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A simple atmospheric pressure room-temperature air plasma needle device for biomedical applications

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Rather than using noble gas, room air is used as the working gas for an atmospheric pressure room-temperature plasma. The plasma is driven by submicrosecond pulsed directed current voltages. Several current spikes appear periodically for each voltage pulse. The first current spike has a peak value of more than 1.5 A with a pulse width of about 10 ns. Emission spectra show that besides excited OH, O, N_2(C–B), and N_2^+(B–X) emission, excited NO, N_2(B–A), H, and even N emission are also observed in the plasma, which indicates that the plasma may be more reactive than that generated by other plasma jet devices. Utilizing the room-temperature plasma, preliminary inactivation experiments show that *Enterococcus faecalis* can be killed with a treatment time of only several seconds. © *2009 American Institute of Physics*. [doi:10.1063/1.3258071]

The biomedical applications of atmospheric pressure nonthermal plasma have recently been attracting significant attention.[1–13] Currently, the working gases of most of the plasma jet devices are noble gases or mixtures of the noble gases with a small amount of O_2 or air.[14–25] If ambient air is used as the working gas, several serious difficulties are encountered in the plasma generation process. Among these are high gas temperatures and disrupting instabilities.[26,27] Equally important, for biomedical applications, it has strict requirements for the safety of plasma devices. It is preferable that the device can be handheld and the plasma can be directly touched by a human without any harm.

In this letter, we present a method whereby stable plasma in air can be generated. The gas temperature of the plasma is at room temperature. The plasma can be touched by a human finger without any harm. Figures 1(a) and 1(b) show the schematic of the device and photograph of the plasma touched by a human finger. Figure 1(c) is the photograph of the device.

The main body of the device is made of a stainless steel needle. The diameter of the needle tip is about 100 μm. The stainless steel needle serves as the electrode, which is connected to a high-voltage (HV) submicrosecond pulsed direct current power supply through an 80 kΩ ballast resistor and a 36 pF capacitor, where both the resistor and the capacitor are used for controlling the discharge current and the voltage on the needle. The device is similar with that used for corona discharge. However, for traditional corona discharges, the plasma cannot be touched by a human and the peak discharge current is low. Because of the series-connected capacitor and the resistor, the discharge current is limited to a safety range for a human. Therefore, it can be used for biomedical applications. This is an advantage of the device.

Because the device has only one electrode, the plasma is generated between the HV needle electrode and the human finger when the plasma is touched by a human finger. To have a better understanding of the plasma, the applied voltage V_1, the voltage after the capacitor V_2, and the voltage V_3 on the needle are measured by three P6015 Tektronix HV probes, respectively. The discharge currents are measured by a CT1 Tektronix current probe. The voltage and current waveforms are recorded by a Tektronix DPO7104 wideband digital oscilloscope. Figures 2(a) and 2(b) show the voltage and current waveforms.

As we can see from Fig. 2(a), several current spikes appear periodically for one voltage pulse. To have a clear view of the discharge current spikes, Fig. 2(b) zooms in the first three current spikes. It clearly shows that, when the voltage applied on the needle reaches about 1.5 kV, the first discharge appears and the first current spike has a peak value of more than 1.5 A with a pulse width of about 10 ns. The following current spikes have a peak value of about 0.5 A. The pulse width of each current spike is about 10 ns. The time between each current pulse is about 100 ns. Figure 2(b) also shows that the voltage on the needle drops from 1.5 kV

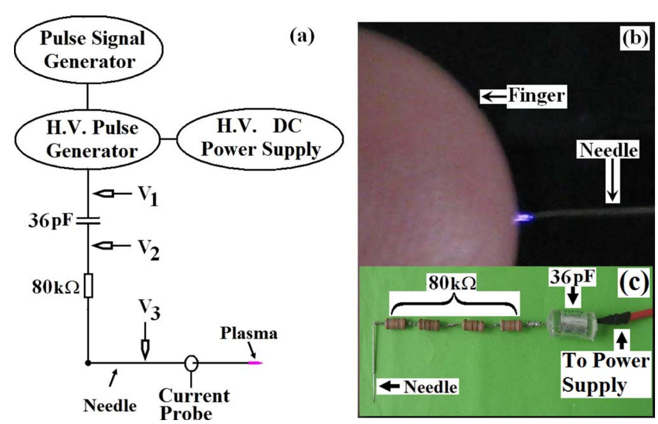

FIG. 1. (Color online) (a) Schematic of the device. (b) Photograph of the air plasma touched by a human finger. The distance between the needle tip and the finger is about 1 mm. (c) Photograph of the device.

