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Measurements of the Propagation Velocity of an Atmospheric-Pressure Plasma Plume by Various Methods

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***Abstract*—The propagation behavior of atmospheric-pressure plasma plumes has recently attracted lots of attention. In this paper, five different methods are used to measure the propagation velocity of an atmospheric-pressure plasma plume. The first method, named the "current method," obtains the propagation velocity of the plasma plume by measuring the currents carried by the plasma plume at different positions. The second method, named the "voltage method," obtains the plume propagation velocity by measuring the plasma plume voltage potential at different positions along the plasma jet with a voltage divider. The third method, called the "charge method," which significantly interferes with the plume propagation, estimates the plume propagation velocity by measuring the charges deposited on the surface of a quartz tube. The fourth method, which is the noninterference method, obtains the plume propagation velocity by capturing the dynamics of the plasma plume with an intensified charge-coupled device camera. Finally, the fifth method estimates the plume propagation velocity based on the temporal optical-emission intensity measurement of the selected species by using a spectrometer. The advantage and disadvantage of each method are discussed. The experimental results show that plasma plume velocities obtained from the five methods have reasonable agreement with each other. They are all in the range of 10^4 m/s.**

***Index Terms*—Atmospheric-pressure plasma, dielectric barrier discharge, plasma jet.**

I. INTRODUCTION

ATMOSPHERIC nonequilibrium plasmas have recently attracted lots of attention because of their emerging applications in various fields, such as the biological and chemical decontaminations of media [2]–[10], surface modification/functionalization of polymers [11]–[13], water treatment [14]–[16], and synthesis of nanomaterials [17]–[19]. Atmospheric-pressure plasma jet devices, which can generate plasma plumes in open space rather than in confined discharge gaps, have lots of advantages over traditional discharge devices. For example, it can be used for root canal treatment, which cannot be realized by traditional discharge devices.

However, due to the high collision frequency at atmospheric pressure, it is not easy to generate a long nonequilibrium plasma plume at atmospheric pressure. Fortunately, some progress has recently been achieved on the generation of nonequilibrium plasma plume [3], [20]–[25]. Furthermore, studies on the fundamentals of plasma plumes show that plasma plumes are not a continuous volume of plasma; rather, plumes are more like a bullet formed by a small and well-confined plasma volume that travels from the exit aperture and terminates somewhere in the surrounding air. The propagation velocities of plasma plumes vary from $\sim 10^4$ to 10^5 m/s, which are several orders of magnitude higher than gas velocities. However, up to now, this is still not well understood. More studies are needed to have a better understanding of the plasma bullet behavior.

On the other hand, to obtain the plume propagation velocities, costly high-speed intensified charge-coupled device (ICCD) cameras are currently used in most of the experiments reported [26]–[30]. Somehow, the price of an ICCD is pretty high, and not every plasma laboratory has an ICCD. In order to find relatively simple and cheaper methods for estimating the plasma plume propagation velocity, five different methods are investigated in this paper. They can be classified as follows: 1) current method; 2) voltage method; 3) charge method; 4) ICCD method; and 5) spectroscopy method. The other four methods are not as direct as the "ICCD method," but they have their own advantages. The "current method" and the "charge method" give us the current carried by the plasma plume and the charge distribution information along the plasma plume, respectively. For the "voltage method," it gives us the voltage potential distribution along the plasma plume. For the fifth method, the detail spatial–temporal behavior of the selected lines could be obtained, such as N_2 (337.1 nm) and N_2^+ (391.4 nm) emission. The details of the experimental setup will be described in Section II, and the experimental results will be presented in Section III. The advantage and disadvantage of each method are discussed in Section IV. This paper concludes in Section V, where the main results are summarized.

II. EXPERIMENTAL SETUP

The schematic of the device used in this paper is shown in Fig. 1. The high-voltage wire electrode made of a copper wire with a diameter of about 2 mm is inserted into a one-end-closed quartz tube with a length of 5 cm, whose inner and outer diameters are 2 and 4 mm, respectively. The quartz tube

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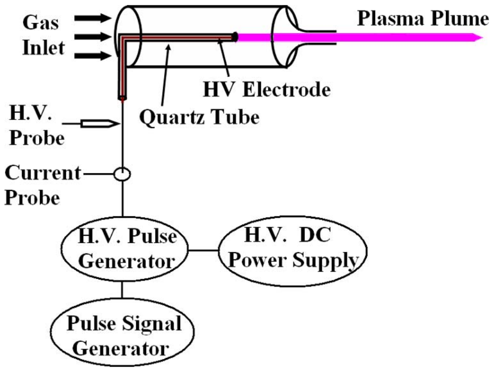


Fig. 1. Schematic of the atmospheric-pressure plasma jet device.

