd) of 5 Torr-cm. Therefore, in theory, a 1 cm gap at 5 Torr would require a voltage greater than 150 V for a break down. It has a breakdown voltage of 150 V. Similarly, for Argon gas, the breakdown minimum is about 200 V at a pd of 0.7 Torr-cm. Therefore, Ar gas would need about 6 times higher voltage to break down. From the Paschen data, we conclude that a chamber below 1 cm diameter can be used for a plasma with voltages near a kV in He and Ar[24]. The chamber is designed in the form of a cylinder with grooves to hold the electrodes for the outputs from the previous step. Thus, it is intended to have eight grooves for the eight sine-wave outputs. The chamber is also designed to withstand a good vacuum at a fraction of a Torr. There is an inlet given for the gas and to pull out the vacuum. The other side of the cylinder is kept open to watch the discharge by placing a glass window. Two designs are created with slightly large and smaller diameter for separate trials. The models are created in Autodesk inventor and are 3D printed. The designs are illustrated in the following paragraphs.

3.2 DISCHARGE CHAMBER MODEL 1

The model is built with the following dimensions. The inner diameter of the cylinder is 15mm, and the outer diameter is 18mm. The cylinder is made 50 mm long. For one side of the cylinder, a small hole of 7mm is drawn to insert a pipe for gas and vacuum. The other side of the cylinder is designed to incorporate an over ring, which helps to hold the glass and create a vacuum. The design is shown below in steps.

Firstly, we prepare an outline drawing with all the measurements in mind. It is a 2D sketch. All the measurements are in inches in Autodesk Inventor. The inner diameter is set to be 15mm(0.295in), and the outer diameter is 9mm (0.354in). The model is built to be 3.5in long. The 2D sketch is shown in Figure 3.1 below. The 2D sketch is revolved and then converted to a 3D model, and all the other design elements are considered for further drawing. A hole of diameter 7mm is made for a vacuum pipe on the left side of the cylinder. The grooves are designed to slip the electrodes in them, which graze the cylinder's outer surface. The right hand part of the cylinder is designed to hold a glass window for the vacuum and also to give a viewing point for the plasma.

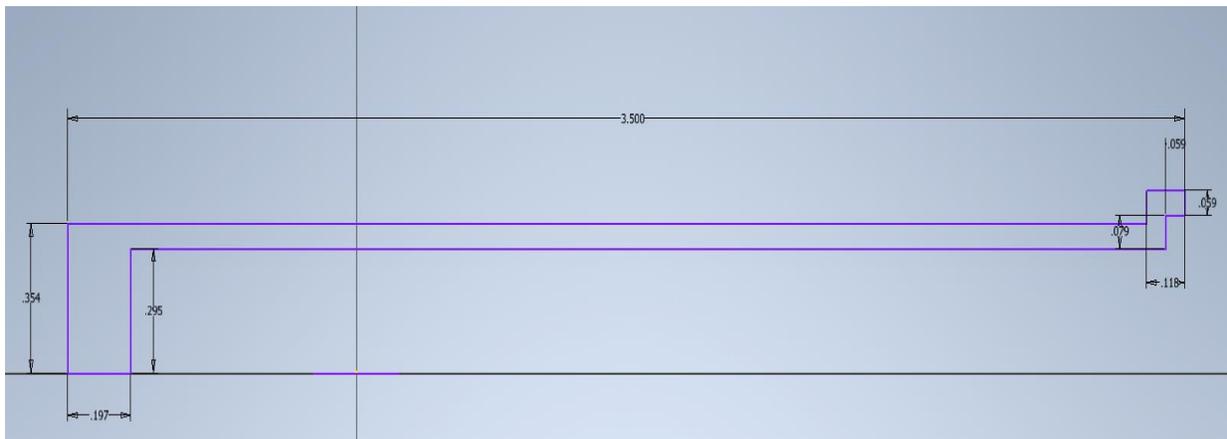


Figure 3.1: A 2-dimensional figure of a basic sketch of the model.

The completed model is shown below. This model is saved and exported in the form of an .STL file and then sent to be 3D printed.

