Radio Frequency Metrology for Mobile Atmospheric Pressure Plasma Devices

V. J. Law, N. O'Connor, and S. Daniels
National Center of Plasma Science and Technology, Dublin City University
Collins Avenue, Glasnevin, Dublin 9, Dublin, Ireland

Abstract — Real-time time-domain and frequency-domain measurement of mobile atmospheric pressure plasma is described. The measurements are non-invasive and deployed on the main power-line to the plasma device.

1. INTRODUCTION
The atmospheric pressure coaxial dielectric barrier discharge (DBD) has been established for non-thermal plasma processing for more than 20 years [1, 2]. Their potential for direct impact on society in the guise of surface modification of engineering materials and the destruction of microbial pathogens on contaminated surfaces are now becoming apparent. Recently atmospheric pressure glow discharges in the form of: plasma pencil [3] needle [4, 5], jet [6] and torch [7] have been reported to have low electrical power consumption. The common feature of these devices is that they have a volume discharge that acts as a source of ion species and an expanding plume that is driven by the flow of gas passing through the chamber volume. The drive circuitry typically employs a variety of sinusoidal or pulse power technology; some of which have fixed frequencies (13.56 MHz [5, 6]) or variable frequencies (7 kHz and 1 MHz [7–9]). Within this body of work and within the water and food purification sectors [10], it is commonly believed that continuous power switching technology has better power conversion efficiencies than sinusoidal excitation.

This paper presents the application of Radio Frequency (RF) metrology to atmospheric pressure plasma devices [11, 12]. In particular, to semiconductor power switching circuitry and Flyback transformer that drives an atmospheric discharge. Section 2 describes active RF metrology deployed on the power-line of the Flyback driven DBD. Section 3 describes passive RF metrology on the power-line. Section 4 describes the combination of time-domain and frequency-domain passive RF metrology of a sinusoidal driven plasma. Finally Section 5 provides a conclusion to this work.

2. ACTIVE RF METROLOGY
The salient points of the helium DBD have been presented in [12, 13]. Here only the RF measurement is described. The drive circuitry and the Rohde & Schwarz FSL3 scalar network analyzer is shown in Figure 1. Figure 2 shows the equivalent electrical model (EEM) of the measurement. The EEM comprises a 7 element Chebyshev filter front-end probe, a 1.2 m length of 50-Ohm transmission-line and a variable resistor termination ($R_3$) that represents the plasma. Figure 3 shows the measured frequency dependent modulus of the plasma as a function of power: the resolution bandwidth (RBW) is set to 30 kHz. Here it can be seen that the modulus is plasma dependent at 165 MHz.

A standard linear software package is used to simulate these measurements and after a few parameter iterations the transmission-line responds to the plasma termination at 165 MHz, see Figure 4. At this frequency the EEM yields a resistance termination of 10–21 Ohm with a transmission length of $l = 1.3$ m and a velocity factor of 0.62. N.B. a relative offset of 23 dB is used to normalize the dynamic gain and account for the insertion of the Chebyshev filter. The additional $l = 0.1$ m and reduced velocity factor may also be attributed to the additional line length through filter. These simulations show the depth of the node increasing with applied power, thus indicating the helium DBD is becoming more conductive as the power is increased. From a plasma point-of-view this is expected as the ion/electron density increases with applied power.

3. PASSIVE RF METROLOGY
In this section the same helium DBD is integrated using passive RF metrology to measure the drive oscillator phase noise and frequency pulling as a function of plasma plume-surface interaction [12],
Figure 1: Schematic of SNA and DBD.

Figure 2: EEM of DBD circuit: 50 Ohm transmission = 1.5 m in length.

Figure 3: Reflection modulus of DBD as a function of power.

Figure 4: EEM simulation of DBD. $l = 1.3$ m, velocity factor = 0.62, and R3: 10 and 21 Ohm.

The measurement is made on the power-line as shown in Figure 1. However, in this case the spectrum analyzer is protected from the high voltage input level by a capacitive clamp front-end probe which has a voltage coupling factor of 0.001.

