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Optimum Antenna Design for Microplasma Generation

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Abstract

In the last decade, there has been an increased interest in microplasma properties and applications. Microplasmas have been considered for use in plasma thrusters, displays, and sensors. Microplasmas are small scale plasmas which are typically generated with radio frequency power sources. The small scale of the microplasma requires equally small antennas. The sizing difference can cause difficulties in proper impedance matching for power deposition from the radio. To address this issue, different radio frequency antenna designs were investigated to generate microplasma within a glass capillary tube at the University of Alabama in Huntsville's Johnson Research Center. The experiment setup uses a multi-frequency radio, high power amplifier, and T-type matching network. The test antennas were attached to the output to provide the radio signal to the atmospheric gas inside the glass tube.

The test antenna design variations include dipole and monopole configurations. Antenna materials varied in the investigation. Copper and steel wires of various gages were used to form different length coils to surround the gas tube. Shield and pin antenna designs were also explored.

The standing wave ratio is used to determine the antenna's effectiveness. A low standing wave ratio value, close to 1, indicates a low voltage is reflected back to the source and the antenna has the most power being directed to microplasma generation. The best antenna designs were determined based on microplasma production and standing wave ratio value. The shield and pin antenna design successfully generated a microplasma. This result is consistent with the use of copper and stainless steel shields and a 4-40 threaded pin. The shield and pin design is the most successful because it directs the radio frequency consistently to the pin without any loss that may found in a helix design. The central pin acts as a sacrificial surface for the microplasma to generate from.

I. INTRODUCTION

Microplasmas are small scale plasmas; at least one dimension of the geometry is in millimeter range [1]. These small scale plasmas have different characteristics than larger volume plasmas. The amount of power required to generate microplasma is less than larger volume plasma. This is because the number of molecules that need to be excited in a smaller volume is lower. Microplasmas have lower plasma densities since the microplasma has a lower density of ions and electrons. Larger volume plasmas are in vacuum conditions, whereas microplasmas can be generated at atmospheric conditions. These characteristic differences cause the microplasma to need specific conditions to generate and maintain a discharge. There is increased interest in microplasmas for a variety of applications such as plasma thrusters [2] and super smooth surface polishing in microelectronics [3].

A major advantage of microplasmas is that they can be generated at atmospheric conditions. The plasma is typically generated within the confines of a small millimeter scale cylinder. The cylinder constrains the plasma to a small geometry and allows introduction of different working mediums. Ceramic and silicon devices have been used for millimeter scale geometries [4]. The plasma can be generated using a radio frequency (RF) source [5]. To energize the air with the RF transmission, an antenna must be created that directs the RF power to the working medium efficiently. The antenna design will directly affect the plasma generation.

The scale of the microplasma requires an equally small scale antenna connected to the RF transmitter. Because the antenna size is small, the proper impedance match from the power transmission can be a challenge. This work investigates different antenna designs to determine the geometry necessary for efficient matching to the power system.

II. EXPERIMENTAL SETUP

The approach for this investigation was empirical data acquisition and observation. Figure 1 illustrates the experimental system layout used in this work. The system is comprised of a DC power supply, an RF source operating at 14 MHz, an RF signal amplifier capable of 1 kW output power, a digital wattmeter to measure the SWR, a T-type matching network, and the test antennas.