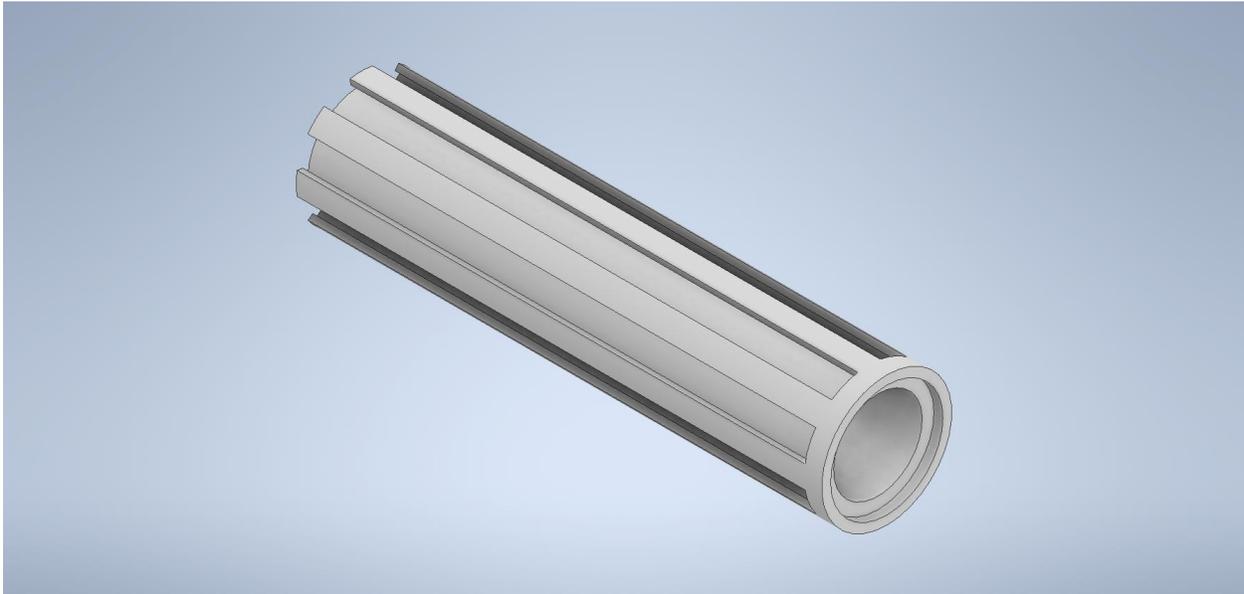


Figure 3.2: Completed 3D model

3.3 DISCHARGE CHAMBER MODEL 2

The second model is built with a considerably smaller cylinder diameter, say 5mm, and the thickness is also reduced to 1mm. The first side of the cylinder is made 20 mm long and a 15mm hole is drilled to stabilize the model. The overall length is increased to 4.5in, and the other end of the model is also kept the same as the previous model. The 2D sketch is drawn, keeping these numbers in mind, as shown in Figure 3.3. Then, by using the revolve command, a cylinder is drawn by revolving the 2D sketch in the previous steps. This is followed by drilling a hole of 15mm into the 20mm solid part because the hole is bigger than the inner diameter which is 5mm. The

remaining solid part can be drilled out. For designing the groove, we consider the other end of the cylinder as a plane, and a 2D sketch of the groove is drawn. Then, by using circular command, eight such grooves are replicated on the surface. These grooves are selected using the extrude command and then extruded on the cylinder surface by leaving a centimeter gap for inserting the electrodes. This gap be seen in the final design which is shown in Figure 3.4.



Figure 3.3: A 2-dimensional figure of a basic sketch of the model.

