A Touchable Pulsed Air Plasma Plume Driven by DC Power Supply

Article *in* IEEE Transactions on Plasma Science · December 2010

DOI: 10.1109/TPS.2010.2082571

4 authors, including:

Shuqun Wu
Nanjing University of Aeronautics & Astronautics
59 PUBLICATIONS **792** CITATIONS
SEE PROFILE

Xinpei Lu
Huazhong University of Science and Technology
170 PUBLICATIONS **6,465** CITATIONS
SEE PROFILE

Zilan Xiong
University of California, Berkeley
32 PUBLICATIONS **759** CITATIONS
SEE PROFILE

A Touchable Pulsed Air Plasma Plume Driven by DC Power Supply

ShuQun Wu, XinPei Lu, *Senior Member, IEEE*, ZiLan Xiong, and Yuan Pan

***Abstract*—It remains a challenge to generate cold air plasma at atmospheric pressure. In this paper, a room-temperature atmospheric-pressure air plasma plume is generated by a dc power supply. Current–voltage measurements show that the discharge actually appears periodically with a frequency of about 25 kHz. The discharge current has a pulsewidth that is less than 100 ns while its peak value reaches about 17 mA. There is no risk of glow-arc transition. The plasma can be touched by a bare hand without any feeling of electrical shock or warmth. The maximum length of the plasma is about 2 cm. The whole device, including the power supply, is less than 1 kg. The preliminary inactivation experiment results show that the plasma can effectively kill *Enterococcus faecalis*, one of the main types of bacterium causing the failure of root canal treatment.**

***Index Terms*—Air plasma, atmospheric-pressure plasma, biomedical application, dc discharge, nonequlibrium plasma, nonthermal plasma, optical emission spectrum (OES), plasma jet, plasma medicine, pulse discharge, sterilization.**

I. INTRODUCTION

ATMOSPHERIC pressure cold plasmas (APCPs) have received a lot of attention recently due to some novel applications, such as surface and material processing [1]–[3], absorption and reflection of electromagnetic radiation [4], synthesis of nanomaterial [5], [6], and biomedical applications [7]–[14]. Among the novel applications, the biomedical applications of the APCPs, such as sterilization, are attracting significant attentions. For the biomedical applications, plasma jet devices, which generate plasmas in open space (surrounding air) rather than in confined discharge gaps only, have a lot of advantages over the traditional dielectric barrier discharge devices [15]–[26]. However, most of the plasma jet devices reported use noble gases or the mixtures of the noble gases with a small amount of O_2 or with a small amount of air as the working gases. If ambient air is used as the working gas, the gas temperature of the plasma is normally quite high, which is unfavorable for biomedical applications [27], [28]. In addition, for biomedical applications, it has strict requirements for the safety of plasma devices. It is preferable that the device can be hand held and that the plasma can be directly touched by a human body without any feeling of electrical shock. Heretofore, various plasma jet devices, particularly those using room air as the working gas, are still urgently needed.

In this paper, a simple atmospheric-pressure room-temperature air plasma device is reported. The device can be hand held, and the plasma can be touched by a human body without any electrical shock. The total weight of the device, including the power supply, is less than 1 kg. The rest of this paper is organized as follows. In the experimental part, the device and the diagnostic system will be described in detail. In the results section, the gas temperature measurement, the current–voltage characteristics of the discharge, the emission spectrum of the plasma, and the preliminary decontamination experimental results will be presented. Finally, a short conclusion will be made in the conclusion section.

II. EXPERIMENTAL SETUP

The device is driven by a homemade dc power supply. The output voltage of the power supply can be adjusted up to 20 kV. The output of the power supply is connected to a stainless steel needle electrode through a resistor R of 120 MΩ. The tip of the stainless steel needle has a radius of about 50 μm. When a counter electrode, such as a finger, is placed close to the needle, a plasma is generated. Fig. 1(a) and (b) shows the schematic of the device and the photograph of the setup. A P6015 Tektronix HV probe is used to measure the voltage on the needle, and a TCP202 Tektronix current probe is used to measure the discharge current. The optical emission spectra are measured by a half-meter spectrometer (Princeton Instruments Acton SpectraHub 2500i).