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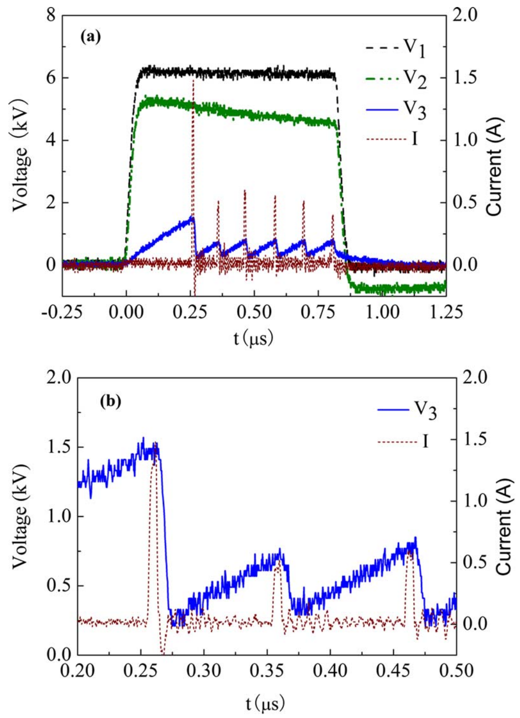

FIG. 2. (Color online) (a) *I-V* characteristic of the plasma. V_1, V_2, and V_3 are the voltages at three different locations, as shown in Fig. 1(a). I is the discharge current. (b) Zoom in the first three discharge current spikes I and the voltage on the needle V_3.

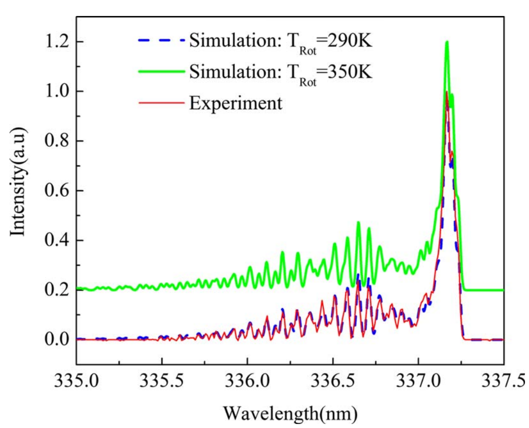

FIG. 3. (Color online) Experimental and simulated spectra of N_2 second positive system 0-0 transition.

to about 250 V after the first discharge. This is due to the breakdown of the air gap between the needle and the human finger. Then the voltage on the needle increases slowly to about 750 V until the next discharge current spikes appears. It should be emphasized that the maximum voltage on the needle before the first discharge is about two times higher than that of the subsequent discharges. This may be due to the residue charge particles and excited species, which results in the lower breakdown voltage.

For biomedical applications, the gas temperature of the plasma needs to be at or close to room temperature. By comparing the simulated spectra of the C $^3\Pi_u$–B $^3\Pi_g$ (0-0) band transition of nitrogen with the experimental recorded spectra, the rotational temperatures of the nitrogen can be obtained when best fit is achieved.[25] Figure 3 shows that the simulated spectrum of rotational temperature of 290 K gives a good fit to the measured spectrum. When the T_{rot} is 350 K, the simulation results show that the rotational band of the spectrum expands to short wavelength direction much further than the spectrum obtained from the experiment. Therefore, the gas temperature of the plasma plume is at room temperature.

To investigate what kinds of excited species are presented in the plasma, a half meter spectroscopy (Princeton Instruments Action SpectraHub 2500i) is used to measure the optical emission of the plasma plume. Figure 4 shows the emission spectra of the plasma. It clearly shows that, besides excited OH, O, N_2(C–B), and N_2^+(B–X) emission, excited NO, H, N_2(B–A), and even N emission are observed in the plasma, which indicates that the plasma may be more reactive than that generated by other plasma jet devices.

