AIAA 2016-0197

AIAA SciTech
4-8 January 2016, San Diego, California, USA
54th AIAA Aerospace Sciences Meeting

Direct Position Control of Dielectric Barrier Discharge Filaments

Matthew C. Paliwoda[*], Joshua L. Rovey[†], and Mitchell Wainwright[+]
Missouri University of Science and Technology, Rolla, Missouri 65409

Controllable patterns of plasma filaments are being explored for reconfigurable metamaterial applications. When operated in a filamentary mode, volume dielectric barrier discharges are known to produce patterns of self-organizing plasma filaments. In this work the presence and intensity of a single filament at a fixed location is controlled by an isolated and independently electrically adjusted needle electrode. Time-averaged normalized light intensity, current, and voltage are measured while varying the voltage of the needle through a self-biasing resistance. For a 7.5 kV, 3.2 kHz DBD, the needle-controlled filament discharges similar to adjacent filaments at low potentials but stops discharging at a maximum potential of 560 V. Control of the needle-controlled filament intensity is demonstrated by making voltage changes over the range of 7% of the driving voltage. The required potential difference for fully turning on and off the filament is 100 V, and is not affected by the applied DBD driving voltage.

I. Introduction

VOLUME filamentary dielectric barrier discharges (DBDs) have shown the ability to construct plasma-based metamaterials for manipulating electromagnetic waves.[1] Metamaterials are periodic microstructures that exhibit properties on the macroscale not found in natural materials. Solid metamaterials have been shown to possess the properties of negative permeability, negative permittivity, and negative index of refraction.[2] Potential applications for materials with these unique properties include wave guides, antennas, and perfect lenses.[3,4]. The plasma based metamaterial, with a microstructure formed by periodically spaced plasma filaments, possesses additional benefits due to its dynamic structure which can be modified during operation and plasma density gradients that widen the frequency band.

The position of the filaments - a major parameter for the design of microstructures with macroscale properties[5] - has previously been electrically controlled by varying driving frequency and voltage in self-organized filament discharges.[6] The plasma's electron frequency which governs the plasma columns' permittivity, is also controlled by the power of the DBD.[1] In addition, variations in voltage and frequency affect the individual size of the plasma filaments.

The work presented here attempts to control an individual filament, independent of the driving signal and surrounding filaments. An insulated needle passing through a gap in a wire mesh that serves as the DBD's grounded electrode directs current through the dielectric at the needle's location, initiating a selective filament discharge in the gas gap. The mesh initiates filaments at a fixed distance and in close proximity to the needle's filament. The needle filament's discharge is then controlled independent of the surrounding filaments by limiting the current through the needle. Wire mesh electrodes have been used to preferentially discharge filaments at the mesh nodes.[7] Height variations of the mesh due to wire intertwining create the shortest distance to the opposite electrode enhancing the local electric field.

Volume dielectric barrier discharges (DBD) consist of two parallel surface electrodes with a dielectric barrier and a gas gap in between. An applied electric field between the plates, sufficient to cause gas ionization, forms a plasma discharge between these plates. The relevant DBD has a dielectric on both electrodes, and operates on an AC voltage creating discharges during the positive and negative voltage rises. The applicable form of DBD is

---

[*] Graduate Research Assistant, Department of Mechanical and Aerospace Engineering, 160 Toomey Hall, 400 West 13th Street, Student Member AIAA.

[†] Associate Professor of Aerospace Engineering, 292D Toomey Hall, 400 West 13th Street, Associate Fellow AIAA.

[+] Undergraduate Research Assistant, Department of Mechanical and Aerospace Engineering, 160 Toomey Hall, 400 West 13th Street filamentary, compared to the uniform discharge, since it creates a microstructure forming the metamaterial. The role of the dielectric is to collect charge transferred by the filament.

The characteristics of a filamentary discharge are governed by the charge build up on the dielectric surface and the space charges during operation.[8] After the initial discharge, restrikes preferentially occur in the same location since both space and surface charge from the previous filament increase the electric field across the gas gap.[9] Due to the requirement for charge to initiate and sustain a current, the location and number of discharges are limited by the surface charge.[10]

The following sections describe an experiment wherein we demonstrate control of a DBD filament with an independently electrically controlled needle electrode. Adjusting the potential of the needle through a self-biasing resistor controls the presence and intensity of the filament. The following sections describe the experimental setup, results, analysis, and conclusions.