III. EXPERIMENTAL RESULTS

When the dc power supply is turned on, a plasma is generated between the tip of the needle and the finger. The plasma is similar to the positive corona discharge. However, the plasma generated by this device can be touched by a human body directly, as shown in Fig. 2, which is not the case for the traditional corona discharge. The device has no risk of glow-arc transition. The maximum length of the plasma is about 2 cm. The gas temperature of the plasma is kept at room temperature, which can be measured by a thermal meter or estimated according to the emission spectrum of the nitrogen second positive system $C^3\Pi_u - B^3\Pi_g(\Delta v = -2)$ emission band. It is about 300 K, according to the thermal meter measurement.

Manuscript received August 22, 2010; revised September 23, 2010 and September 26, 2009; accepted September 26, 2010. Date of publication October 25, 2010; date of current version December 10, 2010. This work was supported in part by the National Natural Science Foundation under Grants 10875048 and 51077063 and in part by the Chang Jiang Scholars Program, Ministry of Education, People's Republic of China.

The authors are with the College of Electrical and Electronics Engineering, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: 670367263@qq.com; luxinpei@hotmail.com; xiongzilan@qq.com; panyuan@hust.edu.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2010.2082571

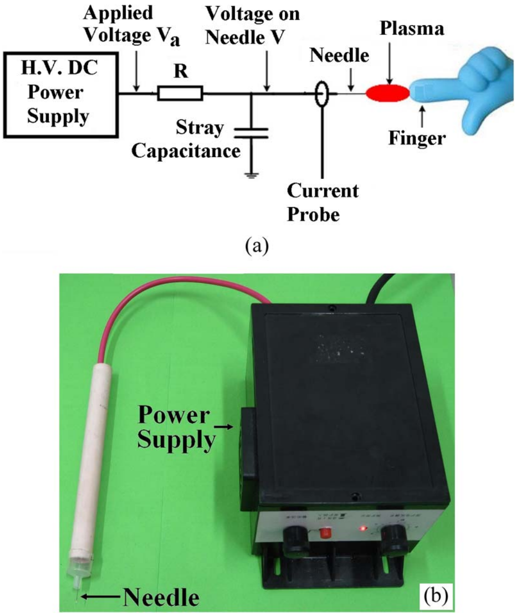


Fig. 1. (a) Schematic of the device. (b) Photograph of the setup.

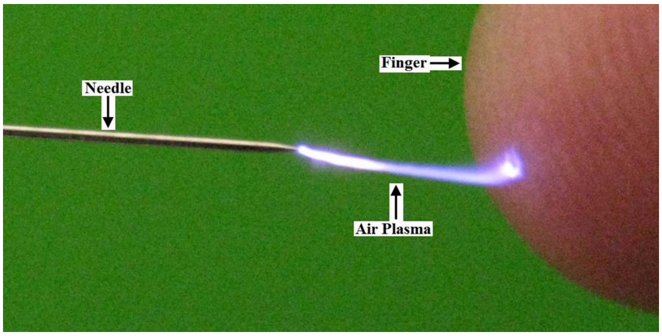


Fig. 2. Plasma touched by a finger.

To study the I–V characteristics of the plasma, a P6015 Tektronix HV probe is used to measure the voltage on the needle, and a TCP202 Tektronix current probe is used to measure the discharge current. In order to generate the plasma, the supplied voltage can be varied from about 5 to 20 kV, and the distance between the tip of the needle and the finger can be adjusted from zero to a maximum of about 2 cm. Fig. 3(a) shows the I–V characteristics of the discharge for a gap distance of 5 mm. It is interesting to notice that the discharge actually appears periodically with a frequency of about 25 kHz. This is similar to the well-studied positive corona discharge [29]–[32].

