DEVELOPMENT OF ELECTRODE MANIPULATED CLOSE-PACKED MICROPLASMA JET ARRAYS IN A TRANSPARENT POLYMER

BY

PENG SUN

THESIS

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Adviser:

Professor J. Gary Eden
ABSTRACT

Close-packed arrays of novel microplasma jets at atmospheric pressure have been realized in a moldable, resilient, and optically transparent polymer in multiple dimensions. A micromolding-based assembly process enables microplasma jets to be generated in cylindrical microchannels with diameters \( \leq 350 \, \mu m \), and jet lengths up to \(~4 \, mm\) when the He backing pressure is \(~840 \, Torr\). Driven by a 20 kHz sinusoidal ac voltage waveform, the operating voltages are as low as 1 kV rms. Arrays as large as 121 jets in a cross-sectional area of 100 mm\(^2\) and having excellent jet-to-jet uniformity have been developed to date. The packing density of this technology has been increased more than an order of magnitude relative to previous technologies. Simulation of experimental emission spectra for the first negative system of N\(_2\)\(^+\) (B \( ^2\Sigma_g^+ \) \( (v' = 0, J') \rightarrow X \, ^2\Sigma_g^+ \) \( (v'' = 0, J'') \)) show the gas temperature of the microplasma to be \( 290 \pm 10 \, K \). Optical emission spectroscopy has been employed to investigate the chemical kinetics of the He (2\(^1\)S) and He\(_2\) (a \( ^3\Sigma_u^+\)) excited states interacting with laboratory air. For the first time, three-dimensional microplasma jet arrays have also been demonstrated. Curved and structured targets can be accomplished smoothly with three-dimensional arrays. Examination of He microplasma with an ICCD camera reveals considerable structure on the spatial emission profiles for the jets. Individual microchannel control has been developed in an array device. For glow regions of the microplasma, the peak intensity is produced 88-112 \( \mu m \) from the wall of the microchannel, which is consistent with a sheath thickness on the order of 10–30 \( \lambda_D \), where the Debye length \( \lambda_D \) is \(~3 \, \mu m\) for \( n_e = 10^{13} \, cm^{-3} \). The ability to shape the individual geometry of plasma in a microchannel array while maintaining a stable glow, in combination with the resilience, transparency, and size of the array, suggests that the future of this microplasma array jet is promising, particularly for applications as diverse as personalized medical therapeutics and materials processing.
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# TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION .................................................................................................................. 1

CHAPTER 2: BACKGROUND ..................................................................................................................... 3
  2.1 Gas Breakdown ............................................................................................................................... 3
  2.2 Microplasma Array ......................................................................................................................... 4

CHAPTER 3: DEVELOPMENT AND CHARACTERISTICS OF MICROPLASMA JET ARRAYS ..... 6
  3.1 Array Structure and Fabrication Process ....................................................................................... 6
  3.2 Development of Microplasma Jet Arrays In Two and Three Dimensions .................................... 8
  3.3 Temperature Evaluation ................................................................................................................. 11
  3.4 Physical, Electrical, and Optical Characteristics .......................................................................... 12

CHAPTER 4: TEMPORALLY RESOLVED BEHAVIOR OF ADDRESSABLE JETS ......................... 17
  4.1 Representative Illustration ............................................................................................................ 17
  4.2 Temporally Resolved Behavior Recorded by ICCD Detector Camera ........................................... 19

CHAPTER 5: CONCLUSIONS .................................................................................................................. 23

REFERENCES ........................................................................................................................................ 24
CHAPTER 1: INTRODUCTION

According to Paschen’s curve, which describes the breakdown voltage at which an electrically ionized gas becomes conducting, in order to keep the critical voltage the same, the distance between electrodes should be decreased, when the operation pressure is increased [1, 2]. Although shrinking the distance between two electrodes to the centimeter range provides a possible way to produce atmospheric pressure non-equilibrium plasma, doing so inevitably produces instabilities resulting from the transition to a streamer-dominant arc discharge [3, 4]. Microplasma is a subdivision of plasma, which suggests the plasma has been confined to a small volume, ranging from tens to thousands of micrometers. This offers a promising approach for producing stable discharge at atmospheric pressure [3]. Most microplasmas that have been used in commercial applications are cold plasmas.