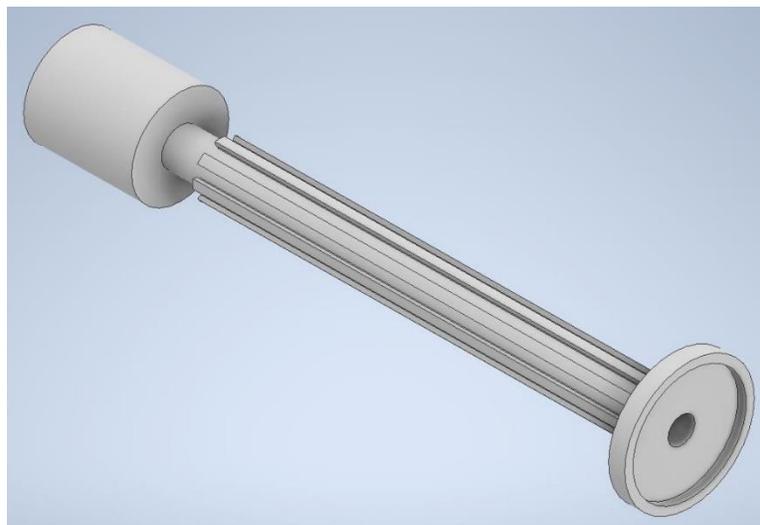


Figure 3.4: Completed 3D model

3.4 MODEL ASSEMBLY

The models are exported as STL files and sent for 3D printing. The 3D printer used is Stratasys Objet30 Pro, a high precision printer, and Objet VeroWhitePlus RGD835 is the material used to print the model. The material is in a liquid state. The flash point of this material is greater than 100 degrees centigrade. This material is rigid and is stable under laboratory conditions.[25]. The printer is equipped with UV light, which turns the material into a solid-state while printing layer by layer. The 3D model takes 7-8 hours for printing. The printer is available in ODU's mechatronics lab, where the model is printed. Then, copper sheets are inserted in the grooves, which serve as electrodes for the plasma discharge. The back end of the assembly is threaded, and a pipe is connected, which is, in turn, connected to the vacuum pump and the gas chamber. The completed model shown in Figure 3.5 below, is then clamped to plexiglass. The eight connections from the output of the amplifier circuit are given to the electrode assembly.

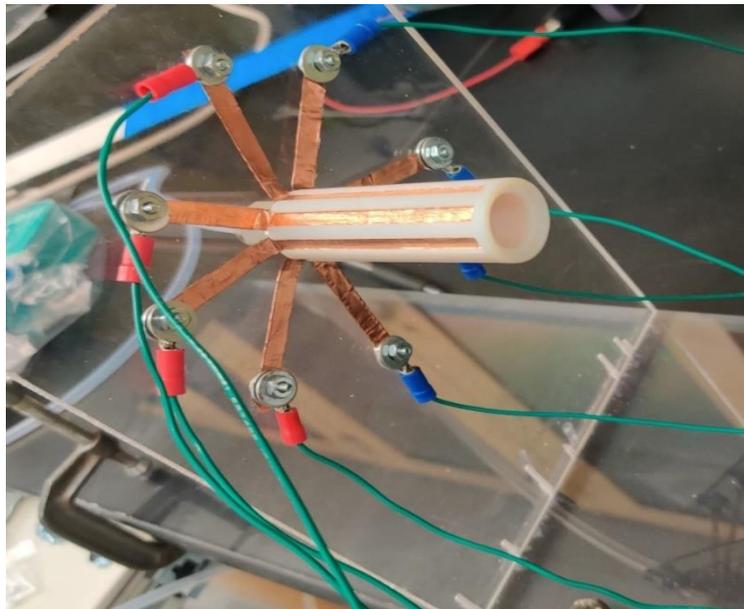


Figure 3.5: Completed electrode assembly (model 1) clamped to a plexiglass

CHAPTER 4

PLASMA DISCHARGE ASSEMBLY

4.1 PLASMA

Plasma is called the fourth state of matter. Matter changes its state when energy is applied to it. Solid becomes liquid; liquid becomes gas. If more energy is applied to gas, then it breaks down to become plasma [26]. Plasma is nothing but a cloud of freely moving protons, neutrons, and electrons where all the electrons have come loose from their respective atoms. Plasma is more like a gas than any other state as all the atoms are not in constant contact with each other, but it also behaves differently from gas. This is called a collective behavior [27].

Applications of plasma:

- Plasma is used in cleaning surfaces without leaving any residue.
- Plasma reduces metal oxides.
- Plasma strengthens surfaces and helps induce phase transition.
- Plasma is used to deposit chemically functional groups.
- Plasma microscopically roughens surfaces [28].
- Plasma is used in industries for plasma coating or plasma spraying of protective layers, plasma hardening, plasma activation of surfaces.
- Plasma has many medical applications for tumor therapies and attacking pathogens. It is effective against bacteria and viruses and is used to sterilize medical products.
- Plasma is also used in plasma chemical reactions.