The ballast resistor used in this paper is much higher than that used by Staack *et al.*, which is no more than 1 MΩ [33], [34]. In their experiment, Staack *et al.* observed a direct current rather than a pulsed current. The gas temperature of the plasma in their experiment depends on the working gas and the dc current. When the discharge current is about 1.4 mA, their gas temperature is about 370 K for pure helium and 1000 K for pure air. In their experiment, when helium or argon is used, the discharge voltage remains the same when the discharge current increases from 0.8 to 3.8 mA. On the other hand, when air is used, the discharge voltage drops from about 470 to 380 V while the discharge current increases from 0.8 to 3.8 mA.

To have a close look on the I–V characteristics of each pulse, Fig. 3(b) shows the current and voltage waveforms of a single pulse. As we can see from this figure, the discharge current lasts for about 100 ns. During the discharge, the applied voltage only drops to about 170 V. The repetition frequency of the pulse current strongly depends on the gap distance. When the applied voltage is about 18 kV, the repetition frequency is about 35 kHz for a gap distance of 3 mm and less than 10 kHz for a gap distance of 17 mm.

To further investigate how the applied voltages V_a affect the repetitive frequencies f and the peak value I_{peak} of the discharge currents, the repetitive frequencies f and the peak value I_{peak} of the discharge currents for different applied voltages V_a are measured. The gap distance is fixed at 4 mm for the measurement. Fig. 4(a) and (b) shows how f and I_{peak} change with V_a. Fig. 4(a) shows clearly that f increases with the increase of V_a when V_a is lower than 12 kV. The repetitive frequencies f remain at about 35 kHz when V_a keeps increasing. On the other hand, as can be seen from Fig. 4(b), the peak value I_{peak} of the discharge currents has a linear relationship with V_a. The higher the V_a, the bigger the I_{peak}.

It should be mentioned that the stray capacitor plays a very important role during the discharge. After each pulse, the stray capacitor is recharged until it reaches the breakdown voltage. Then, the following discharge pulse appears. The stray capacitance is estimated according to the voltage drops on the needle and the total charge for a single current pulse for the gap distance of 5 mm. When the applied voltage is 20 kV, the total charge Q for a single current pulse is about 0.7×10^{-9} C. The voltage drop ΔV on the needle is about 170 V. Therefore, according to $C = Q/\Delta V$, the stray capacitor can be estimated to be about 4 pF. Because the stray capacitor is small and the ballast resistor is big, the discharge current pulse only lasts for a very short time. Therefore, the gas temperature of the plasma remains at room temperature. Moreover, although the discharge current peak value is quite high, the pulsewidth of the current is only about 100 ns. These two characteristics result in the plasma being able to be touched by a human body without any feeling of warmth or electric shock, which are two of the distinguishing features of the device.

An optical emission spectrum (OES) allows the analysis of the radiation emitted by the atoms, ions, molecules, and radicals. The OES is very useful for diagnostic purposes, which give important information about the plasma. The optical emission is collected from the plasma that is about 5 mm away from the tip of the needle. The entrance and exit slits of the spectroscopy are fixed at 100 μm. A grating of 1200 g/mm is used for the measurement. Fig. 5 shows the emission bands from the air plasma in the wavelength range of 250–800 nm. As can be seen, the spectrum is dominated by N_2 emission. Moreover, there is also an O-atom emission. As we know, O atoms are very active and play a very important role in the applications of plasma medicine [14].

Finally, to investigate how active the plasma generated by the device is, the preliminary inactivation experiment results are presented next. *Enterococcus faecalis*, one of the main types of bacterium causing the failure of root canal treatment, is used.