The spatial confinement of a low-temperature atmospheric pressure plasma to a microcavity has been demonstrated to yield a unique class of photonic/electronic devices, and to open new avenues in plasma science and technology [3]. When low temperature plasma is generated in a flowing gas system, the interactions with a material surface provide a candidate for biological and chemical processing. By monitoring the surrounding medium or tailoring the input gas, specific radicals and excited species can be produced within the plasma, which greatly benefits the range of accessible applications. Through producing targeted species and transient molecules with a stable discharge, atmospheric pressure glow discharge sources offer a broad spectrum of plasma-chemical reactions.

Recently, preliminary data for microjet arrays as large as 5 × 2 and fabricated in a moldable polymer was reported by Ma et al. [5]. An advanced version of this design will be introduced here, in which microplasma jet arrays generated in microchannels have been developed in silicone polymer. Molding in a transparent and flexible polymer has resulted in microplasma jet arrays having as many as 121 microchannels in an 11 × 11 configuration. This technology increases the jet packing density by at least
an order of magnitude relative to previous technologies. For the first time, three-dimensional microplasma jet arrays have been demonstrated. More importantly, the ability to address specific jets has been achieved by shaping the geometry of the plasma, while maintaining a stable glow discharge. For the first time, controlled plasma behavior in a jet within an array has been demonstrated at atmospheric pressure by shaping the electrical field in the microchannel. The novel microplasma jet arrays described here provide the opportunity to impact applications as broad as personalized medical therapeutics and materials processing.
CHAPTER 2: BACKGROUND

2.1 Gas Breakdown

Plasma is the fourth state of matter, aside from solid, liquid, and gas states. Over 99.9% of matter in the universe can be cataloged as plasma [6]. Ionization can be induced by introducing energy into a gas, thereby producing plasma. Plasma as a whole is quasi-neutral, which suggests it contains equal quantities of positive and negative charged particles. Electrons, ions, and excited species in plasma form a soup of species to produce a unique plasma chemistry environment. Plasma can be divided into two categories: thermal plasma and non-thermal plasma. Non-thermal plasma is also known as the non-equilibrium plasma, which indicates the ion temperature is much lower than the electron temperature. The electron temperature is typically around ~1 eV. When the plasma temperature is close to 300 K, which is room temperature, it is known as cold plasma or low temperature plasma.

Paschen’s curve, shown in Fig. 2.1 [6], describes the relationship between breakdown voltage (the threshold voltage that produces self-sustaining plasma) and the production of the pressure and electrode separations. With the same electrode separations as when the operation pressure increases to atmospheric pressure, the breakdown voltage is increased. Increase of the breakdown voltage will lead to high current density and instabilities. In order to keep the critical voltage the same in terms of producing plasma in atmospheric conditions, the distance between the electrodes should be decreased.
2.2 Microplasma Array

Microplasma is a subfield of plasma physics in which plasma has been confined in a cavity of small dimensions, ranging from tens to thousands of micrometers. It offers a promising approach to produce stable discharge at atmospheric pressure [4]. Microplasma can operate with a power density of $10^4$ to $10^6$ Wcm$^{-3}$ and electron density from $10^{13}$ to $10^{17}$ cm$^{-3}$, which provides a great candidate for various applications, including material surface treatment and biological processing. As the dimensions of the plasma shrink to micrometer range, the sheath region becomes the dominant region while the length of the positive column region decreases. Electrons produced by secondary electron emission, which is due to the increase of surface-to-volume ratio, are involved more frequently in sustaining a discharge. Microplasmas have been investigated intensively in the past few years with different configurations in terms of excitations, including direct current, low frequency alternating current, radio frequency, and microwave. Increased interest in this aspect of microplasma is due to the fact that industrial applications will require moderate operating voltages at atmospheric pressure [3, 4].
Since the late 1990s several groups [7 - 10] have extensively studied, atmospheric pressure jets. Along with other prospective applications, disinfection and wound healing have considerable promise. Although most applications require scaling the cross-sectional area, virtually all of the atmospheric pressure jets reported to date are single channel plasma jet with limited scalability. A few studies [11 - 15] have been conducted for multi-jet design, but the configurations applied are bulky, and packing densities below 10 cm\(^2\) were reported. Furthermore, no research has been demonstrated to assemble plasma jet arrays in three dimensions.
CHAPTER 3: DEVELOPMENT AND CHARACTERISTICS OF MICROPLASMA JET ARRAYS