4.2 PLASMA DISCHARGE CHAMBER SETUP

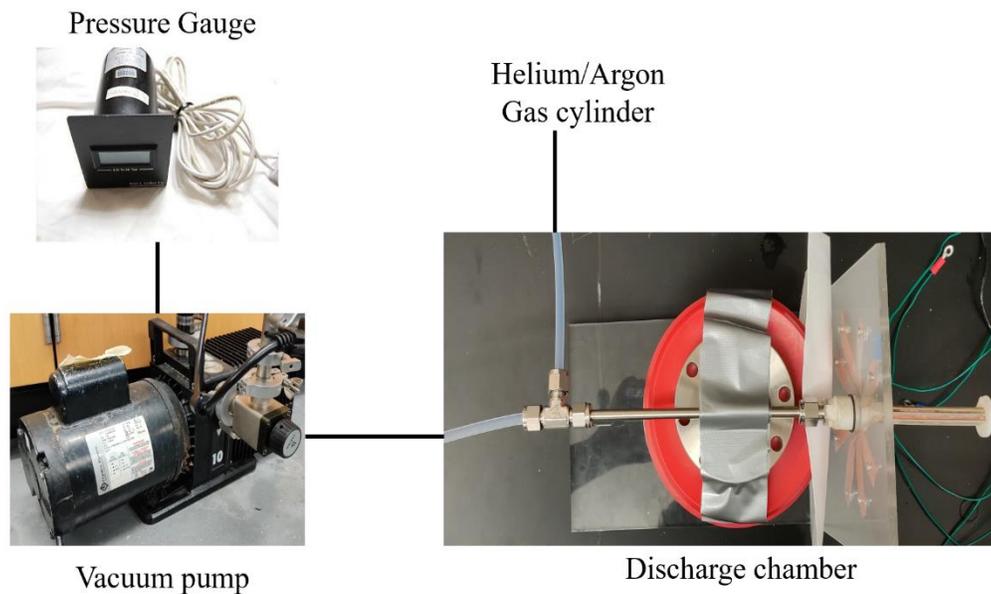


Figure 4.1: Plasma discharge setup.

The plasma is generated in an electrode assembly with electrodes mounted on its outer surface. This 3D model is connected to the vacuum pump and a gas chamber. The vacuum pump is connected to a pressure gauge to monitor pressure during the operation. The electrodes are energized by the outputs from the amplifiers from the previous stage which creates a rotating electric field. The following steps are carried out to test the plasma in the discharge chamber.

- A glass window covers the free end of the electrode assembly with a rubber over-ring, which maintains the vacuum.
- The vacuum pump is switched on, and the valve is released to pull the vacuum from the electrode assembly.

- The gas is sent into the discharge chamber, and a pressure of 3-4 torr is maintained inside the chamber.
- The amplifier is given the sine wave inputs, and then a positive and negative voltage of +1kV and -1kV is given to the amplifier. The output is, in turn, connected to the electrodes on the discharge chamber.
- The amplified sine wave is used to power the electrodes of the electrode assembly.

When high voltage sine waves power the electrodes, they form a rotating magnetic field that can break down the gas in the chamber. When the gas breaks down, a glow-like discharge is seen called plasma.

In our case, the gas did not break down under the above conditions. The common reason for this might be the dielectric of the electrode assembly, which considerably reduces the voltage's strength. Also, the power supplies which we used gave 1kV as maximum voltage. The amplifiers support 2.5kV voltage. The experiment can be repeated with a higher range of power supply.

CHAPTER 5

RESULTS

5.1 INTRODUCTION

This chapter consists of the results from all the sections. It consists of waveforms from the digital to analog conversion circuit, the output from the high voltage amplifier circuit and the final 3D printed designs.

5.2 PROGRAMMING WITH DE-0 NANO

The DE-0 nano is programmed in Quartus II, where four sets of data points are generated using MATLAB code. These are in the form of digital waves i.e., 0 and 1. We see square pulses on the oscilloscope from MSB to LSB. The pulses are shown in the Figure 5.1 below.

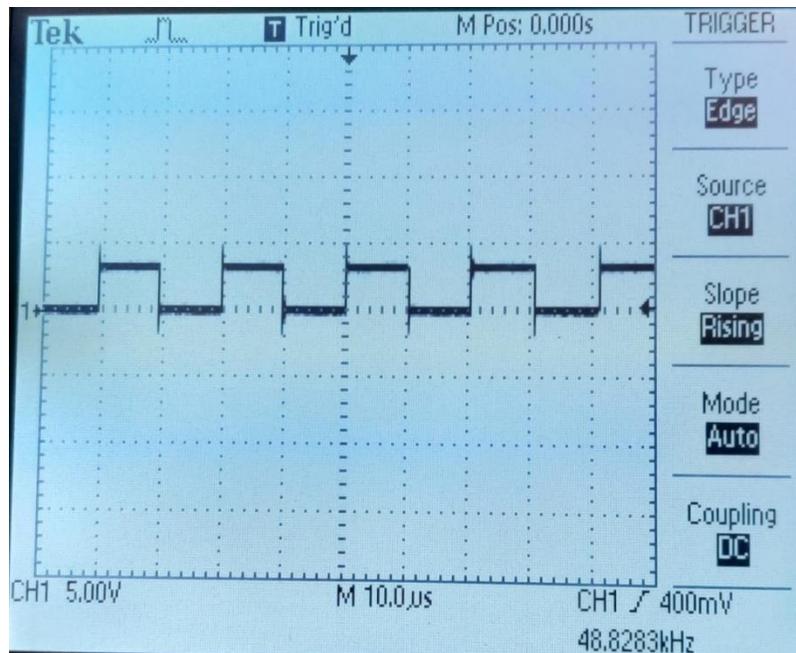


Figure 5.1: Analog pulses from the MSB of the DE-0 nano

The voltage and the frequency can be varied in the software by altering the program.