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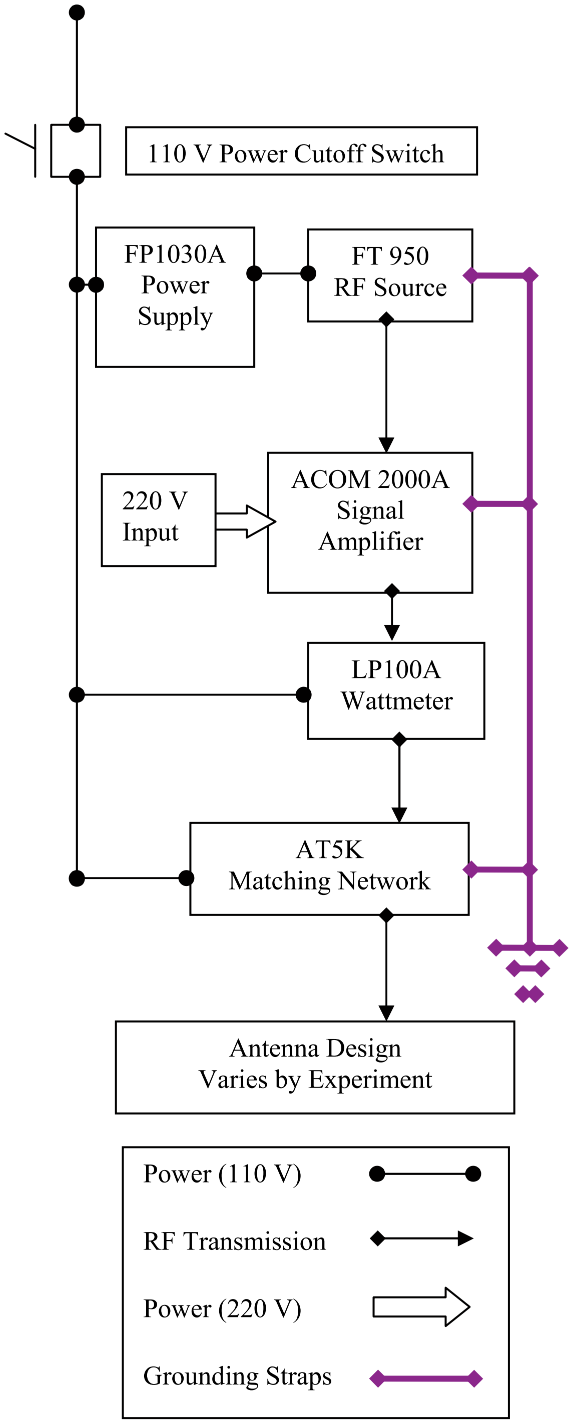


Figure 1. RF system layout and legend.

The LP100A wattmeter measures the SWR value and displays it for the researchers. The researchers attempt to balance an antenna by adjusting the capacitance and inductance values on the AT5K matching network. There are two capacitors that adjust the resistance in the RF system. The inductance has a range of values from 0 to 229.

The antenna is enclosed in a polycarbonate containment to prevent any possible glass fractures from leaving the test site during RF transmission. The polycarbonate is 1/2" thick and clear on the top and side to allow for experimental viewing. The polycarbonate containment is surrounded by a steel mesh cage that is grounded to minimize the projected RF effects from the antenna. The cage reduces the RF waves and a RF meter is used to record the RF levels during testing.

III. RESULTS AND DISCUSSION

When the radio wave is transmitted through the antenna, the molecules of the gas within the tube should excite enough to generate microplasma. The difficulty lies in designing an antenna that is a good match for the size scale and medium. The standing wave ratio (SWR) is the value that determines if an antenna has a good match to the system. The SWR is the ratio of the amplitude of a partial standing wave at an antinode to the amplitude of an adjacent node in a transmission line [6]. The antinode position is the maximum value and the adjacent node is a minimum value. Often, the SWR is defined as a voltage ratio [6]. The SWR is used to measure efficiency of a transmission. When there is an impedance mismatch in the cables, radio waves can be reflected back toward the source. The reflection prevents all of the power from being transmitted to the load.

In these experiments, the antenna is the transmitter for the RF power. The goal is to have all of the RF transmission directed to the gas and plasma mediums. When the SWR value indicates reflection, not all of the power is directed to the antenna or the microplasma. The SWR value should be low; very close to 1.0. This is because the SWR measures the degree of mismatch between the load and the transmission line's characteristic impedance [7]. The value of 1.0 is measured when reflection in the transmission line does not occur. The equation for SWR (Eq. 1) is given in terms of forward RF power (P_F) and reflected RF power (P_R).

$$SWR = \frac{\sqrt{P_F}+\sqrt{P_R}}{\sqrt{P_F}-\sqrt{P_R}} \tag{1}$$

The main variable tested was the antenna. Antenna designs that vary in material or shape will have different starting SWR values. Each antenna is calibrated to the system so that its SWR is close to 1.

In the experiment, each antenna is attached to the RF transmitter and matching network to transfer RF power to a glass capillary tube with outer diameter (OD) 0.25 inches and inner diameter (ID) approximately 0.125 inches. Table 1 shows the antenna designs that were tested. In the table, Cu refers to copper; SS, stainless steel.

Table 1. Antenna design testing matrix.