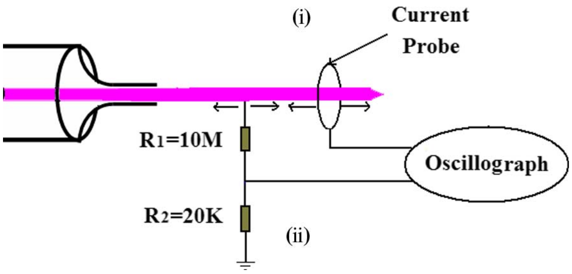


Fig. 2. Schematic of the (i) "current method" and (ii) "voltage method." Both the current probe and the thin wire connected to the endpoint of R_1 could move along the plasma plume.

is put coaxially inside a hollow syringe. The inner diameter of the hollow syringe is 6 mm. The device is driven by pulsed dc voltage. More details about the device can be found in [22]. The plasma plume generated by this device is about 4 cm long in open air.

For all the experimental results reported in this paper, working gas helium with a flow rate of 2 L/min is used. The pulse frequency and the pulsewidth are fixed at 4 kHz and 1600 ns, respectively.

Fig. 2 shows the schematic of the "current method" (i) and the "voltage method" (ii) for measuring the plasma bullet velocity. For the current method, the plasma plume is flowing through the current probe jaw (model TCP 202). By moving the current probe along the jet propagation direction, the current carried by the plasma plume appears at different time. Therefore, the plasma bullet velocity can be estimated according to the current probe positions and the current appearing times. The voltage method measures the voltage potential along the plasma plume by using two resistors in series, as shown in Fig. 2, where the resistances of R_1 and R_2 are 10 MΩ and 20 kΩ, respectively. A thin wire with a diameter of about 100 μm, which is connected to R_1, is in contact with the plasma plume. When the thin wire is moving along the plasma plume, the voltages along the plasma plume can be obtained. Similar to that in the current method, the plasma bullet velocity can be calculated according to the positions of the thin wire and the obtained voltage curves. It should be emphasized that because the resistance of R_1 is very big, the propagation of the plasma plume is not affected by the thin wire.

Fig. 3 shows the schematic of the "charge method." As shown in Fig. 3, the plasma plume is in contact with the quartz tube. The contacting point of the plume with the quartz tube is covered by a 2-mm-wide conducting ring made of thin aluminum foil. Another conducting ring with the same width is added to the inner surface of the quartz tube opposite to the outer ring. The inner ring is connected to the ground. The charge deposited on the outer aluminum foil is obtained through integration of the current flowing through the ground wire.

For comparison, the propagation velocity of the plasma plume measured by the ICCD camera is also presented in the paper. Fig. 4 shows the schematic of the experimental setup with the ICCD camera (iv). In addition, the experimental setup for the evaluation of plume propagation velocity based on the temporal optical emission of the selected species by using a spectrometer (v) is also shown in Fig. 4. By adjusting the grating and the position of the spectrometer, the temporally

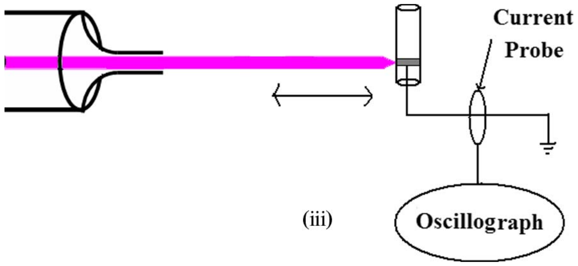


Fig. 3. Schematic of the "charge method." The quartz tube could move along the plasma plume.

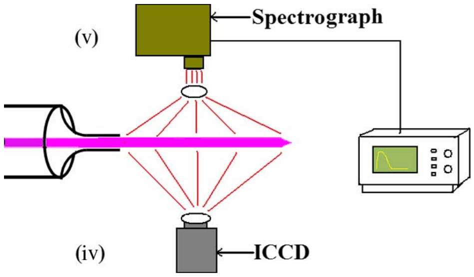


Fig. 4. Schematic of the "ICCD method" (iv) and (v) "spectroscopy method."