II. Experimental Setup

A. Volume DBD Physical and Electrical Setup

The DBD investigated in this work consists of two parallel copper mesh electrodes, both covered with glass ($\varepsilon = 3.5$). The driving signal mesh electrode allows for end on photos of the filament position across the surface of the dielectric surface. The mesh and dielectric barrier of the driving electrode are of dimensions that create a uniform charge distribution over the discharging surface: 0.15 mm opening (#100 mesh size), 0.056 mm wire diameter, and 1.0 mm thick dielectric[7,11] The grounded mesh electrode has an opening of 0.85mm (#20 mesh size), a 0.40 mm diameter wire, and a dielectric barrier thickness of 0.12 mm. The larger mesh size and thinner dielectric barrier is sufficient to create an electric field on the surface of the grounded dielectric barrier that causes a spatial variation filaments preferentially discharging at the mesh nodes.

The DBD is mounted on an ABS plastic stand with acme screws on the side to permit fine gap width adjustment. The air gap between the two plates is set at 1.0 mm. The mesh electrodes and dielectric cover a 22 mm by 22 mm area. Adhesive gel on the edge of the mesh prevents charge from making a direct path to the electrodes and thus ensuring the current path through the dielectric. A photograph of the DBD is shown in Figure 1. The DBD is operated at 6.5 kV and 7.5 kV at 3.2 kHz.

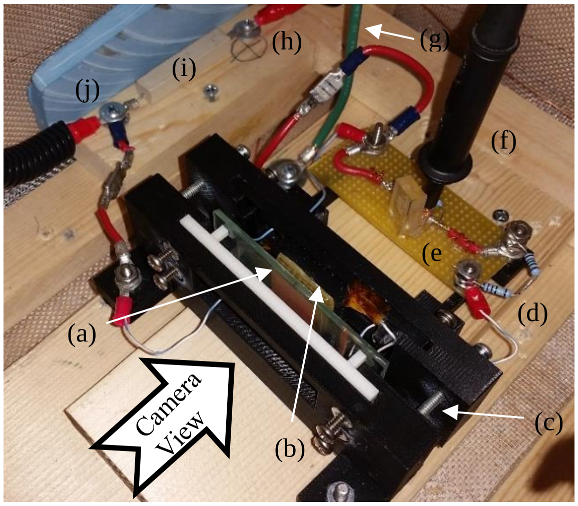


Figure 1: Photograph of DBD setup. ***The DBD consists of two parallel glass plates back with (a) powered electrode and (b) grounded electrode. The air gap is controlled by (c) acme screw. Current limited by resistors (d) is measured by the 10:1 voltage probe (f) and 200kΩ resistor (e). Both grounded electrode and the voltage divider reference from the ground lead (g). Current supplied from the transformer (k) is limited by a 5.9kΩ resistor (g) to protect the transformer. The lead from the high voltage probe (i) measures voltage across the DBD.***

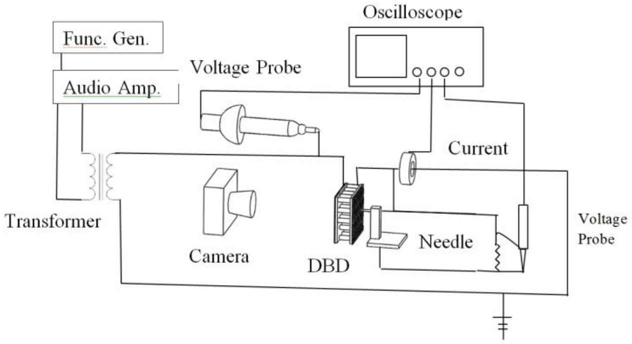


Figure 2: Diagram of experimental set up.

A Canon EOS Rebel XL records the time-averaged discharge of the filament position and light intensity at an exposure time of 125 seconds. As shown in Figure 2, the driving voltage signal is created by a Rigol DG-1022 Function Generator, the power is supplied by a Crown Macro-Tech 1202 Audio Amplifier, and a Corona Magnetics 5525-2 Transformer with a turn ratio of 1:357 increases the voltage signal, producing a maximum voltage of 25 kV with a frequency range of 0.9 – 5 kHz. A North Star PVM-5 High Voltage Probe with a 1:1000 ratio monitors the voltage supplied to the DBD. A 1:1 Pearson Current Probe, Model 114 monitors the current through the system. A 1:10 Tektronix P2221 passive voltage probe reads the voltage across a 100kohm resistor in series with the larger resistor controlling the voltage at the positioned needle. Both the Pearson and the North Star Probes are read from an Agilent Infinium 500MHz 1GSa/s Model #54815A Oscilloscope.