5.3 OUTPUTS FROM THE DIGITAL TO ANALOG CONVERSION CIRCUIT

By converting the digital signal to an analog signal, we get eight phase-shifted outputs that are 45° apart. The sinusoidal waves are shown below. For the waveforms shown below, we keep a constant channel of the oscilloscope and change the other channel and save the waveforms, so the phase difference between a fixed waveform is checked with the other seven waveforms, which gives the phase shift between each waveform.

Figure 5.2 shows the phase shift of 45° between two output waves. The waveforms are of frequency 12kHz and a peak-to-peak voltage of $5V_{p-p}$. These values are variable in the Verilog program and can be varied from 10-100kHz frequencies.

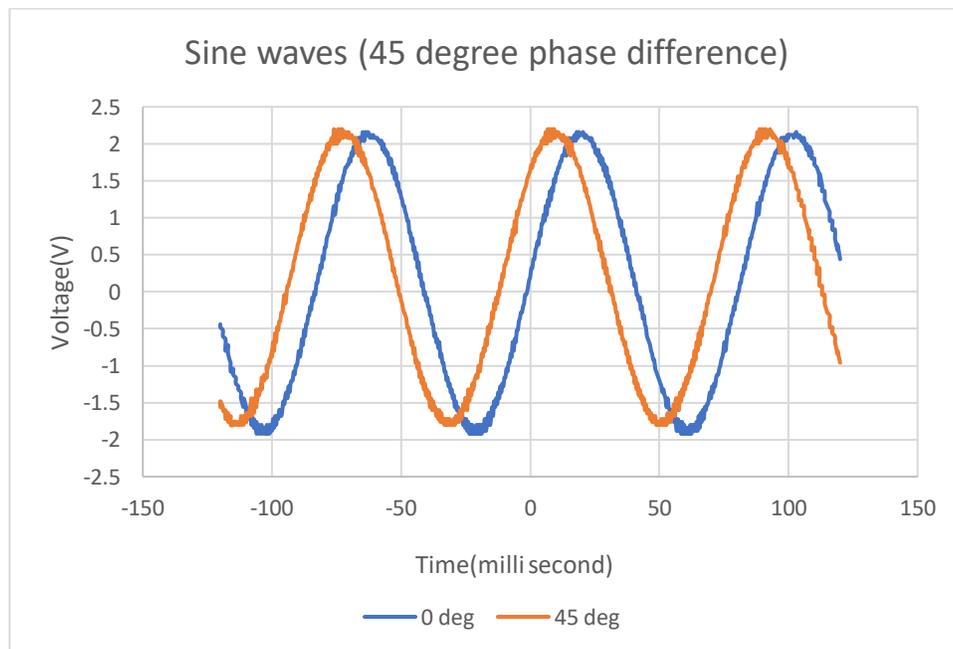


Figure 5.2: Sine waves with 45 degree phase difference

All the waveforms are recorded similarly, and graphs are plotted to check the phase difference between the sine waves. The complete set of sine waves with all eight waveforms is also plotted and is shown in Figure 5.3 below.

