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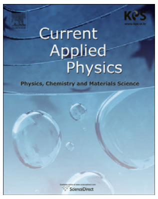

Measurement of optical signals as a plasma propagation in the atmospheric pressure plasma jet columns

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A B S T R A C T

The propagation of plasma jets with argon gas is characterized in terms of two factors, the effect of electric field distribution along the tube and the effect of voltage polarity, from the observed results of optical signals along the entire column of plasma. The optical signal of plasma propagates from the high electric-field region of high-voltage electrode toward the low field region of the open air-space, regardless of the polarity of the voltage. The optical intensity and the propagation velocity are higher for the positive voltage than for the negative voltage. Moreover, the length of plasma plume exited from the end of the glass tube into the open air is shorter for the negative voltage. When the optical intensity is strong enough, a secondary peak signal follows the primary peak. In the plasma column on the inside of the glass tube, the optical intensity and the propagation velocity depend on the strength of the electric field; they are both high at the high-field region of voltage terminal and decay toward the end of the tube. The velocity is as fast as 10^4 m/s at the high-field region and slows down to 10^3 m/s at the low-field region of the glass-tube end. However, the plasma accelerates drastically to be (10^4–10^5) m/s after exiting the glass tube toward open air, even though the electric field is a quite low and thus the optical signal decays low before fading out. The experimental observations present in this report are explained with the propagation of the plasma diffusion waves.

1. Introduction

"Plasma bullets," which are a form of plasma jets or plumes in open air, have been observed in previous studies of atmospheric plasma [1–9]. The behavior of bullet propagation and of plasma jet has been studied through the use of various methods. The speed of the plasma bullets has been observed to be of about (10^4–10^5) m/s by using high-speed photography via intensified charge-coupled devices (ICCDs). The spatial behavior of plasma jet has also been investigated using laser absorption [10], laser spectroscopy [11], and through optical measurements made with a photomultiplier tube [12].

These plasma bullets have been described using a streamer propagation model based on photo-ionization [1,2], through computer simulations of streamer propagation [6,7], with a fast ionization wave discharge [13], and, recently, as a plasma diffusion wave-packet with velocity of (10^4–10^5) m/s [14,15]. However, the underlying mechanism of plasma propagation has not yet been clearly understood. Even though several theories of plasma jet propagation have been proposed [1–15], they have only estimated the magnitude of the velocity of the plasma bullet in open air.

The purpose of this report is to provide details on plasma propagation with respect to time and to axial variations in the whole column of plasma jet. Plasma behavior is investigated along the long plasma jet column formed within a combined system with a glass tube. These experiments are conducted with and without a ground electrode in order to understand the response of the plasma propagation to the changes in the electric field. The other goal of this report is to present reproducible data of plasma propagation according to the change in polarity of the operating voltage. Thus, we expect that the mechanism for plasma behavior can be discovered with the use of the data provided in this report.

Even though conventional observations with an ICCD [1–9] or through spectroscopic analysis [10–12] provide precise data of the behavior of plasma jets, additional observations are still required. In this report, the axial behavior of the plasma along the entire column of plasma will be described, and the results of previous studies [1–12] will also be confirmed. The optical observation technique introduced in this report provides the comprehensive information of the entire plasma-column in a convenient experimental setting, without involving sophisticated diagnostic tools.

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In this study, we present a method for measuring optical signals with an optical probe combined with a photo-sensor amplifier. The optical probe is used to measure radiation emanating from the plasma, and the signals are monitored with an oscilloscope. A similar technique was introduced to study light propagation along a plasma column in long tube lamps [16–18]. In ICCD measurements, real-time variations in the plasma propagation are visually captured, yet the cost of the camera equipment is restrictive. On the other hand, low-cost optical probe measurements can be adapted for use toward long plasma columns. Furthermore, the behavior of the plasma jets can be analyzed with respect to spatial variation through the transformation of the optical signals to the time domain. Precise information of plasma propagation can also be expeditiously obtained with the optical probe of a photo-sensor amplifier.

2. Experimental setup

Fig. 1 shows the schematics of the experiment [19]. The syringe electrode is inserted into a glass tube with an outer diameter of 5 mm, length of 60 mm, and inner diameter of 3 mm. Ar gas is injected through a Teflon tube into syringe needle electrode, and a high voltage with a sinusoidal frequency of 45.5 kHz is applied to the electrode by a DC-AC inverter. The optical signals are measured with an optical probe at a distance of 0.5 mm away from the surface of the glass tube. The signals are then captured by an optical probe and are transmitted through the optical fiber to light-to-voltage photo-sensor amplifier (HAMAMATSU C6386-01). The sensing wavelength is in the range of (400–1100) nm, and the frequency response has a wide range from DC to MHz. The diameter of the opening at the head of the optical probe is of 1 mm, and the detection slit window of the same size is installed with the gap of 0.5 mm from the surface of the glass tube. The radiation emanating from the plasma is detected with an optical probe, and the optical signals as well as the voltage and the current are monitored through the oscilloscope. The behavior of the plasma can be visualized by mapping the signal captured at a specific point in the plasma column by the oscilloscope into the time domain.