B. Needle Electrode Setup

An independently electrically controlled needle is used to control the presence and intensity of a plasma filament within the DBD. The needle and its electrical setup are shown in Figure 1 and Figure 2. The needle is constructed from a magnetic wire whose flattened tip is flush to the back surface of the grounded dielectric barrier. The wire (diameter 0.57 mm) with an added Kapton insulation layer (0.14 mm thickness, $\varepsilon = 3.5$) is centered between the mesh, so that the only electrical connections between the two are through the dielectric or their respective lead wires. Resistors connect the needle to ground causing the needle to have a non-zero floating potential or self-biasing potential. By adjusting the resistance, the self-biasing potential of the needle can be adjusted.

III. Results

The following section presents the results from needle-controlled filament tests in the DBD. In cases the DBD has 1mm gas gap, the voltage is set at 6.5 kV or 7.5 kV and a driving frequency of 3.2 kHz. When the DBD is set at 1.5mm air gap, the DBD is set to 9kV with the same driving frequency. The driving voltage waveform is a sinusoid. Results are shown below for different DBD voltage, different needle electrode self-biasing resistance, surface cleansing, and gas gap. Resistances from 100 kΩ up to 10 MΩ were investigated.

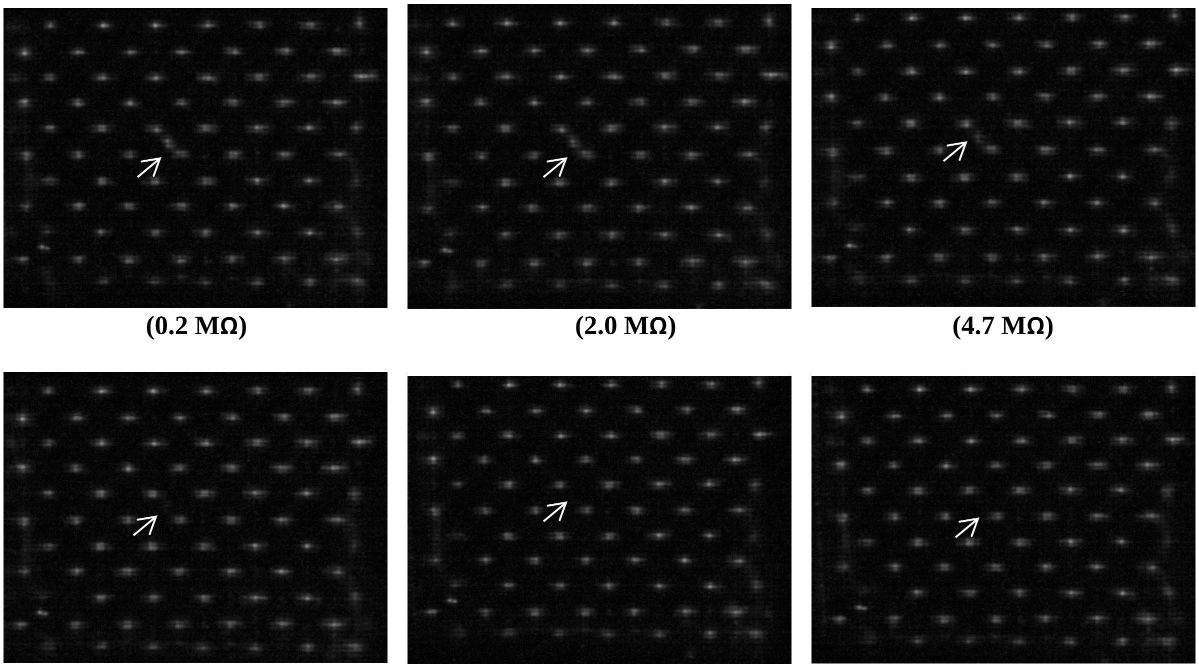
A. Filament Photographs

Photographs of the DBD filaments for different self-biasing needle resistances are shown in Figure 3. These data are for the 6.5 kV DBD driving voltage. The regular pattern of dots are individual DBD plasma filaments. The filaments form at alternating nodes over the grounded wire mesh electrode since the meshes horizontal wires are slightly below the mesh surface plane. For resistances below 4.7 MΩ a filament clearly forms in between the wire mesh nodes at the needle location. As the needle self-biasing resistance increases the filament light intensity decreases. It is clear from these photographs that the independently electrically controlled needle can control both the presence and intensity of the new filament. Resistances below 200 kΩ was investigated with a 1kΩ resistor however, prominent current spikes reduce the reliability of the measurement. Resistances above 30 MΩ were not investigated because the data showed further increases had no effect on the discharge and filaments.