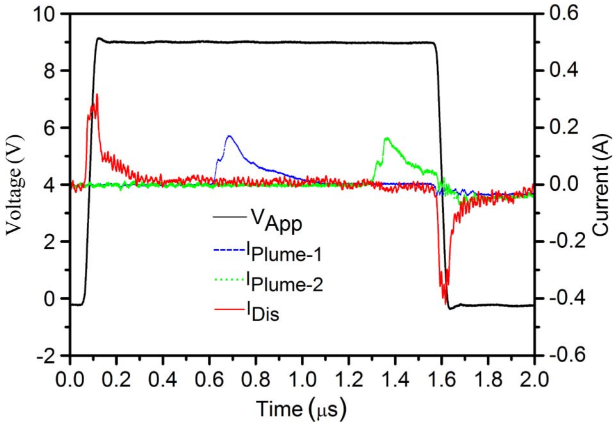


Fig. 5. Applied voltage V_{app}, discharge current I_{dis}, and plume currents $I_{\text{plume}-1}$(1 cm from the nozzle) and $I_{\text{plume}-2}$ (3 cm from the nozzle) versus time.

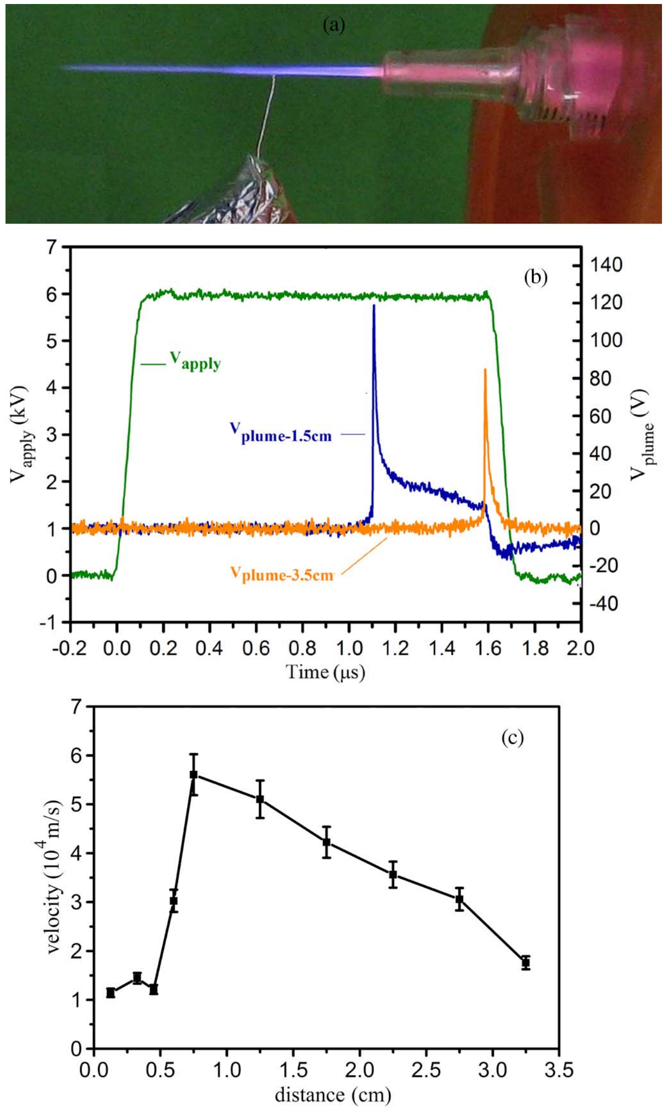


Fig. 6. (a) Photograph of the plasma plume that keeps propagating even if the thin wire is in contact with the plasma plume. (b) Applied voltage V_{app} and plume voltages $V_{\mathrm{plume}-1.5\,\mathrm{cm}}$ (1.5 cm from the nozzle) and $V_{\mathrm{plume}-3.5\,\mathrm{cm}}$ (3.5 cm from the nozzle) versus time. (c) Spatially resolved plasma plume velocity.

and spatially resolved optical emission of the plasma plume is obtained, and the propagation velocity of the plume can be evaluated.