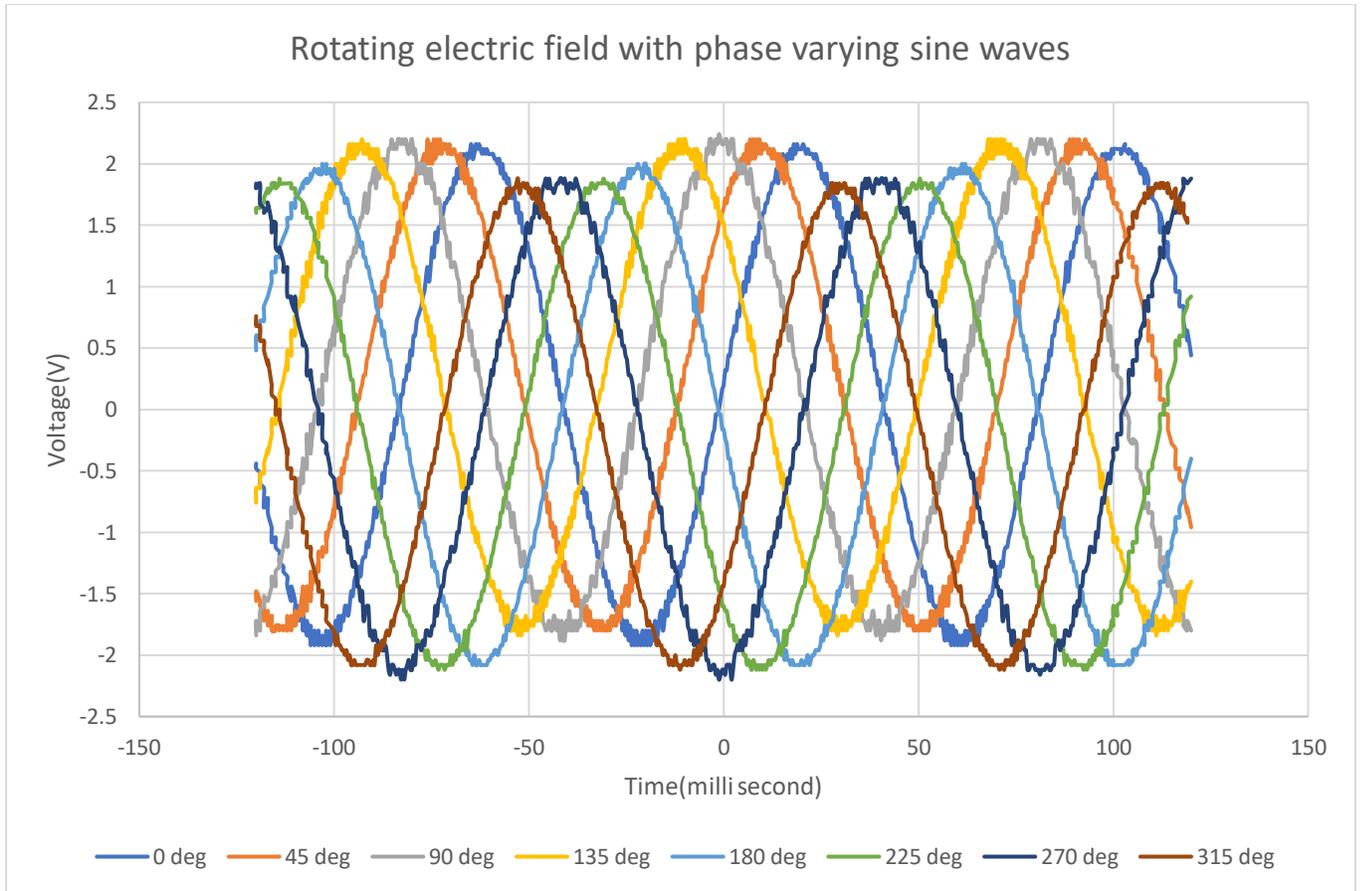


Figure 5.3: Rotating electric field

5.4 OUTPUT FROM POWER OPERATIONAL AMPLIFIER

The power operational amplifier circuit amplifies the input given to it based on the circuit's gain. The peak input voltage shown is $8V_p$, and then the $+V_s$ and $-V_s$ are given as $1kV$ and $-1kV$, respectively. The output from the amplifier circuit is $1600V_{p-p}$. A 1000:1 probe is used to record this waveform, and eight similar circuits generate eight such waveforms. All the eight waveforms are 45° apart, just as the results from the previous low voltage section.