To get a better measure of the intensity change of the needle-controlled filament, a photographic analysis was done. Specifically the numerical value of the photograph pixel at the needle-controlled filament location was compared with the pixel value for a DBD filament and for a region with no filament (i.e., the mid-point **between** two DBD filaments). A standard square section of the photograph, fitting the size of the filament, was selected using Photoshop software then the average luminosity value of the area was used as the numerical value. The same size square section was used to select the numerical value of a region with no filament and a mesh node filament. In this way the intensity of the needle-controlled filament is compared with a DBD filament and also a region with no plasma filament.

Figure 4, shows the results as the ratio of needle filament to DBD filament and the ratio of needle filament to mid-point for both 6.5kV and 7.5kV. The light intensities of both the mesh node filament and the mesh gap are constant relative to their respective photos. The needle-controlled filament has a distinct on and off state. For resistances below 15 MΩ the ratio of the needle-filament to the mid-point goes to one, signifying that the light intensity is the same as a mid-point no filament region. The needle-filament is off. As resistance decreases, the needle-filament turns on and becomes more intense as resistance decreases. At the lowest resistance tested, 1kΩ, the needle-filament has an intensity that remains at 80% the intensity of the DBD filaments at the mesh nodes and 6 to 8 times brighter than the background mid-point region where no filaments are present for 6.5kV and 7.5kV.

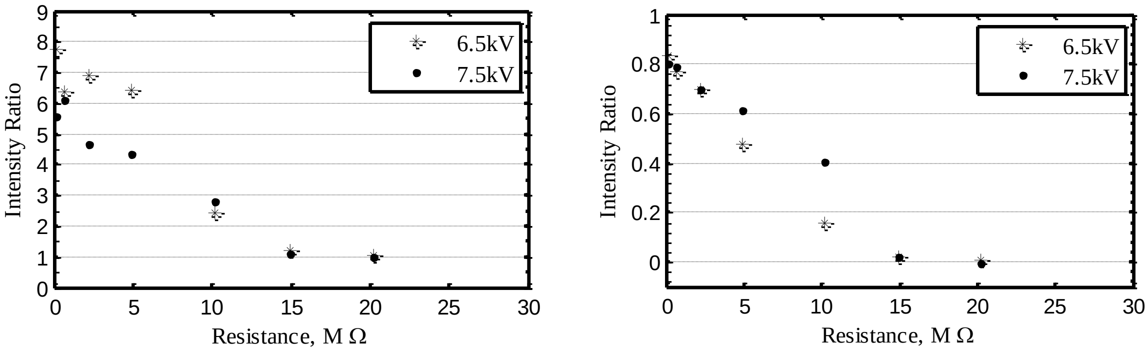
At 1kOhms, the needle filament is still less than the surrounding node filaments. Since the needle filament is surrounded by two other node filaments, it competes for surface charge with these nodes. If the needle filament was not surrounded by two other filaments it’s ratio would raise to near 1 at 1kΩ resistance. As the resistance increases, the filament eventually stops discharging. At this point the ratio of the needle filament to the non-discharging midpoint is 1:1 and the ratio to the surrounding filaments goes to zero, since the background light is subtracted from both values in this ratio. Assuming there is no discharge in the mesh gap, this ratio signifies that no discharge occurs at the needle’s position. The measured luminosity in the regions without filaments is due to reflections from the backing supporting the mesh electrode, keeping the mesh flush against the glass surface. The camera’s photos also have an inherent background light value that contributes to the intensity.