We have two experimental set-ups in Fig. 1(a) and (b). Fig. 1(a) has a long plasma column within an electric field that is generated by the high-voltage electrode, through a glass tube, toward open air that acts as a virtual ground at the infinite space. In Fig. 1(b), the optical signals are measured according to the change in the electric field caused by the presence of the ground electrode on the external surface of the glass tube, within which there can be a region with a strong electric field or a region without an electric field.

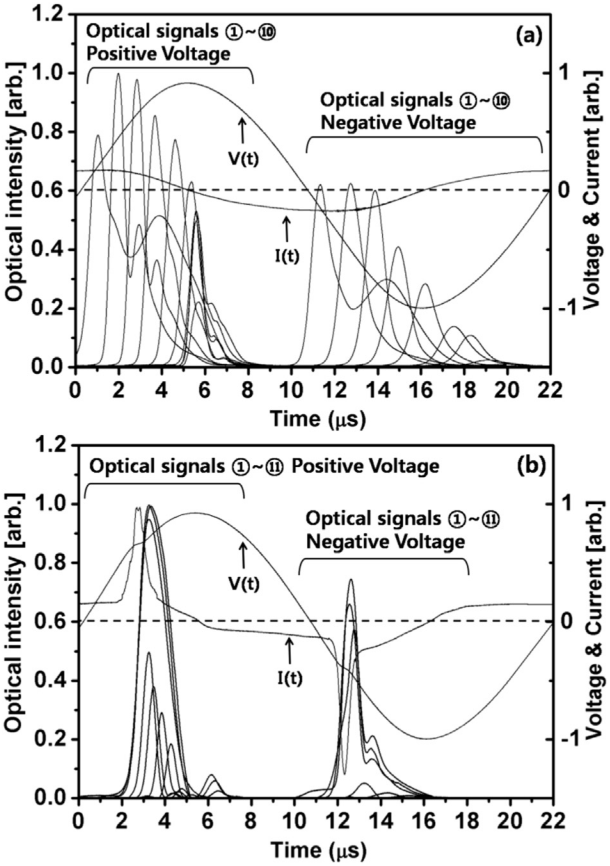

Fig. 2. Voltage V(t) and current I(t) of the system and optical signals measured at points 1–11. Two groups of optical signals are shown according to the polarity of the voltage. (a) and (b) correspond to the signals without the ground electrode and with ground electrode, as shown in Fig. 1(a) and (b), respectively.

In Fig. 1(a), the measuring points are numbered 1–10. Points 1–6 inside the tube are at distances of 7.5, 17.5, 27.5, 37.5, 47.5, and 57.5 mm from the high-voltage electrode at the glass tube, and the numbers 7–10 extending into the open air outside the tube are at distances of 62.5, 67.5, 72.5 and 75.5 mm. A picture of the plasma jet discharge is shown at the bottom of Fig. 1(a). When a root mean square (RMS) voltage and current of 1.9 kV and 2.5 mA are applied, the plasma plume extends about 18 mm from the end of the glass tube into the open air.

Fig. 1(b) shows the schematics with the ground electrode connected to the glass tube externally. The ground electrode has a 5 mm width and is installed at a distance of 17 mm along the glass tube length. The measuring points are numbered 1–11. Numbers 1–3 are in region with an electric field extending from the nozzle to the ground electrode. Numbers 4–8 are in the region from the

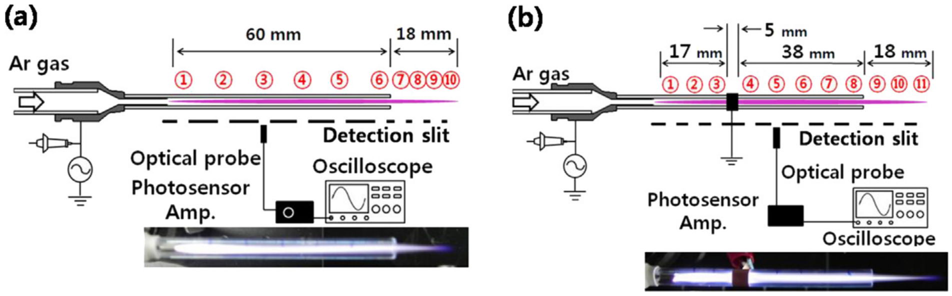

Fig. 1. Schematics of the optical signal measurement system. The measuring points inside and outside the glass tube are noted with numbers, and a picture of the discharge is shown in the bottom of each figure. (a) Without a ground electrode, the optical signals measured inside the glass tube are numbered 1–6 and outside glass tube 7–10. (b) With the ground electrode between Points 3 and 4, the signals are numbered 1–8 inside the glass tube and 9–11 outside.