III. EXPERIMENTAL RESULTS

A. Current Method

By placing the current probe at different positions along the plume, the currents carried by the plasma plume with different delay time can be obtained. Fig. 5 shows two typical plume current waveforms along with applied voltage V_{app} and discharge current I_{dis}. Details about I_{dis} can be found in [22]. It clearly shows that when the current probe is placed closer to the jet nozzle, the current appears early. Thus, the velocity of the plasma bullets can be estimated according to the appearing time of the plasma plume current. The average propagation velocity of the plasma plume is about 50 km/s. The problem with this method is that the dimension of the probe is too big. It is about 1 cm thick. Thus, it is difficult to obtain the spatially resolved plasma propagation velocity.

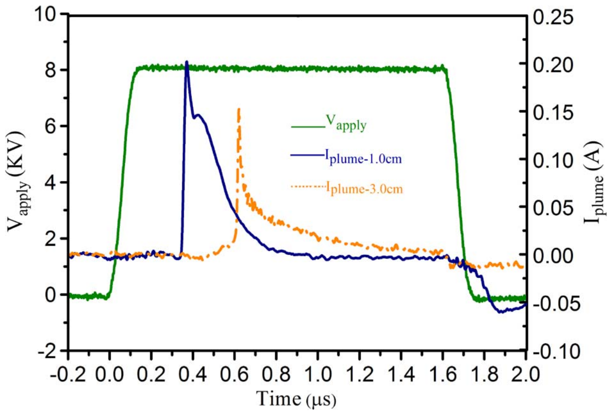


Fig. 7. Applied voltage V_{app} and plume currents $I_{\mathrm{plume}-1.0\,\mathrm{cm}}$ (1.0 cm from the nozzle) and $I_{\mathrm{plume}-3.0\,\mathrm{cm}}$ (3.0 cm from the nozzle) versus time.

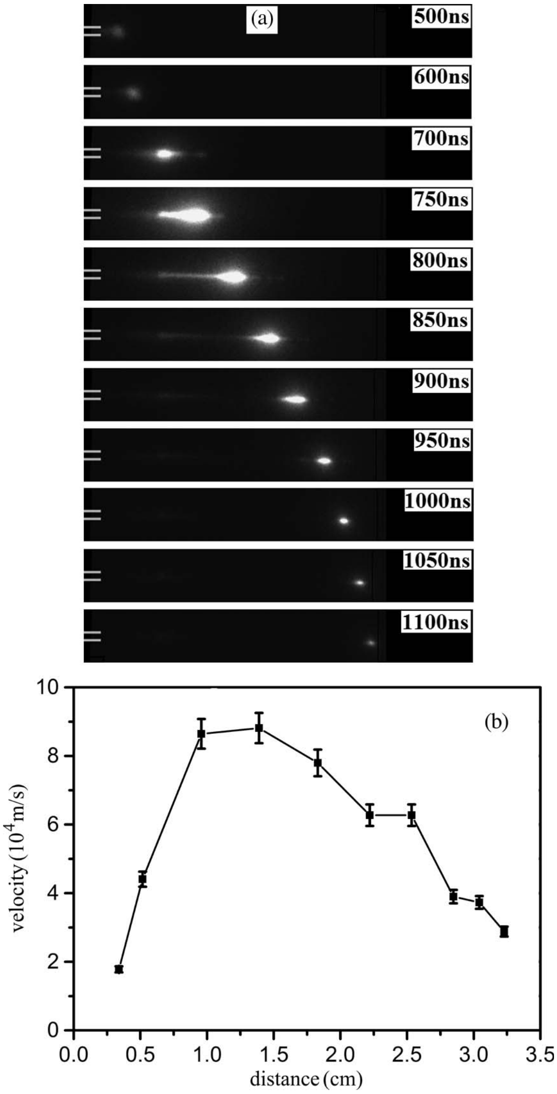


Fig. 8. (a) High-speed photographs of the plasma plume/bullets at different times during the period of the discharge. The exposure time is 10 ns. (b) Plume velocity versus time. The applied voltage V_{app}, the frequency, and the pulsewidth are 8 kV, 4 kHz, and 1600 ns, respectively.