(0.2 MΩ) **(2.0 MΩ)** **(4.7 MΩ)**

(10 MΩ) **(15 MΩ)** **(20 MΩ)**

Figure 3: Photographs of the filament at the needle: on and off. ***End on view of the dielectric surface operating at 6 kV with a 0.1 MΩ resistor (left) and a 3.5 MΩ resistor (right) between the needle and ground reference. The arrow indicates the needle position.***



(a) **(b)**

Figure 4: Light intensity as a function of resistance at 6.5kV and 7.5kV. ***Light intensity at the needle position,(a) as a ratio to the light intensity of a mesh gap midpoint, and (b)as a ratio to a mesh node filament.***

B. Needle Current and Voltage

Adjusting the needle self-biasing resistance affects the needle voltage and current. These results are shown in Figure 5. The effect on voltage is shown in Figure 5A. The voltage at the needle does not rise linearly as it begins to curve with increased resistance. Although the voltage appears as though it may approach a limit the point of interest, where the filament at the needle ceases to discharge, is met before any definitive evidence of a limit. The voltage for the turn off of the filament positioned at the needle for the 6.5kV and 7.5kV is 476V and 560V respectively. Both of these values correspond to 7% of the voltage across the DBD. The difference between the observed on and off state, 10MΩ to 15MΩ, is 108V and 119V.

The external voltage suppression caused by the resistor at the 7.5 kV driving voltage is not large enough to bring the voltage difference across the DBD, at the needle, to the level of the 6.5 kV driving discharge. This implies the discharge is not purely a result of reducing the voltage difference, but rather preferential discharge at peak locations and there is a minimum difference in peak locations where the needle filament will still discharge. More complex surface charge dynamics are responsible for these results.

The current through the needle is shown in Figure 5B. The current decreases linearly with resistance. Although current continues to pass through the needle, the amount of charge that is allowed to displace on the surface is below a minimum value necessary for a filament to form. The current plot dips at 200kΩ and then spikes to 80microAmps at 1kΩ.

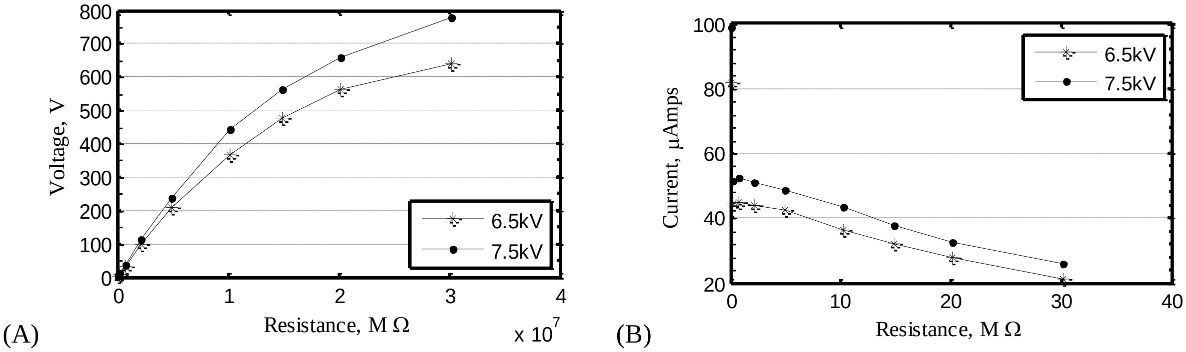
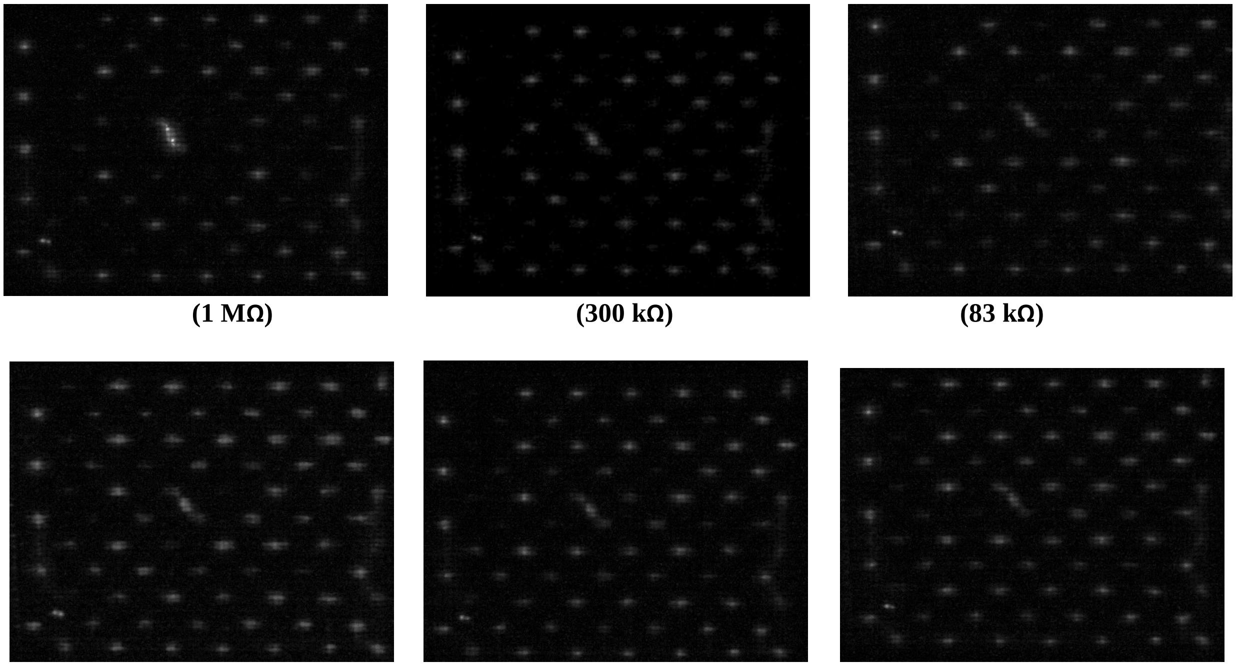