Finally, the preliminary inactivation experiment results are presented next. The bacterial samples that are treated by the plasma are *Enterococcus faecalis*, one of the main types of bacterium causing the failure of root canal treatment. A suspension of 100 μl containing *Enterococcus faecalis* bacterium concentrations of 10^6 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 mm. During the treatment, the Petri dish moves with a speed of about 2 mm/s in a crisscross pattern. Accordingly, the total treatment time is about 60 s. As shown in Fig. 5, the bacteria are completely removed in the exposed area. For a typical He plasma jet,[23] it takes about 2 min to sterilize one exposed area in a Petri dish. When the treatment time is reduced to 1 min, the area treated by the plasma jet is not completely sterilized.

In conclusion, a simple plasma device, which can generate atmospheric pressure room-temperature air plasma, is presented. The plasma can be touched by humans without

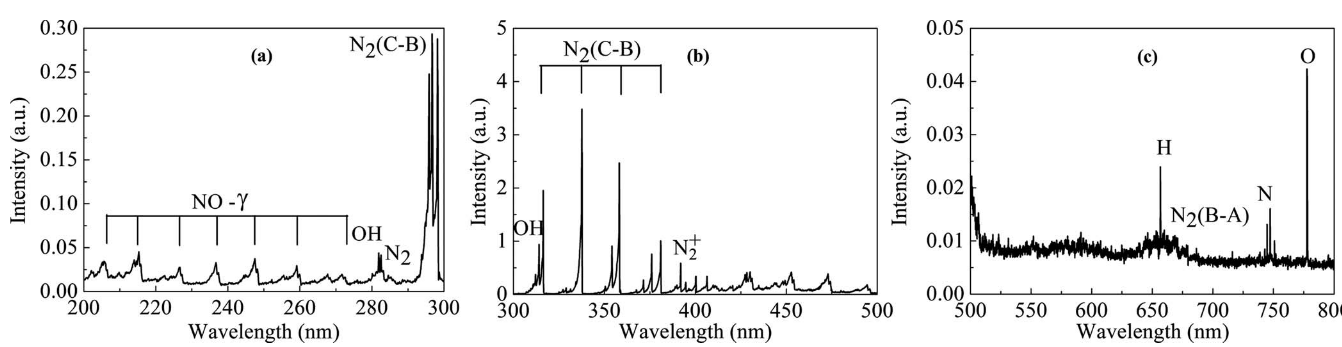

FIG. 4. The emission spectra of the plasma for (a) 200–300, (b) 300–500, and (c) 500–800 nm.

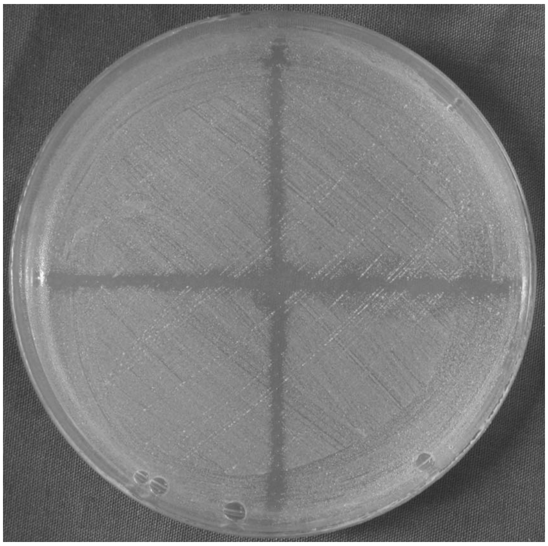

FIG. 5. Photograph of *Enterococcus faecalis* on agar in Petri dish treated by the plasma. The distance between the needle tip and the bacteria sample is about 1 mm. During the treatment, the Petri dish moves with a speed of about 2 mm/s in a crisscross pattern.

any harm. Emission spectra show that there are strong NO, N, $N_2(B-A)$, and H emission, which are not observed in other atmospheric pressure room-temperature plasma jet devices. Preliminary inactivation experimental results show that the plasma can kill *Enterococcus faecalis* effectively.