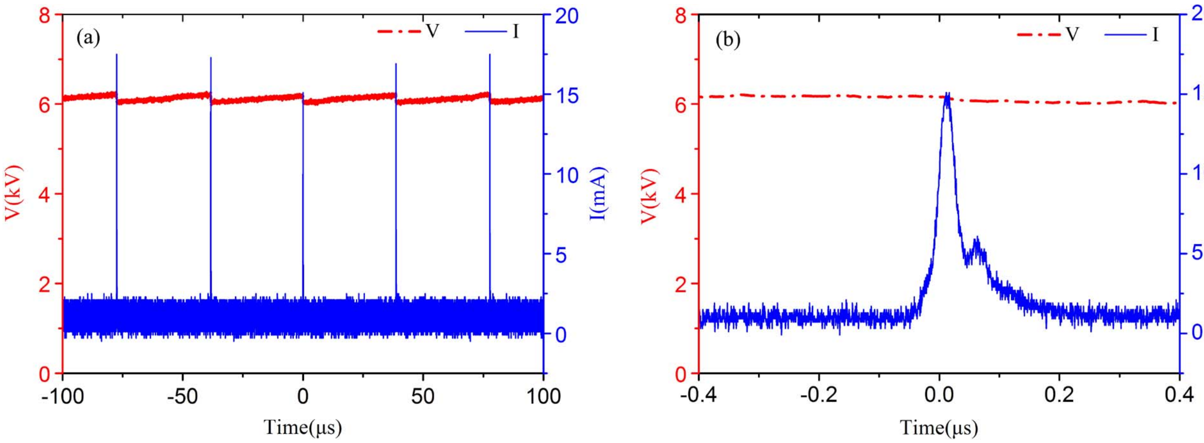
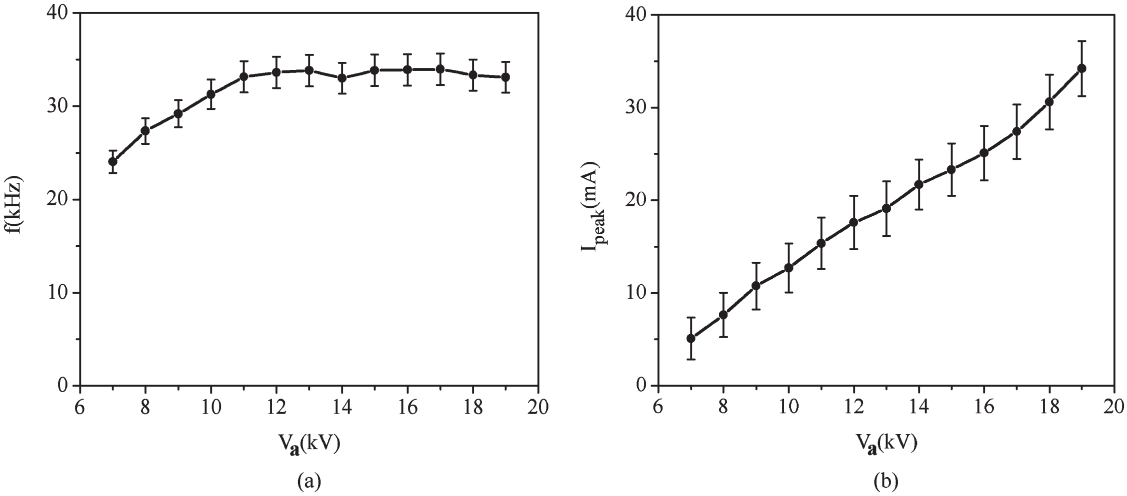


Fig. 3. (a) Typical I–V characteristics of the plasma. (b) Close look on the I–V characteristics of a typical single pulse.



(a)

(b)

Fig. 4. (a) Repetitive frequency f and (b) peak value I_{peak} of the pulse discharge current for different applied voltages V_a. The gap distance is fixed at 4 mm for the measurement.