Figure 5: Effect of changing self-biasing resistance on the needle (A) voltage and (B) current.

C. Increased Filament Intensity

Figure 6 shows the resulting filament changes from reversing the self-biasing process. The needle lead wire is attached directly to the ground reference and increasing loads are applied between the mesh electrode and the ground. The preference for discharge is now switched to the needle with increasing voltage. Although the resistance load is applied to the majority of the circuit, the 1MΩ only creates a 3% voltage decrease applied to the 3.1pF DBD. As the potential on the mesh increases, the lower potential at the needle draws more charge from the surrounding surface. The reduction in available surface charge decreases the intensity of the surrounding filaments until all the mesh node filaments that are one mesh gap distance away from the needle position have an intensity less than twice the mid-mesh intensity. The two mesh nodes adjacent to the filament also reduce in intensity however at 1MΩ there are two bright spots located between the needle and these mesh nodes. Resistances beyond 1MΩ were not investigated since current discharges of amps in magnitude suggested a transition of away from the preferred filament discharge to an arc that would damage the set up.

The intensity of the needle filament rises to 173% of the unaffected filaments. Due to the interaction with more than 10 surrounding filaments, the intensity of the needle filament holds less consistently than the self-biased needle intensity values in Figure 4: Light intensity as a function of resistance at 6.5kV and 7.5kV. *Light intensity at the needle position,(a) as a ratio to the light intensity of a mesh gap midpoint, and (b)as a ratio to a mesh node filament.*. The change observed in with the self-biased mesh occurs over a logarithmic space where orders of magnitude larger resistances are required to increase the intensity of the needle positioned filament. The maximum voltage, created by the 1MΩ resistance, was measured as 470V, a similar change in magnitude to the self-biased needle for an intensity change of 80% of the mesh node filaments.



(1 MΩ) **(300 kΩ)** **(83 kΩ)**

(18.3 kΩ) **(3 kΩ)** **(300 Ω)**

Figure 6: Photographs of the decreasing filaments surrounding the needle position. ***End on view of the dielectric surface operating at 7 kV with increasing resistances between the mesh electrode and ground reference. Surrounding turn off with while the needle filament intensity grows.***