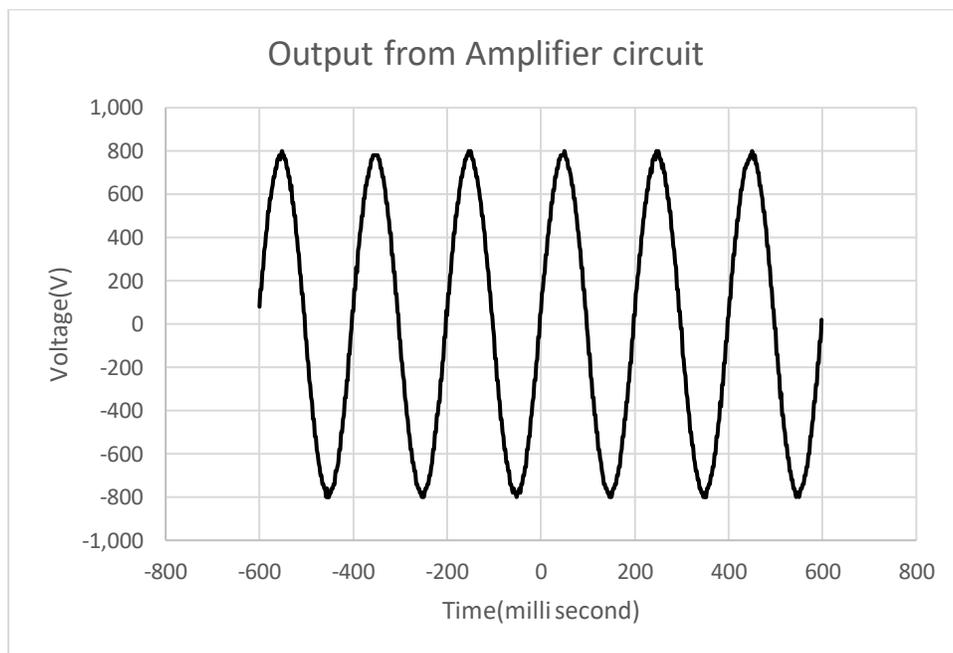


Figure 5.4: Amplified sinusoidal wave

5.5 DISCHARGE CHAMBER AND ELECTRODE SYSTEM

The 3D printed discharge chamber 1 is shown in Figure 3.5 (see Chapter 3). Discharge chamber 2 is shown in Figure 5.5 below.

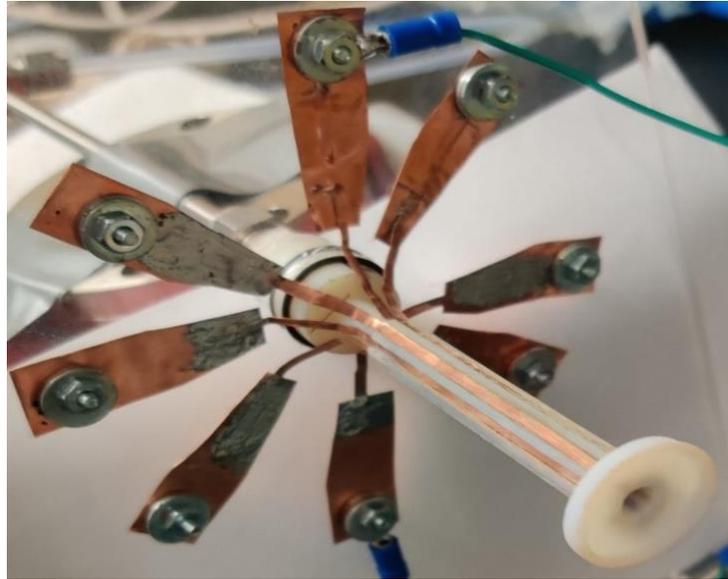


Figure 5.5: Discharge chamber 2

The discharge chamber shown in Figure 5.5 is used for testing plasma. For testing the plasma, I used a vacuum pump to pull out the vacuum. I could achieve a stable vacuum inside the discharge chamber by using a vacuum paste on the over-ring, which held the glass window. Now, I let helium gas inside the chamber and maintained a stable pressure of 3 to 4 torr. Next, I excited the electrodes to generate a plasma. I could not see any plasma in the chamber at $800V_p$ (refer Figure 5.4) at 5kHz frequency. The power supplies have a limitation of 1kV maximum voltage. Thus, I could not test the setup at higher voltages. Also, at higher frequencies, the output from the

PA99 amplifier started to slew (refer to section 2.7 for slew rate calculation). Another reason might be the material used to build the electrode assembly, as it was the only material available for 3D printing. We can use a different material of higher dielectric. If we get a higher range of power supply and increase the amplifier's gain, we will most likely achieve a discharge. A better vacuum would also help to operate at lower voltages. The new design should result in better vacuum handling.

CHAPTER 6

CONCLUSION

A multiphase voltage plasma source was designed and assembled for the generation of atmospheric pressure plasma. The design used an FPGA, which is programmed by Verilog to generate phase-shifted sinusoidal waveforms. This signal source can generate sinusoidal waveforms for varying magnitude in the frequency range of 10 to 100 kHz. A high-voltage amplifier is also designed by using a power operational amplifier which is used to amplify the multiphase voltages generated earlier. The power system was tested and characterized over the required operating parameters. Several discharge chambers were fabricated with 3-D printing to provide the necessary vacuum and hold the electrode assembly. This was tested for the desired vacuum and found to be adequate. Additional testing will be done in the future with proper high-voltage DC supplies. Thus, a working model is developed step by step in the laboratory.