3.1 Array Structure and Fabrication Process

Representative diagrams of a multi-jet array design are shown in Fig. 3.1. Figure 3.1 (a) is a perspective view of a 3×3 array, as observed from the front of the polymer structure. A glass tube with 4 mm diameter was attached to the backside of the polymer to supply the gas input. The polymer was chosen because it is transmissive throughout the visible and well into the deep ultraviolet (UV; ~250 nm). Plasma channels (350 ±5 μm diameters) were produced by embedding an array of metal rods in the polymer. The rods will be removed after assembly was completed and the polymer cured. The polymer was subsequently cured at 80 – 100 °C for a period up to few hours. Uniform glow discharges are produced from cylindrical microchannels by the application of a sinusoidal voltage to electrode wire arrays imbedded within the silicon polymer. A side-view illustration of the device structure is shown in Fig. 3.1 (b).

![Figure 3.1 Diagrams illustrating the structure of a microplasma jet array in (a) perspective and (b) side view. The diameter of the glass tube connection to the array head is 4 mm. The electrical connections shown here are for illustrative purposes only.](image-url)
The arrays of electrodes that power the microjets are embedded in polymer and the electrode axes are perpendicular to these of the plasma jets. One possible electrode connection pattern is indicated in Fig. 3.1 (b), where electrodes are connected at both sides of the device. It should be pointed out that other connections also functioned well.

![Diagram](image)

Figure 3.2 Process sequence for fabricating close-packed array of microplasma jets operating in atmospheric pressure gas flows. The specific electrode/microchannel assembly illustrated here is that for a 5 × 5 jet array.

The process of fabrication is illustrated in a sequence of diagrams shown in Fig. 3.2. The process begins with the mold (Fig. 3.2 (a)), which is used for supporting the electrode arrays. Figure 3.2 (b) shows the installation of the electrode arrays, and in Fig. 3.2 (c), metal rods with a diameter of ~350 µm are inserted into the hole pattern on the bottom of the mold. Every row of metal rods is parallel with the electrode and lies between two electrodes. After building the electrode array and metal rods, a temperature-curable silicon polymer is poured into the mold (Fig. 3.2 (d)). After curing at 80 – 100 °C for one hour, the entire assembly is taken out of the mold. Once the polymer is cured, the microchannels are
formed by removing the metal rods. Assembling of the jet array is accomplished by cutting the entire piece into a 4 mm thick slab (Fig. 3.2 (e)). By attaching a 4 mm diameter glass tube at the either side of the polymer, the device is completed. The silicon polymer was chosen because it is transmissive through the visible and into the deep ultraviolet (UV; ~250 nm) range, which provides the opportunity to monitor the plasma optically inside the microchannel.

Figure 3.3 Schematic diagram of the structure of a microplasma jet array. (a) Perspective view of a 5 x 5 twenty-five channel device; (b) end-on view of a microjet array, illustrating the dimensions of the electrodes and their positioning relative to the plasma channels.

In order to provide detailed specifications regarding the relative position of the copper electrode wires and the cylindrical microchannels, Fig. 3.3 shows a magnified view of a part of a microplasma jet array. Electrode wires with a diameter of 255 μm are separated by a distance of 1 mm from each other. The diameter for each microchannel is 355 ±5 μm and the microchannel pitch is 1 mm. The closest distance between surfaces of the electrode to the edge of a microchannel is 195 μm. With the above parameters, the array packing density is ~121 cm⁻², which is more than an order of magnitude higher than the previous publications.

3.2 Development of Microplasma Jet Arrays In Two and Three Dimensions

Figure 3.4 is a photograph of an 11x11 array of microjets with perspective view, operated with a 20 kHz sinusoidal voltage and a helium backing pressure of 780 Torr. According to the specifications
described earlier, the devices in Fig. 3.4 are fabricated with 100 mm$^2$ of surface area, with a jet-to-jet distance of only 1 mm. With this structure, uniformity of jet length and the luminosity of each jet have been demonstrated. Regardless of the size of the microchannels (200 μm or 500 μm), no perturbation of one jet by its neighbors has been observed. In other words, the jets do not perturb one another despite the close-packing of the array. All jets ignited simultaneously and maintained excellent jet-to-jet operation uniformity over a wide operating range.