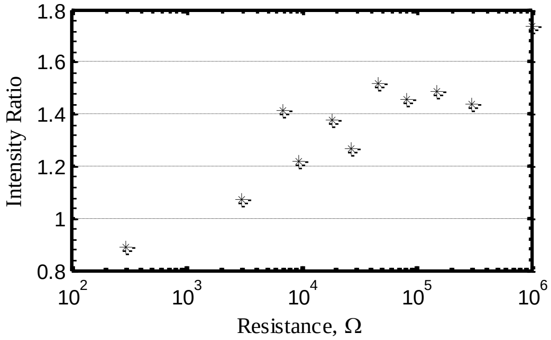
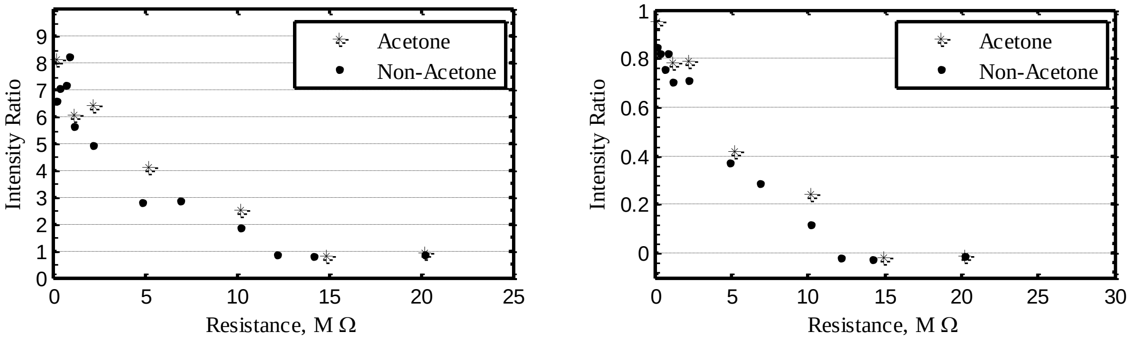


Figure 7: Light intensity as a function of resistance for a self-biased mesh. ***Light intensity at the needle position as a ratio to a filament two mesh gap distances outside the affected decreasing intensity area.***

D. Effect of Residual Charge

Charge build up on a DBD affects the charge transfer of a DBD.**Error! Bookmark not defined.** To analyze this effect on the filament's turn off voltage, the dielectric surface was wiped while replicating selected points of the 1.5mm 18kV gap data set. The acetone was applied to a Kimwipe over a razor blade to fit between the dielectric gap then both surfaces were wiped prior to discharging. A high breakdown voltage was noted while investigating this aspect. To replicate the previous conditions, the voltage was increased to breakdown by turning the amplifier nob up one notch to 10kV then reducing back to 9kV.

Figure 8b, shows an increase of 5MΩ in resistance for the acetone data before the needle filament turns off. The acetone treatment also increases the light intensity of the filament above the background intensity of the mesh gaps, Figure 8b. Although elevated in magnitude, the trend of the acetone data follows that of non-acetone treatment as it curves towards its limits. This intensity ratio difference at 200kΩ, the lower limit of resistance is 1.6 for the needle to mesh gap ratio and 0.1 for the needle to filament ratio.



(a) (b)

Figure 8: Light intensity of the Acetone and non-Acetone treatment as a function of resistance at 1.5mm and 18kV. ***Light intensity at the needle position,(a) as a ratio to the light intensity of a mesh gap midpoint, and (b)as a ratio to a mesh node filament.***

The maximum voltage difference between the two samples, shown in Figure 1, at 20MΩ is 169V. However at the needle filament turn off point for the non-acetone data, of 12MΩ, the difference between the two is only 32V. The acetone line curves back to the non-acetone line reducing the difference between the two at lower values. The reduction in the acetone data's voltage with resistance, results in the higher required resistance to produce the necessary filament turn off voltage.

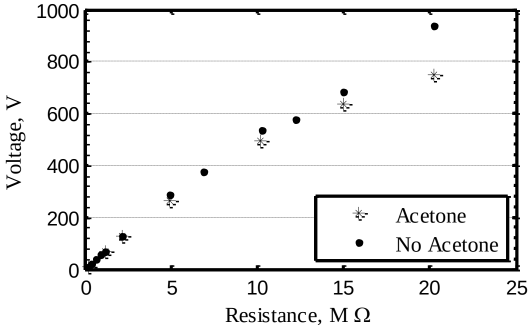


Figure 9: Comparison of the acetone wipe treatment. ***Cleaning the surface charge build up before each discharge proportionally increases the voltage bias of the needle.***

IV. Conclusions

The data presented demonstrates the capability of a resistive load to turn on and off a single filament while adjacent to other filaments in the DBD, by limiting the current to the selected area. The lack of mobile charges inhibits the filaments buildup of surface charge. The light intensity of the filament ranges between that of adjacent filaments and that of the non-discharging gaps. A voltage of 476V and 560V is required to completely turn off the filaments, relative to areas with no discharge. However lesser voltage changes of 100V or an additional resistance of 5MΩ can cause the transition between discharging and none discharging or vary the light intensity to a perceptible degree. The transition from discharge to no discharge at the needle depends on a decreased voltage but does not require the externally applied voltage to decrease below the breakdown voltage. Preferential discharge occurs where the current finds the least resistance, directing the filament limiting charge to those locations.