Future work

To generate a plasma, a 3D model can be built with a different material with a less dielectric. Also, power supplies of higher ranges can be used to increase voltage across the electrodes. Further improvements can be made to change the amplitude and frequency of the voltages. The slew rate of the PA99 also limits the sinusoidal waveform which can be amplified from the circuit for higher voltages. We can use a step-up transformer to boost the output voltage. A better vacuum would also help to operate at lower voltages. The new electrode assembly design should account for better vacuum handling.

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APPENDIX A

The Printed Circuit Board etching procedure is explained below.

The materials required for wet etching are as follows:

- i. Pre-sensitized copper clad board
- ii. AZ400K developer solution
- iii. Ferric chloride
- iv. DI water
- v. Hot plate

Procedure:

- The circuits are designed in a computer program and are printed out on a transparent film.
- The boards used for wet etching are called positively sensitized photosensitive boards that have a thin film of the photosensitive coating.
- The etching is carried out in a yellow lighted room, which will not destroy the sensitive coating.
- The transparent film is kept on the photosensitive surface, and UV light is passed through it.
- Then a developer solution is used to develop the board. The developer solution used is AZ400K. The developer solution is diluted to a concentration of 1 part solution and 3 parts deionized water. The board is dipped in the solution and moved such that the solution reacts with the photo-sensitive film.
- The photo-sensitive film which was exposed to the UV light starts to dissolve, leaving behind the circuit on the board. The copper is exposed from all the parts except the circuit.

- Ferric chloride solution is heated on a hot plate at 50°C until fumes show up. The board is then dipped in the solution and moved slowly so that the solution reacts with the copper and eradicates it.
- The copper starts to come off from the sides of the board, and we can see the entire plastic of the printed circuit board.
- The circuit is safe under the photo-sensitive film. The copper dissolves entirely, and just the circuit remains.
- The board is then removed from the ferric chloride solution and washed with tap water.
- The board is then dipped in a concentrated AZ400K developer solution to reveal the circuit.
- Then, the holes are drilled to insert the components, which are then soldered on the board.

APPENDIX B

The 3D designing procedure for electrode assembly is as follows:

- The measurements for the model are noted, and a single 2D profile of the model is drawn in Autodesk Inventor.
- The revolve command is used to revolve the 2D profile, which forms a cylinder of the desired design.
- Then, a hole of required diameter is made by extruding the 2D sketch of a circle and is used to insert the gas and vacuum pipe.
- A groove is designed on the outer surface of the cylinder. The groove is 2D drawn using a 45° line as a reference and then lines of angles 35°, 41°, 49°, and 55° for a 'T' shaped groove for holding the copper electrodes.
- These grooves are replicated using a circular command. Eight grooves are created.
- These grooves are extruded throughout the length of the cylinder.
- The length of the completed design can be varied by varying the 2D sketch drawn at the beginning of the design.
- The design is saved in Autodesk Inventor format.
- The design is exported in STL format and is sent for 3D printing.

APPENDIX C

The process for creating a New Library in Autodesk Eagle is described below.

As the Autodesk Eagle does not contain the libraries of all the components used, we need to create our own libraries for the equipment which are unavailable in the software.

Steps to create a new library:

- Click on File, New, and Library.
- First create a symbol for the equipment by clicking the edit a symbol button, naming the symbol, and confirming it.
- Draw a symbol shape as the equipment is seen.
- Draw pins by selecting a draw pin button.
- Name pins per the circuit diagram of the given equipment.
- Now, the symbol is completed. Move forward to the package.
- Name specific pins as input and output pins based on the pin diagram.
- Click the edit symbol button and name it accordingly.
- Draw the package by considering the measurements given in the datasheet.
- The package is drawn, and the pins are placed. The pins are named accordingly.
- Now, link the symbol to the package by clicking the edit a device button. Then name the device and confirm it.
- Now select the symbol created earlier and place it so the center is on the origin.
- Add a package to the device in this step by selecting a new button and selecting the package already created.
- Click the same pins in the symbol and package and hit connect. Save for further use.

APPENDIX D

Miscellaneous equipment used during the research:

- Positive power supply of range 100V to 1kV,
- Negative power supply of range -100V to -5kV,
- High voltage 1000:1 probes,
- Helium gas cylinder,
- Vacuum pump (Franklin Electric),
- Oscilloscope,
- DC supply ($\pm 25\text{V}$).

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