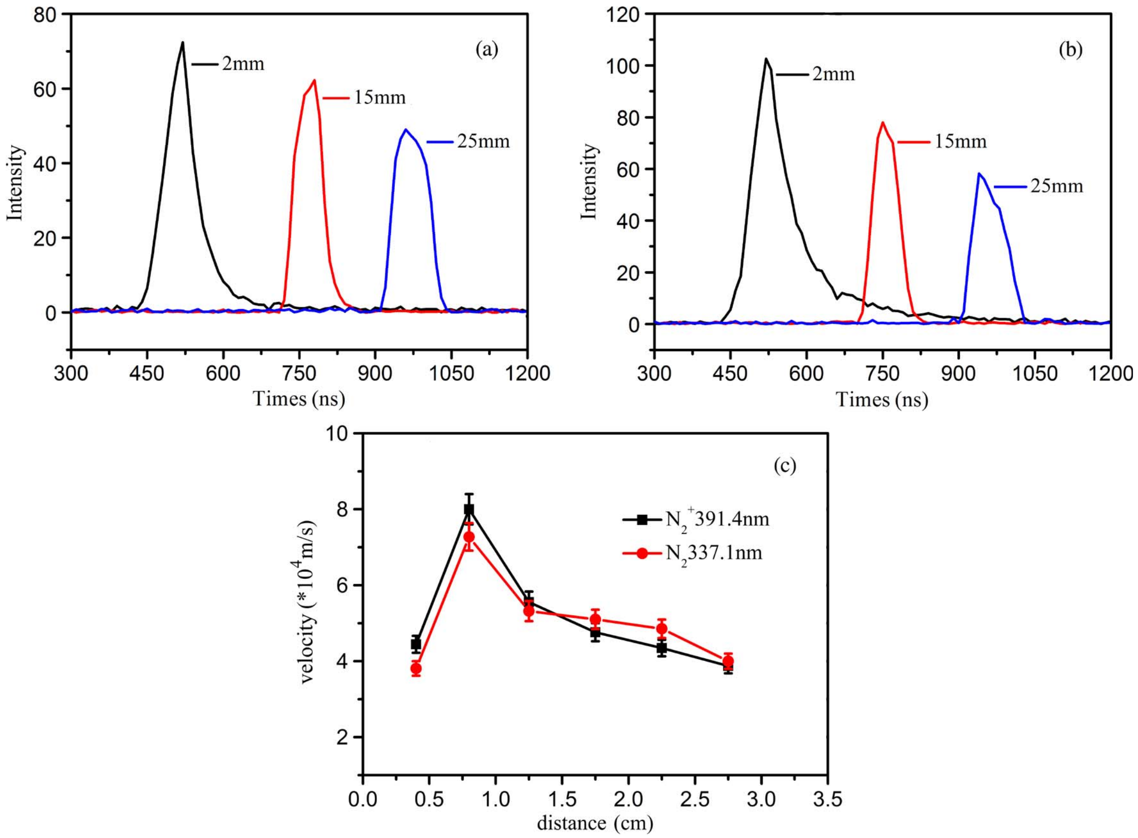


Fig. 9. Temporal emission behavior of the selected band heads of (a) N_2 337.1 nm and (b) N_2^+ 391.4 nm. The emission is from the plasma plume at 2, 15, and 25 mm away from the nozzle. (c) Velocity of the plasma bullet versus time based on the N_2 337.1-nm and N_2^+ 391.4-nm measurements. The applied voltage V_{app}, the pulse frequency, and the pulsewidth are 8 kV, 4 kHz, and 1600 ns, respectively.

B. Voltage Method

As mentioned previously, because the resistance of R_1 is very big, the propagation of the plasma plume is not affected by the thin wire. Fig. 6(a) shows that the plasma plume keeps propagating even if the thin wire is in contact with the plasma plume. When the thin wire is in contact with the plasma plume at different positions, the voltage potential waveform of the plume is measured, as shown in Fig. 6(b). For convenience, the applied-voltage waveform is also shown in this figure. The two voltage waveforms shown in Fig. 6(b) are corresponding to the plume voltage potential at 1.5 and 3.5 cm away from the nozzle. Similar to that in the current method, the closer the contacting position of the thin wire is to the nozzle, the earlier the plasma plume voltage appears. To estimate the plume propagation velocity, the spatially resolved plasma plume voltage potential is measured. Then, the plume propagation velocity is calculated, as shown in Fig. 6(c). It shows that the plasma plume accelerates first. It reaches a peak velocity of about 55 km/s.