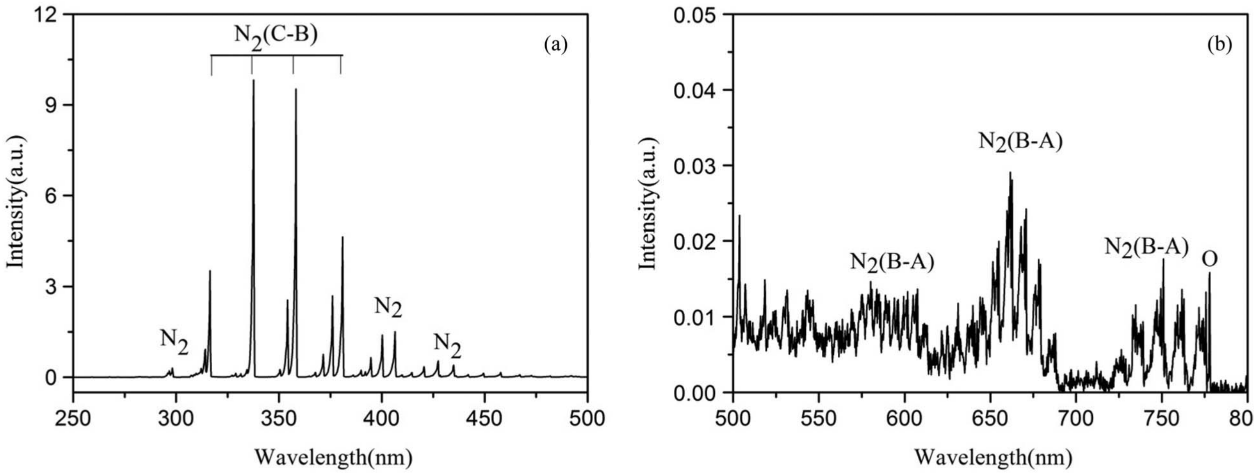


Fig. 5. Emission spectrum of the plasma. (a) 250–500 nm. (b) 500–800 nm.

A suspension of about 100 μL containing *E. faecalis* bacterium concentrations of 10^4 CFU/mL is evenly spread over each agar plate in a Petri dish. The diameter of the Petri dish is about 6 cm. The distance between the needle tip and the bacteria is about 1 cm. The applied voltage is 9 kV. The treated sample acts as the cathode. During the treatment, the plasma needle is

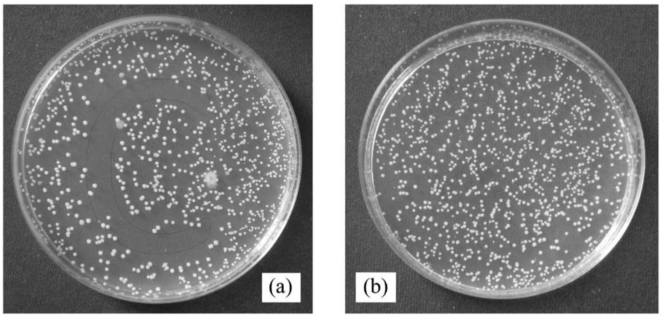


Fig. 6. Photograph of *E. faecalis* on agar in Petri dish. (a) Treated by the plasma. (b) Control. The distance between the needle tip and the bacteria sample is about 10 mm. During the treatment, the petri dish moves with a speed of about 3 mm/s in a letter "C" pattern.

moving with a speed of about 3 mm/s in a letter "C" over the Petri dish. The total treatment time is about 1 min. As shown in Fig. 6(a) and (b), the bacteria are completely removed in the exposed area.

IV. CONCLUSION

In short, an atmospheric-pressure air plasma is generated by a homemade dc power supply. The I–V waveforms show that the discharge is actually pulsed. It appears periodically with a pulse frequency of about 25 kHz. The pulsewidth of the discharge current is only about 100 ns, which results in the gas temperature remaining at room temperature and the plasma being able to be touched by a human body. Preliminary inactivation experimental results show that the device can be used for applications such as root canal treatment.

REFERENCES

[1] 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.

[2] D. Mariotti, "Nonequilibrium and effects of gas mixtures in an atmospheric microplasma," *Appl. Phys. Lett.*, vol. 92, no. 15, pp. 151 505-1–151 505-3, Apr. 2008.

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

[4] M. Laroussi, "Interaction of microwaves with atmospheric-pressure plasmas," *Int. J. Infrared Millim. Waves*, vol. 16, no. 12, pp. 2069–2083, Dec. 1995.