To exemplify this measurement, Figures 5 and 6 shows the helium DBD driven at 177 KHz with an applied dc power of 11 W under stable and unstable modes of operation due to flow rate conditions. The terms stable and unstable are used to classify visual instabilities within the plasma plume. Here the only operating difference between the stable and unstable mode is the gas flow rate: 2 standard liters per minute (slm) for Figure 5 and 5 slm for Figure 6. These results show that the spectrum analyzer captures the flow rate instability as a 2 kHz modulation of the drive carrier frequency. This instability is in the audible range of the human ear and can be clearly heard and captured on a microphone.

In the second example the oscillator drive frequency is measured as a function of plasma plume interaction with two different surfaces (copper connected to ground and glass) at a distance of 16 mm, and plume expanding into free-space. The helium flow for these measurements is 2 slm at a drive frequency of 172.9 kHz and applied dc power of 10.5 W. The results for the copper (dotted-line) glass (dashed-line) and air (solid-line) are shown in Figure 7. The result shows frequency pulling of $\sim 700$ Hz from free space to metal coupling with the plume. For example: 172.9 kHz without
the work-piece; 172.6 with the glass slide and; 172.2 kHz with the copper strip. This equates to a frequency pulling ratio of $f_{\text{max}} / f_{\text{min}}$ of 1.004. This result indicates that the plume-surface interaction is adding a reactive component to the circuit. It is thought that this affect may have many processing applications.

4. PULSE CURRENT WIDTH MODULATION

In this section a Dow Corning plasma solutions Labline\textsuperscript{TM} reel-to-reel helium atmospheric pressure plasma system [13] is monitored using passive RF metrology. The time-domain voltage and current waveforms are captured and compared to the frequency-domain current signal. The purpose of these measurements is to identify the effective pulse of the current drawn by the plasma in each half of the driving frequency period. The voltage and current waveforms for a 1400 W helium plasma is shown in Figures 8 and 9. The spectrum analyzer frequency-domain envelope measurement was optimized by setting the RBW to be larger than the carrier frequency, but significantly smaller than the effective current pulse width, see Figure 10.

A comparison between time-domain and frequency-domain measurements reveals a correlation between the envelope nulls and the current pulse width. For example the nulls have a frequency span ($\tau$) of $\sim$ 140 KHz which approximate to the current pulse width ($\sim$ 7 µs). In effect the current
pulses drawn appears to be pulse width modulating the carrier. If this is the case, the micro-scale events (Figure 6: 0.1 µs with current amplitudes of ∼ 0.15 A) may have an influence on the effective current and hence the power dissipated in the plasma.

5. CONCLUSION

This paper has presented active and passive RF metrology measurement of atmospheric pressure plasmas. These measurement are non-invasive (they are only placed on the power-line). Hence they are not limited by the size of the plasma device: This being an important factor when the plasma device is miniaturized for mobile hand-held applications.

The active RF Metrology approach provides an indication of the DBD electrical performance, and when coupled with an EEM the scalar measurement provides information on plasma termination. To gain access to the plasma impedance a vector network measurement needs to be implemented. Passive RF metrology measurements do not require an EEM to interpret the results in that they can be directly correlated to gas flow and plume-surface interactions. The reduction in instrumentation complexity when compared to active RF metrology makes this approach attractive. The frequency-domain measurements provide both temporal (instabilities) and spatial (plume-surface interaction) information. Both of these attributes are necessary for monitoring plasma-surface interactions. The combination of time and frequency-domain measurements allows the current drawn by the plasma to be interrogated. Micro-scale plasma events in the current waveform are likely to modify the effective current pulse width and hence the power developed.
within the plasma. The origin and timing of these micro-scale events are of great interest as they may disclose the underlying plasma physics and chemistry.

ACKNOWLEDGMENT
This work is supported by Enterprise Ireland under grant number CFTD/7/IT/304.

REFERENCES