C. Charge Method

As mentioned earlier, when the plasma plume is in contact with the aluminum foil, as shown in Fig. 3, the charges carried by the plume are deposited on the aluminum foil surface. The charge deposited on the foil surface can be measured through the current probe. When the quartz tube moves close to the nozzle, the charges deposited on the aluminum foil surface appears earlier, as shown in Fig. 7. The two typical current waveforms correspond to the quartz tube placed at 1 and 3 cm away from the nozzle. According to Fig. 7, the average velocity of the plasma bullets is estimated to be about 60 km/s. It should be emphasized that when the quartz tube is placed too closer to the nozzle, the discharge is affected by the tube, and it probably affects the plasma plume propagation velocity.

D. ICCD Method

The ICCD method has been used by many different groups to estimate the plasma bullet velocity. Fig. 8(a) shows the dynamics of the plasma plume. It clearly shows that the plasma plume is indeed a bulletlike volume of plasma, which travels at high speed. To have a more detailed discussion about plume dynamics, the plume velocity versus time is shown in Fig. 8(b). It clearly shows that the plume starts to accelerate as soon as it is launched from the nozzle. It reaches a peak velocity of about 85 km/s. Then, it drops quickly until it cannot be captured anymore. This behavior is similar with that obtained through the voltage method. Although the peak velocity is about 30% higher than that obtained through the voltage method.

E. Spectroscopy Method

The spectroscopy method, as shown in Fig. 4 (v), estimates the plasma plume propagation velocity according to the spatially and temporally resolved emission spectra of several selected emission band heads of a certain molecular ion. The band heads selected in the following experiments are N_2 $(\mathrm{C-B, v=0-0})$ transition (337.1 nm) and N_2^+ $(\mathrm{B-X, v=0-0})$ transition (391.4 nm). Fig. 9(a) and (b) shows the temporal emission behavior of the selected band heads. The emission is from the plasma plume at 2, 15, and 25 mm away from the nozzle. For both band heads, the optical emission from the plasma plume close to the nozzle appears earlier. Therefore, the plasma bullet velocity can also be estimated according to the distance from the nozzle and the corresponding appearing time of the band heads. Fig. 9(c) shows the velocity of the plasma bullet versus time based on the N_2 337.1-nm and N_2^+ 391.4-nm measurements. This result is also close to that measured by the ICCD camera.

IV. DISCUSSION

The first method, i.e., the "current method," is simple and can be used directly to estimate the velocity of the plasma bullet. However, as mentioned previously, due to the relative large dimension of the probe, it is difficult to obtain the spatially resolved plasma propagation velocity. On the other hand, the "voltage method" can be used to obtain the spatially resolved plume propagation velocity. However, this method may interfere with the propagation of the plasma plume even if the plasma plume keeps propagating, as seen by bare eyes. The "charge method" can also be used to obtain the spatially resolved plume propagation velocity by collecting charges on an equivalent capacitor. However, it may have some influence on the plasma propagation velocity because the propagation of the plasma is interfered. The "ICCD method" is the most direct way to show the dynamics of plasma bullet propagation, but the ICCD camera is quite expensive. Finally, the "spectroscopy method" can be used to obtain the spatially resolved plume propagation velocity. It may also give us inside information about the plasma plume, but it is expensive.

In a word, the first three methods (i.e., the "current method," the "voltage method," and the "charge method") are simple and cheap but not precise enough. The last two methods (i.e., the "ICCD method" and the "spectroscopy method") are very precise but expensive. All the five methods could be used to measure the spatially resolved plasma propagation velocity.

V. CONCLUSION

Five different methods to measure an atmospheric-pressure nonequilibrium plasma plume propagation velocity have been reported. The advantage and disadvantage of each method have been discussed. The obtained velocities of these methods have good agreement, which indicates that these methods are reliable.

REFERENCES

[1] M. Laroussi, "Low-temperature plasmas for medicine?" *IEEE Trans. Plasma Sci.*, vol. 37, no. 6, pp. 714–725, Jun. 2009.