Figure 3.4 Array of 121 plasma jets in an 11 × 11 configuration and operating with a helium backing pressure of 780 Torr. The amplitude of the 20 kHz voltage driving the array is 0.92 kV (rms).
Figure 3.5 Photographs of microplasma jet arrays when driven with a voltage of 1.1 kV (rms) and the helium pressure set to 800 Torr. Five $5 \times 5$ microplasma jet arrays are located on five sides of a cube.

By using microplasma jets to treat targets in three dimensions, three-dimensional microplasma jet arrays have been demonstrated for the first time. Figure 3.5 presents two photographs of a unique structure having $5 \times 5$ arrays of microplasma jet arrays on five surfaces of the cube. By assembling microplasma jet arrays on five sides of the cube, interactions with the curved or structured feature surfaces are now possible.
A geometric pattern of the letters “UIUC”, formed by microjets has been achieved. This result demonstrates the potential of versatile device structures. Figure 3.6 (a) and (b) are photographs showing end-on and perspective views of the patterned microjets. Since the length of the microplasma array jet is a function of the gas flow pressure, delivering a pressure of 860 Torr to the array results in a jet length of ~4 mm. Because of the adoption of these production techniques, various geometric microplasma arrays are possible.

### 3.3 Temperature Evaluation

Clearly resolved rotational structures for the R-branch of the $\text{N}_2^+$ first negative system are illustrated in Fig. 3.7 (a), which corresponds to the electronic transition of the molecule of $B \, ^2 \Sigma_u^+ (\nu'=0, J') \rightarrow X \, ^2 \Sigma_g^+ (\nu'' = 0, J'')$. This spectrum was recorded with a driving voltage of 1.7 kV (rms), a He pressure of 860 Torr, and the microjets expanding into laboratory air. The alternation of the intensities of the rotational lines was observed, which is attributed to the difference in the degeneracy of the nuclear spin of
homonuclear diatomic molecules [16]. The N$_2^+$ rotational temperature has been predicted by fitting the N$_2^+$ first negative system band from 388 nm to 392 nm for 391.4 nm ($v' = 0, v'' = 0$) line with SPECAIR.

![Normalized Intensity vs Wavelength (A)](image)

Figure 3.7 Measured and calculated nitrogen optical emission spectra from 1 × 5 microplasma array with 1.7 kV (rms) voltage input and 860 Torr helium gas supply. Observed spectra of the B $^2\Sigma^+_u$ ($v' = 0, J'$) → X $^2\Sigma^+_g$ ($v'' = 0, J''$), excitation of N$_2^+$ in the range of 388 - 392 nm. The alternate structure of the rotational levels is clearly resolved. The inserted figure illustrates comparing the spectrum of N$_2^+$ predicted by SPECAIR under rotational temperature of 270 K and 340 K with measurement.

The insert to Fig. 3.7 illustrates the results of fitting conventional expressions data. The two simulated curves correspond to N$_2$ rotational temperatures of 270 K and 340 K. These results suggest the microplasma rotational temperature to be 290 ±10 K. The gas temperature is defined as the kinetic temperature of the heavy particles in the plasma, and the rotational-translational relaxation rate is assumed to be sufficiently fast to equilibrate the rotational and gas temperatures.

3.4 Physical, Electrical, and Optical Characteristics
Figure 3.8 illustrates the dependence of the plasma plume length on the gas pressure for a $1 \times 5$ array driven by an rms voltage varied from 1 kV to 2.5 kV. The helium pressure was varied between 760 and 900 Torr. A rapid increase in the plasma plume length was observed up to 840 Torr, and the maximum jet length of $3.8 \pm 0.2$ mm is reached for $V_{\text{RMS}} = 1.8$ kV and a backing pressure of 840 Torr. This maximum is likely due to turbulence at the interface between the gas input glass tube and the polymer block. Increased plasma plume lengths could be expected by improving the design of the gas flow.