[5] I. Levchenko, K. Ostrikov, and E. Tam, "Uniformity of postprocessing of dense nanotube arrays by neutral and ion fluxes," *Appl. Phys. Lett.*, vol. 89, no. 22, pp. 223 108-1–223 108-3, Nov. 2006.

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

[7] 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.

[8] 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, pp. 111 501-1–111 501-3, Sep. 2008.

[9] G. Fridman, A. Brooks, M. Galasubramanian, 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.

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

[11] C. Jiang, A. A. Mohamed, R. H. Stark, J. H. Yuan, and K. H. Schoenbach, "Removal of volatile organic compounds in atmospheric pressure air by means of direct current glow discharges," *IEEE Trans. Plasma Sci.*, vol. 33, no. 2, pp. 1416–1425, Aug. 2005.

[12] X. Lu, Z. Xiong, F. Zhao, Y. Xian, Q. Xiong, W. Gong, C. Zou, Z. Jiang, and Y. Pan, "A simple atmospheric pressure room-temperature air plasma needle device for biomedical applications," *Appl. Phys. Lett.*, vol. 95, no. 18, pp. 181 501-1–181 501-3, Nov. 2009.

[13] 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.

[14] 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, pp. 053 309-1–053 309-5, Sep. 2008.

[15] G. Fridman, G. Friedman, A. Gutsol, A. B. Shekhter, V. N. Vasilets, and A. Fridman, "Applied plasma medicine," *Plasma Process. Polym.*, vol. 5, no. 6, pp. 503–533, Aug. 2008.

[16] 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).

[17] 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, pp. 191 501-1–191 501-3, May 2009.

[18] M. Laroussi and X. Lu, "Room-temperature atmospheric pressure plasma plume for biomedical applications," *Appl. Phys. Lett.*, vol. 87, no. 11, pp. 113 902-1–113 902-3, Sep. 2005.

[19] 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, pp. 231 504-1–231 504-3, Jun. 2009.

[20] 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, pp. 151 504-1–151 504-3, Apr. 2008.

[21] E. Stoffels, I. E. Kieft, R. E. J. Sladek, L. J. M. van den Bedem, E. P. van der Laan, and M. Steinbuch, "Plasma needle for *in vivo* medical treatment: Recent developments and perspectives," *Plasma Sources Sci. Technol.*, vol. 15, no. 4, pp. S169–S180, Nov. 2006.

[22] D. Mariotti, V. Svrcek, and D. G. Kim, "Self-organized nanostructures on atmospheric microplasma exposed surfaces," *Appl. Phys. Lett.*, vol. 91, no. 18, pp. 183 111-1–183 111-3, Oct. 2007.

[23] X. Lu, Y. Cao, P. Yang, Q. Xiong, Z. Xiong, Y. Xian, and Y. Pan, "An RC plasma device for sterilization of root canal of teeth," *IEEE Trans. Plasma Sci.*, vol. 37, no. 5, pp. 668–673, May 2009.

[24] Y. Xian, X. Lu, Y. Cao, P. Yang, Q. Xiong, Z. Jiang, and Y. Pan, "On plasma bullet behavior," *IEEE Trans. Plasma Sci.*, vol. 37, no. 10, pp. 2068–2073, Oct. 2009.

[25] F. Iza, M. G. Kong, and J. K. Lee, "Electron kinetics in radio-frequency atmospheric-pressure microplasmas," *Phys. Rev. Lett.*, vol. 99, no. 7, p. 075 004, Aug. 2007.

[26] G. C. Kim, G. J. Kim, S. R. Park, S. M. Jeon, H. J. Seo, F. Iza, and J. K. Lee, "Air plasma coupled with antibody-conjugated nanoparticles: A new weapon against cancer," *J. Phys. D, Appl. Phys.*, vol. 42, no. 3, p. 032 005, Feb. 2009.

[27] J. Kolb, A. Mohamed, R. Price, R. Swanson, A. Bowman, R. Chiavarini, M. Stacey, and K. Schoenbach, "Cold atmospheric pressure air plasma jet for medical applications," *Appl. Phys. Lett.*, vol. 92, no. 24, pp. 241 501-1–241 501-3, Jun. 2008.