Antenna Design	Material	Dimensions	Number of Turns	Notes
1. Coil	Cu	20 gage, 1/2" ID	25	
2. Shield & Pin	SS & Steel	1/4" Tubing, 1" long & 1/4" 4-40 Thread		Shield at Pin End
3. Coil & Pin	Cu & Steel	20 gage, 1/2" ID & 1/4", 4-40 Thread	25	
4. Coil & Pin	SS & Steel	0.064", 1/2" ID	25	
5. Dual 1/4" Coil & Pin	SS & Steel	0.032", 1/4" ID each	4 Per Terminal	Vary Distance
6. Dual 1/2" Coil & Pin	SS & Steel	0.064", 1/2" ID each	4 Per Terminal	Vary Distance
7. Shield & Pin	SS & Steel	1/4" ID Tubing, 1.5" long & 1/4" 4-40 Thread		
8. Shield & Pin	Cu & Steel	0.342" ID Tubing, 1.5" long & 1/4" 4-40 Thread		

Coil antenna designs were fabricated using a threaded rod for guidance. The threading allowed the wire to be bent and maintain a consistent helix (Fig. 3).

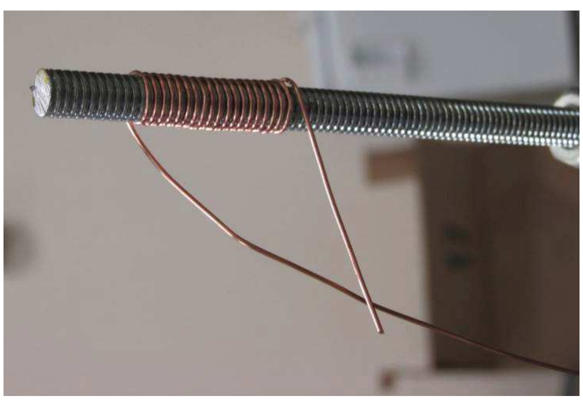
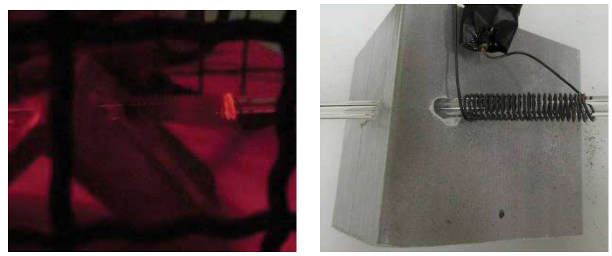


Figure 3. Coil antenna fabrication.

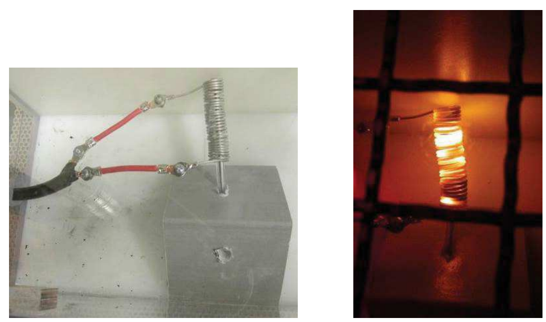
Antenna design 1, a 14 gage copper coil, was tested in the microplasma setup (Table 1). The tests failed to generate plasma; however, the antenna showed signs of resistive heating. The resistive heating is evidence that the antenna experienced power transmission. The single coil heated and turned red when power was transmitted (Fig. 4a). After the test, the surface copper was oxidized by the heat and turned black (Fig. 4b).



(a) (b)

Figure 4. (a) Antenna design 1 during RF power transmission exhibits glow due to resistive heating. (b) Antenna design 1 after RF power transmission.

It is plausible that the single coil antenna design does not act as an antenna since the wire directly connects the dipole ends of the transmitter. The coil may be acting as a resistor and the power is directed in a closed circuit. The other designs, dual coil, coil and pin, and shield and pin, have spacing between the dipole ends. These designs were tested since the spacing would allow the power to be projected from one pole to the other through the glass capillary tube. This would direct the power from the antenna to the air in the tube to directly excite the molecules and generate a microplasma plume. The coil and pin design, design 4 from Table 1, exhibited similar results to the coil antenna (Fig. 5).



(a) (b)

Figure 5. Stainless steel coil with pin in glass capillary tube.

The dual coil design did not yield an SWR value low enough to be considered a match when the coils were not touching. As the distance between the coils decreased, the SWR value was able to decrease; however, it was not low enough for amplified operation until the coils were touching. When the two coils were in contact, the result was resistive heating.