[2] M. Laroussi, "Low temperature plasma-based sterilization: Overview and state-of-the-art," *Plasma Process. Polym.*, vol. 2, no. 5, pp. 391–400, Jun. 2005.

[3] A. Shashurin, M. N. Shneider, A. Dogariu, R. B. Miles, and M. Keidar, "Temporal behavior of cold atmospheric plasma jet," *Appl. Phys. Lett.*, vol. 94, no. 23, p. 231 504, Jun. 2009.

[4] M. K. Boudam, M. Moisan, B. Saoudi, C. Popovici, N. Gherardi, and F. Massines, "Bacterial spore inactivation by atmospheric-pressure plasmas in the presence or absence of UV photons as obtained with the same gas mixture," *J. Phys. D, Appl. Phys.*, vol. 39, no. 16, pp. 3494–3507, Aug. 2006.

[5] Q. Nie, C. Ren, D. Wang, S. Li, J. Zhang, and M. G. Kong, "Self-organized pattern formation of an atmospheric pressure plasma jet in a dielectric barrier discharge configuration," *Appl. Phys. Lett.*, vol. 90, no. 22, p. 221 504, May 2007.

[6] G. Fridman, A. Brooks, M. Balasubramanian, A. Fridman, A. Gutsol, V. Vasilets, H. Ayan, and G. Friedman, "Comparison of direct and indirect effects of non-thermal atmospheric-pressure plasma on bacteria," *Plasma Process. Polym.*, vol. 4, no. 4, pp. 370–375, May 2007.

[7] J. L. Walsh and M. G. Kong, "Contrasting characteristics of linear-field and cross-field atmospheric plasma jets," *Appl. Phys. Lett.*, vol. 93, no. 11, p. 111 501, Sep. 2008.

[8] X. Lu, T. Ye, Y. Cao, Z. Sun, Q. Xiong, Z. Tang, Z. Xiong, J. Hu, Z. Jiang, and Y. Pan, "The roles of the various plasma agents in the inactivation of bacteria," *J. Appl. Phys.*, vol. 104, no. 5, p. 053 309, Sep. 2008.

[9] J. L. Zhang, J. Sun, D. Z. Wang, and X. G. Wang, "A novel cold plasma jet generated by capillary atmospheric DBD discharge," *Thin Solid Films*, vol. 506/507, pp. 404–408, May 2006.

[10] E. Stoffels, I. Kieft, and R. Sladek, "Superficial treatment of mammalian cells using plasma needle," *J. Phys. D, Appl. Phys.*, vol. 36, no. 23, pp. 2908–2913, Dec. 2003.

[11] R. Dorai and M. J. Kushner, "A model for plasma modification of polypropylene using atmospheric pressure discharges," *J. Phys. D, Appl. Phys.*, vol. 36, no. 6, pp. 666–685, Mar. 2003.

[12] P. Chu, "Plasma-treated biomaterials," *IEEE Trans. Plasma Sci.*, vol. 35, no. 2, pp. 181–187, Apr. 2007.

[13] K. N. Ostrikov, S. Kumar, and H. Sugai, "Charging and trapping of macroparticles in near-electrode regions of fluorocarbon plasmas with negative ions," *Phys. Plasmas*, vol. 8, no. 7, pp. 3490–3497, Jul. 2001.

[14] X. Lu, "One-dimensional bubble model of pulsed discharge in water," *J. Appl. Phys.*, vol. 102, no. 6, p. 063 302, Sep. 2007.

[15] P. Bruggeman and C. Leys, "Non-thermal plasmas in and in contact with liquids," *J. Phys. D, Appl. Phys.*, vol. 42, no. 5, p. 053 001, Mar. 2009.

[16] P. Bruggeman, L. Graham, J. Degroote, J. Vierendeels, and C. Leys, "Water surface deformation in strong electrical fields and its influence on electrical breakdown in a metal pin-water electrode system," *J. Phys. D, Appl. Phys.*, vol. 40, no. 16, pp. 4779–4786, Aug. 2007.

[17] K. Ostrikov, "Colloquium: Reactive plasmas as a versatile nanofabrication tool," *Rev. Mod. Phys.*, vol. 77, no. 2, pp. 489–511, Apr. 2005.