![Figure 3.8](image)

Figure 3.8 Variation of the microplasma plume length with the backing pressure of the helium feedstock gas. Data are presented for RMS voltages of 1.0 kV (○), 1.8 kV (●), and 2.5 kV (△), and estimated uncertainties are indicated for several measurements.

Voltage-current characteristics for $1 \times 1$ to $5 \times 5$ microplasma jet arrays are presented in Fig. 3.9. Data are given for operation of the arrays in helium at a pressure 800 Torr, and the arrays are driven by a sinusoidal voltage with a frequency of 20 kHz. The positive slopes indicate these microplasma arrays are operating in the abnormal glow discharge mode [6]. Such unique characteristics indicate that these microplasma jet arrays can be operated without the need for external ballast, which is a substantial asset for commercial applications. With the same volume ($5 \times 5 \times 5$ mm$^3$), increasing the number of plasma channels will decrease the volume of the silicone polymer, which decreases the resistance of the device.
Noticeably, at a constant voltage an increased number of plasma channels led to an increase of current consumption. By monitoring the current flowing into the plasma, the power deposited into each jet is between ~3 mW to ~96 mW, which suggests a power density 1.5 – 15 W/cm$^3$. Thus the energy efficiency for these microjet arrays is a factor of 5 to 10 times higher than the previous report [17].

![Figure 3.9 V-I characteristics for 1×1, 2×2, 3×3, 4×4, and 5×5 microplasma jet arrays. The arrays were operated in helium at pressure 800 Torr, and the driving voltage was sinusoidal with a frequency of 20 kHz.](image)

Optical emission was observed at 90° to the axis of the microplasma jets and near the center of the jets. The most prominent of these is the B$^2\Sigma_u^+ (v' = 0) \rightarrow X^2\Sigma_g^+ (v'' = 0 - 2)$ bands of N$_2^+$ at 391.4 nm and 427.8 nm, the C$^3\Pi \rightarrow B^3\Pi$ transition of N$_2$ (second positive system) with bandhead at 316, 337, 357, and 380 nm, the 3p$^2$ 5P$_2 \rightarrow 3$S$_2$ transition of atomic oxygen at 777.3 nm, and the 706.5 nm and 471.3 nm lines of He (3S$_1 \rightarrow 2$P$_0$ and 4S$_1 \rightarrow 2$P$_{0,2}$, respectively) shown in Fig.3.10. The dependence of the
relative emission intensities for these spectral features on the He backing pressure is illustrated in Fig. 3.10 (b). Owing to the rate constant for the collisional process \( \text{He} (2^3\text{S}_1) + \text{N}_2 \rightarrow \text{N}_2^+ (B \Sigma_u^+ \rightarrow \text{He} + e^- + \Delta E) \), \( \text{N}_2^+ \) is the most dominant feature in the 300-500 nm region. Penning ionization of \( \text{N}_2 \) by the He \( (2^3\text{S}_1) \) metastable is well-known [18]. The linear increase of the \( \text{N}_2^+ \) fluorescence with helium pressure (Fig. 3.8) is attributed to Penning ionization being the main process for populating the \( \text{N}_2^+ (B \Sigma_u^+) \) state.

Figure. 3.10 Optical emissions of the microplasma jets in the channel (blue line) and expanding into laboratory air (plasma plume, red line. (a) Emission spectra in the range of 300 – 800 nm recorded from microplasma jet in He at atmospheric pressure and measured in plan view in channel (blue line) and out of channel (red line). (b) Dependence on the jet backing pressure of the relative intensities for several prominent emitters (OH \((A \rightarrow X)\): ▲; O \((777 \text{ nm})\): △; \( \text{N}_2^+ (B \rightarrow X) \): ○; He \((4^3\text{S}_1 \rightarrow 2^3\text{P}_{0,2}, 471 \text{ nm})\) ○). Results are shown for a \( 1 \times 5 \) jet array viewed orthogonal to the jet axes at a distance of 5 mm from the channel apertures.