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[1]R. Dorai and M. J. Kushner, J. Phys. D: Appl. Phys. **36**, 666 (2003).
[2]M. Laroussi, Plasma Processes Polym. **2**, 391 (2005).
[3]P. Chu, IEEE Trans. Plasma Sci. **35**, 181 (2007).
[4]P. Bruggeman and C. Leys, J. Phys. D: Appl. Phys. **42**, 053001 (2009).
[5]D. Mariotti, Appl. Phys. Lett. **92**, 151505 (2008).
[6]K. Ostrikov, Rev. Mod. Phys. **77**, 489 (2005).
[7]J. L. Walsh and M. G. Kong, Appl. Phys. Lett. **93**, 111501 (2008).
[8]G. Fridman, A. Brooks, M. Galasubramanian, A. Fridman, A. Gutsol, V. Vasilets, H. Ayan, and G. Friedman, Plasma Processes Polym. **4**, 370 (2007).
[9]M. Keidar and I. Belis, Appl. Phys. Lett. **94**, 191501 (2009).
[10]X. Yan, F. Zou, X. Lu, G. He, M. Shi, Q. Xiong, X. Gao, Z. Xiong, Y. Li, F. Ma, M. Yu, C. Wang, Y. Wang, and G. Yang, Appl. Phys. Lett. **95**, 083702 (2009).
[11]M. Laroussi and X. Lu, Appl. Phys. Lett. **87**, 113902 (2005).
[12]D. Mariotti, V. Svrcek, and D. G. Kim, Appl. Phys. Lett. **91**, 183111 (2007).
[13]P. Bruggeman, P. Guns, J. Degroote, J. Vierendeels, and C. Leys, Plasma Sources Sci. Technol. **17**, 045014 (2008).
[14]B. Sands, B. Ganguly, and K. Tachibana, Appl. Phys. Lett. **92**, 151503 (2008).
[15]D. Kim, J. Rhee, B. Gweon, S. Moon, and W. Choe, Appl. Phys. Lett. **91**, 151502 (2007).
[16]R. Sladek, E. Stoffels, R. Walraven, P. Tielbeek, and R. Koolhoven, IEEE Trans. Plasma Sci. **32**, 1540 (2004).
[17]E. Stoffels, I. Kieft, R. Sladek, L. Van den Bedem, E. van der Laan, and M. Steinbuch, Plasma Sources Sci. Technol. **15**, S169 (2006).
[18]M. Laroussi, W. Hynes, T. Akan, X. Lu, and C. Tendero, IEEE Trans. Plasma Sci. **36**, 1298 (2008).
[19]M. Laroussi, IEEE Trans. Plasma Sci. **37**, 714 (2009).
[20]G. Fridman, G. Friedman, A. Gutsol, A. B. Shekhter, V. N. Vasilets, and A. Fridman, Plasma Processes Polym. **5**, 503 (2008).
[21]X. Lu, Y. Cao, P. Yang, Q. Xiong, Z. Xiong, Y. Xian, and Y. Pan, IEEE Trans. Plasma Sci. **37**, 668 (2009).
[22]J. Kolb, A. Mohamed, R. Price, R. Swanson, A. Bowman, R. Chiavarini, M. Stacey, and K. Schoenbach, Appl. Phys. Lett. **92**, 241501 (2008).
[23]X. Lu, T. Ye, Y. Cao, Z. Sun, Q. Xiong, Z. Tang, Z. Xiong, J. Hu, Z. Jiang, and Y. Pan, J. Appl. Phys. **104**, 053309 (2008).
[24]A. Shashurin, M. N. Shneider, A. Dogariu, R. B. Miles, and M. Keidar, Appl. Phys. Lett. **94**, 231504 (2009).
[25]X. Lu, Z. Jiang, Q. Xiong, Z. Tang, and Y. Pan, Appl. Phys. Lett. **92**, 151504 (2008).
[26]K. H. Becker, K. H. Schoenbach, and J. G. Eden, J. Phys. D: Appl. Phys. **39**, R55 (2006).
[27]K. H. Becker, U. Kogelschatz, K. H. Schoenbach, and R. J. Barker, *Non-equilibrium Air Plasmas at Atmospheric Pressure* (Institute of Physics Publishing, Bristol, 2005).