[18] S. Babayan, J. Jeong, V. Tu, J. Park, G. Selwyn, and R. Hicks, "Deposition of silicon dioxide films with an atmospheric-pressure plasma jet," *Plasma Sources Sci. Technol.*, vol. 7, no. 3, pp. 286–288, Aug. 1998.

[19] D. Mariotti, V. Svrcek, and D. G. Kim, "Self-organized nanostructures on atmospheric microplasma exposed surfaces," *Appl. Phys. Lett.*, vol. 91, no. 18, p. 183 111, Oct. 2007.

[20] D. Mariotti, "Nonequilibrium and effects of gas mixtures in an atmospheric microplasma," *Appl. Phys. Lett.*, vol. 92, no. 15, p. 151 505, Apr. 2008.

[21] M. Laroussi and X. Lu, "Room-temperature atmospheric pressure plasma plume for biomedical applications," *Appl. Phys. Lett.*, vol. 87, no. 11, p. 113 902, Sep. 2005.

[22] X. Lu, Z. Jiang, Q. Xiong, Z. Tang, and Y. Pan, "A single electrode room-temperature plasma jet device," *Appl. Phys. Lett.*, vol. 92, no. 15, p. 151 504, Apr. 2008.

[23] X. Lu, Z. Jiang, Q. Xiong, Z. Tang, X. Hu, and Y. Pan, "An 11 cm long atmospheric pressure cold plasma plume for applications of plasma medicine," *Appl. Phys. Lett.*, vol. 92, no. 8, p. 081 502, Feb. 2008.

[24] J. L. Walsh and M. G. Kong, "Room-temperature atmospheric argon plasma jet sustained with submicrosecond high-voltage pulses," *Appl. Phys. Lett.*, vol. 91, no. 22, p. 221 502, Nov. 2007.

[25] M. Keidar and I. Beilis, "Sheath and boundary conditions for plasma simulations of a Hall thruster discharge with magnetic lenses," *Appl. Phys. Lett.*, vol. 94, no. 19, p. 191 501, May 2009.

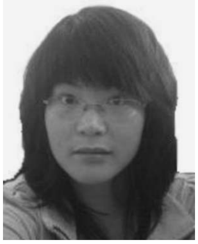
[26] X. Lu and M. Laroussi, "Dynamics of an atmospheric pressure plasma generated by submicrosecond voltage pulses," *J. Appl. Phys.*, vol. 100, no. 6, p. 063 302, Sep. 2006.

[27] X. Lu, Q. Xiong, and Z. Xiong, "Propagation of an atmospheric pressure plasma plume," *J. Appl. Phys.*, vol. 105, no. 4, p. 043 304, Feb. 2009.

[28] N. Mericam-Bourdet, M. Laroussi, A. Begum, and E. Karakas, “Experimental investigations of plasma bullets,” *J. Phys. D, Appl. Phys.*, vol. 42, no. 5, p. 055 207, Mar. 2009, (7pp).

[29] M. Teschke, J. Kedzierski, E. G. Finantu-Dinu, D. Korzec, and J. Engemann, “High-speed photographs of a dielectric barrier atmospheric pressure plasma jet,” *IEEE Trans. Plasma Sci.*, vol. 33, no. 2, pp. 310–311, Apr. 2005.

[30] B. Sands, B. Ganguly, and K. Tachibana, “A streamer-like atmospheric pressure plasma jet,” *Appl. Phys. Lett.*, vol. 92, no. 15, p. 151 503, Apr. 2008.



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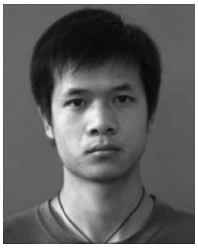

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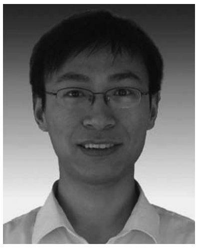

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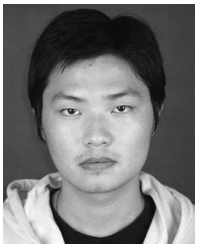

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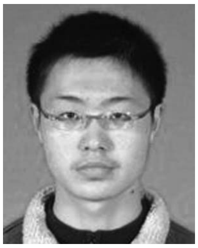

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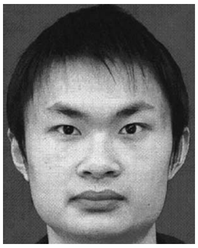

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