Because the He \( (2^3\text{S}_1) \) metastable is the precursor of both the O \((3p \, ^5\text{P}_2)\) and He \((4^3\text{S}_1)\) excited atoms, the dependence of both the He \((4^3\text{S}_1 \rightarrow 2^3\text{P})\) and O \((3p \, ^5\text{P}_2 \rightarrow 3s \, ^5\text{S}_2)\) intensities on the He pressure is similar. Furthermore, when the He pressure \((p_{\text{He}})\) is raised from 760 Torr to 800 Torr, a quadratic increase of the OH \((A \rightarrow X)\) intensity is observed. This behavior indicates that the He \( (2^3\text{S}_1) \) metastable species, which generates \( \text{He}_2 \) \((a \, ^3\Sigma_u^+)\) excited dimer through a three body collision is the dominant species for production of OH(A). The internal energy of the \( \text{He}_2 \) molecule \((\geq 18 \text{ eV})\) is sufficient to break
the OH-H bond of water, with adequate energy narrowing to excite OH radical to the $A^2\Sigma$ electronic excited state. The saturation of the OH radical emission has been observed as $p_{He}$ is increased above ~800 Torr, which may be caused by the rising influence of collisional quenching OH (A) by water vapor or $N_2$. 
CHAPTER 4: TEMPORALLY RESOLVED BEHAVIOR OF ADDRESSABLE JETS

4.1 Representative Illustration

A closer examination of the microplasma with an optical imaging system reveals the existence of structure on the temporally resolved emission profile. The electrode array connection pattern is illustrated in Fig. 4.1 (a). This image compared channels in the middle column (C1) which had four of the six accompanied electrodes connected to a high potential while the other two were grounded, the channels in the side columns (C2 and C3) just had two of the six accompanied electrodes connected with high potential. Figure. 4.1 (b) is an image recorded with a Cannon camera at exposure time of 0.25 s. The device was operating at helium pressure of 860 Torr and only visible emission was recorded. The jet length of the C1 column was ~10% longer than the length of C2 and C3, which was attributed to the different power loading driven by the shaped electric field. The false color images in Fig. 4 (c) were recorded with the same operating conditions as described above, and the right-side image was obtained under conditions identical to those for the left image except that the intensity collected by the intensified charge-coupled device (ICCD) camera was acquired over different accumulation times. The camera exposure time was 50 µs. Emission intensity lineouts for $p_{\text{He}}$ 860 Torr were presented in Fig. 4 (c). Lineouts were obtained by scanning the digital images longitudinally, i.e., along the primary axis of the discharge. Significantly different microplasma performances had been noticed when the electrodes were biased in different patterns. Compared with channels in the two side columns (C2 and C3), the intensity was a factor of 5 higher when compared with the channel in the middle column (C1) which confined itself in the center of the microchannel. Both channels in the two side columns (C2 and C3) illustrated similar temporal behavior which split peak intensity into two regions close to the wall of the microchannel.
Figure 4.1 Electrode configurations manipulated time-resolved behavior in an array device. (a). Systematic picture of electrodes array configuration. (b). Picture of 3 × 3 device performance with electrode connections shown in (a). (c). False color images obtained at pHe = 860 Torr, with ICCD gate width 50 µs. The right-side image inserted in (c) was recorded by attenuating the emission with less accumulation times compared with the left-side image. The lineout was obtained in the longitudinal directions (the primary axis of microplasma jet array). C1 indicates the middle channel column, while C2 indicates left-side channel column and C3 indicates right-side channel column.
4.2 Temporally Resolved Behavior Recorded by ICCD Detector Camera