[28] K. H. Becker, U. Kogelschatz, and K. H. Schoenbach, *Non-Equilibrium Air Plasmas at Atmospheric Pressure*. London, U.K.: IOP Publ. Ltd., 2005.

[29] Z. Machala, I. Jedlovsky, and V. Martisovits, "DC discharges in atmospheric air and their transitions," *IEEE Trans. Plasma Sci.*, vol. 36, no. 4, pp. 918–919, Aug. 2008.

[30] K. Schoenbach, A. El-Habachi, W. Shi, and M. Ciocca, "High pressure hollow cathode discharges," *Plasma Sources Sci. Technol.*, vol. 6, no. 4, pp. 468–477, Nov. 1997.

[31] Z. Machala, C. Laux, and C. Kruger, "Transverse dc glow discharges in atmospheric pressure air," *IEEE Trans. Plasma Sci.*, vol. 33, no. 2, pp. 320–321, Apr. 2005.

[32] D. Antao, D. Staack, A. Fridman, and B. Farouk, "Atmospheric pressure dc corona discharges: Operating regimes and potential applications," *Plasma Sources Sci. Technol.*, vol. 18, no. 3, p. 035 016, Aug. 2009, (11pp).

[33] D. Staack, B. Farouk, A. Gutsol, and A. Fridman, "DC normal glow discharges in atmospheric pressure atomic and molecular gases," *Plasma Sources Sci. Technol.*, vol. 17, no. 2, p. 025 013, May 2008.

[34] D. Staack, B. Farouk, A. Gutsol, and A. Fridman, "Characterization of a dc atmospheric pressure normal glow discharge," *Plasma Sources Sci. Technol.*, vol. 14, no. 4, pp. 700–711, Nov. 2005.

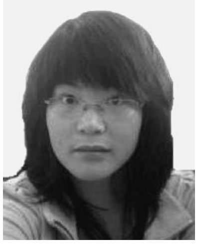
ShuQun Wu received the B.E. degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2010, where he is currently working toward the Ph.D. degree in the College of Electrical and Electronic Engineering.

His research interests include the diagnostics and applications of atmospheric-pressure nonequilibrium plasma sources.

XinPei Lu (M'06–SM'07) received the Ph.D. degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2001.

From 2002 to 2006, he was with the Applied Plasma Technology Laboratory, Old Dominion University, Norfolk, VA, as a Research Associate. Since 2007, he has been with the Huazhong University of Science and Technology, where he is currently a Professor (ChangJiang Scholar) in the College of Electrical and Electronic Engineering. His research interests include low-temperature plasma sources and their applications, the modeling of low-temperature plasmas, plasma diagnostics, and pulse power technology. He is the author or coauthor of about 60 scientific articles in these areas.

Dr. Lu has also served as a Guest Editor of the IEEE TRANSACTIONS ON PLASMA SCIENCE and as a Session Chair at the International Conference on Plasma Science for several years.



ZiLan Xiong received the B.E. degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2008, where she is currently working toward the Ph.D. degree in the College of Electrical and Electronic Engineering.

Her research interests include plasma medicine and the applications of atmospheric-pressure nonequilibrium plasma sources.

Yuan Pan received the degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 1955.

He was with the Institute of 401, the Institute of 585, the Institute of Plasma Physics, CAS, Hefei, China, the Joint European Tokamak, and the Fusion Research Center, University of Texas at Austin, Austin. He is with the Huazhong University of Science and Technology, where he is currently a Professor and the Honorary Dean of the College of Electrical and Electronic Engineering. His main research interests include magnetic confinement nuclear fusion, high-power pulse source technology, superconducting electric power, and pulse power technology. He is the author or coauthor of about 100 scientific articles in these areas.

Prof. Pan is a member of the Chinese committee of experts of the International Thermonuclear Experimental Reactor. He was a member of the Chinese Academy of Engineering in 1997.