The process of applying a self-bias was using resistance applied to the mesh was also demonstrated. The needle filament intensity increased by 80% for a 470V rise in mesh potential. The increased preferences in the needle rerouted surrounding charge away from the mesh node filaments, reducing their value to twice the ambient value or completely turning those filaments off.

The effect of build-up charge was also investigated by comparing acetone wiped surface to none acetone treated discharge. The acetone treatment raised the required discharge resistance and breakdown voltage. This was due to the acetones decrease of the self-biased voltage. The intensity trend of the acetone intensity followed that of the non-acetone discharge but with increased light intensity per resistance. The effect of cleaning the surface increased the requirements for breakdown and turning the filament off while the variation in voltage at the maximum relative resistance of 12MΩ the difference is only 32V.

The intensity of a filament has been demonstrated to be controlled using voltage values less than 10% of the driving voltage, while that filament was surrounded by competing filaments. Investigation also showed a potential larger influence of needle positioned filament than only its immediate neighbors.

.

References

[1] Sakai, O., Tachibana, K., "Plamsa as Metamaterials: A Review," *Plasma Sources Sci. Technol.*Vol 2, No. 013001, pp. 18, 2011

[2] Soukoulis, C.M., Zhou, J., Koschny, T., Kafeski, M., Economou, E., "The Science of Negative Index Materials," *Journal of Physics: Condensed Matte*,. Vol. 20, No. 304217, 2008, pp. 7

[3] Ozbay, E., Bulu, I., Aydin, K., Caglayan, H., Guven, K.,. "Physics and Applications of Photonic Crystals," *Fundamentals and Applications*, Vol. 2, No. 2, 2004, pp. 87-95.

[4] Pendry, J.B, "Negative Refraction Makes a Perfect Lens," *Physcial Review Letters* Vol. 85, No. 18, 2000, pp. 3966 – 3969

[5] Kuzmiak, V., Maradudin, A. A., "Photonic Band Structures of One- and Two-Dimensional Periodic Systems with Metallic Components in the Presence of Dissipation," *Physical Review B*, Vol. 55, No. 12, 1997, pp. 7427-7444.

[6] Fan, W., Zhang, X., Dong, L.,. "Two-Dimensional Plasma Photonic Crystals in Dielectric Barrier Discharge.," *Physics of Plasma* Vol. 17, 2010, 113501.

[7] Ye, Q., Wu, Y., Li, X., Chen, T., Shao, G.,. "Uniformity of Dielectric Barrier Discharges Using Mesh Electrodes," *Plasma Sources Sci. Technol.* Vol. 21, 065008, 2012

[8] Gibalov., V, Pietsh, G., "Dynamics of Dielectric Barrier Discharges in Different Arrangements," *Plasma Sources Sci. Technol.* Vol. 21, 024010, 2012

[9] Kogelschatz, U. "Filamentary, Patterned, and Diffuse Barrier Discharges," *IEEE Transactions on Plasma Science*, Vol. 30 No. 4, 2002, pp. 1400 - 14008.

[10] Boeuf, J.P., Bernecker, B., Callegari, Th., Blanco, S., Fournier, R., "Generation, Annaihilation, Dynamics, and Self-Organized Patterns of Filaments in Dielectric Barrier Discharge Plasmas," *Applied Physics Letters*, Vol. 100, 244108, 2012

[11] Wang, X., Luo, H., Liang, Z., Mao, T., Ma, R., "Influence of Wire Mesh Electrodes on Dielectric Barrier Discharge," *Plasma Sources Sci. Technol*., Vol. 15, 2006, pp. 845-848.

[12] Gibalov, V. I., Samoylovich, V. G., "The Magnitude of the Transferred Charge in the Silent Discharge in Oxygen," *Czech. J. Phys .B*, Vol. 37, 1987, pp. 1248 - 1255