Further examination of the revealed temporal behavior of the microplasma jet array with an optical imaging system at shorter exposure times illustrates the temporally resolved characteristics of these microplasmas. As shown in Fig. 4.2, all the images were obtained with an ICCD gate width of 25 µs but all other operation parameters were the same as those described in previous paragraph. False color images in the right column were obtained under the conditions identical to these for the left image except that the intensity collected by the ICCD camera was scaled with the use of different accumulation times. Upper panel pictures show images captured during negative 25 µs cycle of the 20 kHz driving the waveform are indicated by black solid line in Fig. 4.2 (a), while the lower panel shows that of the positive half cycle (indicated by red dashed line in Fig. 4.2 (a)). It is observed that the peak intensity is always confined in the middle of the channel in the central column (C2) both in the positive and negative half cycles. The lower panel (positive cycle) shows the local maxima of C2 and C3 columns to be faced opposite and toward the center of the channel, while the upper panel (negative cycle) shows the local maxima of C2 and C3 to also face opposite but toward the outside of the channel. Lineouts were obtained along the longitudinal axis (of the microplasma jet array). The longitudinal scans in Fig. 4.2 (a) show the intensity from channels in column C1 always reach maximum in the middle of the microplasma channel. This is attributed to the component of the electrical field in the middle of the microchannel. In contrast, channels in C2 and C3 columns show local maxima associated with negative glow regions on opposite sides of the microchannel, which is attributed to the temporally-varying electrical field in the vertical direction orthogonal to the microchannel. For both glow regions of the microplasma in the columns on two sides, the peak intensity is produced 88-112 µm from the wall of the microchannel, which is consistent with a sheath thickness on the order of 10-30 λ_D, where the Debye length λ_D is ~ 3 µm for n_e = 10^{13} cm^{-3}. The general characteristics of the microplasma temporal emission intensity profile along the longitudinal direction (Fig. 4.2 (a)) are similar to those observed by Park et al. [19] for a 127 µm diameter microcavity and by Boeuf et al. [20] predicted on the basis of a fluid model. Similar phenomenons have also been
observed when microplasma propagates out of the channel, as shown in Fig. 4.2 (b). The yellow dashed line indicates the extended center of the microchannel, while the white dashed line indicates the extended borders of the microchannel. As in Fig. 4.2 (a), false color images in the right column were obtained under conditions identical to those for the images at left except that the intensity was collected by different accumulation times. As shown in the upper panel of Fig. 4.2 (b), plasma was confined in the inner side of the extended channel in the positive half cycle while plasma was confined in the outer side of the extended channel in the negative half cycle as indicated in the lower panel. Temporally resolved microplasma behaviors have been observed here with individual channel control in the array device. Addressable microchannel plasmas, operating at atmospheric pressure, have been demonstrated.
Figure 4.2 Temporally resolved emissions produced in 355 µm microplasma channel with operation pressure of 860 Torr and 25 µs ICCD gate width in 3 × 3 microplasma jet array (a) in the microchannel and (b) out of the microchannel. False color images in the right column were recorded by attenuating the emission from ICCD accumulation times. In both (a) and (b), the upper panel images show emissions captured in the positive 25 µs cycle, while the lower panel shows that of negative 25 µs cycle. In (a), the black solid line indicates the negative half cycle (25 µs), while the red dashed line indicates the positive half cycle (25 µs). Lineouts were obtained in the longitudinal directions (the primary axis of microplasma jet array). C1 indicates the channels of the middle column, while C2 indicates channels of the left-side column and C3 indicates channels of the right-side column. The yellow dashed line indicates the middle of the channel, while the white dashed lines show the extended channel border.
CHAPTER 5: CONCLUSIONS

Novel arrays of microplasma jets, operating at atmospheric pressure, have been generated in a moldable, resilient, and transparent polymer. The development and physical characteristics of a close-packed array of microplasma jets have been illustrated. Excellent uniformity of the luminosity and plume length for jet arrays have been observed and arrays as large as 11 × 11 have been demonstrated. These arrays offer packing densities (up to ~120 cm⁻² to date) that are more than an order of magnitude higher than those reported previously. For the first time, assembling the microplasma jet array in three dimensions has been demonstrated. Lengths of the plasma plumes reach 3.8 ±0.2 mm for a He backing pressure of 840 Torr. The rotational temperatures of the microplasma jets were measured by simulating emission spectra associated with the N₂⁺ first negative system. Emissions from N₂⁺ (B ²Σ⁺), OH (A ²Σ), as well as several familiar lines of atomic oxygen and helium have been observed. From the relationship of fluorescence intensity with helium pressure, one concludes that the collisions of He₂ (a ³Σ⁺) with H₂O at the perimeter of the jets in an air environment leads to production of OH (A). The geometry of the microplasma devices demonstrated here breaks the azimuthal symmetry of the previous designs, and provides for addressability. The ability to shape the geometry of the plasma within each microchannel while maintaining a stable glow, in combination with the resilient, transparent, small weight, and size of the array, suggest that the future of this microplasma array technology is promising, particularly for applications such as personalized medical therapeutics (disinfection and wound healing) and materials processing.
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