Antenna designs 7 and 8 (Table 1) are shield and pin designs. The shield and pin design generated a microplasma. The pin acts as a sacrificial medium to begin the plasma plume. This design allows consistent distance between the dipole ends and equal power in all directions. Both the copper and stainless steel shield and pin designs had successful microplasma generation (Figs. 6, 7).

Figure 6. Stainless steel shield and pin ignition at 440 W.

Figure 7. Copper shield and pin ignition at 600 W.

The stainless steel shield and pin design ignited at 440 W. The plume was maintained for over 30 seconds before the SWR value increased. The plume was maintained with approximately 5 W of output on the transceiver; approximately 150W after amplification.

The copper shield and pin design ignited at 600 W. The plume was initially blue and then changed to the white glow seen in Fig. 7. This plume was maintained for 3 seconds before the SWR increased. The copper shield is constructed from a copper tube that had a larger diameter than the stainless steel tube. The copper tube had a 0.342" ID; the stainless steel, 0.26". The shield lengths also varied slightly with the material. The copper shield measured 1.687" long. The stainless steel shield length measured 1.587".

The quick increase in SWR value at amplified operation indicates there is a change in resistance when the medium changes. The initial state is atmospheric air between the antenna diodes. Neutral air is a dielectric medium, thus RF waves pass through without difficulty. Plasma, on the other hand, is a conducting medium that acts as impedance for RF signals. Thus when a plasma forms, the RF transmission must travel through a new medium. The increased SWR indicates high impedance in the plasma.

The results of the microplasma plume were physical. The sacrificial pin showed signs of wear and the glass tube melted at the point of the pin end (Fig. 8).

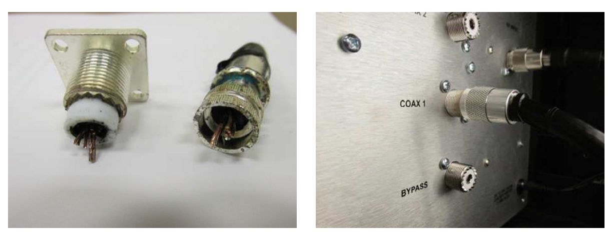
Figure 8. Pin and glass after plasma ignition using the Stainless Steel shield and pin antenna design.

This means the largest amount of power from the plasma plume is at the end of the pin.

The cable and connections used in this experiment are important to the system's behavior. The cable used to carry the RF signal is on the same scale as the antenna and probe (Fig. 9).

Figure 9. Cable, antenna and glass capillary tube sizes.

Since the cable is on the same scale, the connectors will be closely sized to the antenna. Due to the close geometry, the connectors can act as points of matching before the RF signal reaches the antenna. Arcing can be heard when a connector fails due to SWR matching. When this occurs, the connectors may melt or re-solder to the transmitter (Fig. 10).



(a) (b)

Figure 10. (a) Coaxial cable connector after power sent to a connection. (b) Coaxial cable re-soldered to the matching network after RF transmission.

An indication that the connector matched was the impedance value. The impedance value would be around 212 when a connector was matched in the RF system. To remedy the connectors matching instead of the antenna, researchers removed any nonessential connectors. This included a female-female connector that allowed for connection between the matching network and antenna design in polycarbonate containment (Fig. 11).


(a) (b)

Figure 11. (a) Polycarbonate containment with and female-female connection. (b) Dipole connectors for inside the polycarbonate containment to connect female-female connector to antenna design.

The copper and stainless shield antennas had higher impedance values (~214 and 218, respectively). When the SWR is set at non-amplified operation, the RF signal will be very low, around 200 mV, behind the antenna. When a RF meter is moved to the antenna the RF signal increases to above 1000 mV. This is a physical check that the RF transmission is focused in the right area on the glass capillary tube.

IV. CONCLUSION

The results of these investigations are a promising start to the continued research of microplasmas. Two microplasma plumes were ignited at 440W and 600W using shield and pin antenna designs. These power values are well below the maximum power the system can provide. This means that the system is sufficient to carryout microplasma generation.

With the number of tests completed, patterns emerged to assist the researchers. The impedance values are indicators of how well the system will perform. High impedance values like 214 and 218 are desired instead of 212, which may indicate a transmission to a connector instead of the antenna.

Further testing will determine if other materials work better for an antenna. A gas flow will also be introduced in the system to allow cooling and a flow to direct the product. The cooling effects will allow a steady and sustainable microplasma generation. The steady flow of microplasma can then be used for other applications like microelectronics manufacturing.

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