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Filamentary streamer discharges in argon at atmospheric pressure excited by surface plasmon polaritons

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This paper describes a microwave plasma jet in an argon atmosphere capable of generating filamentary streamer discharges within the entire quartz tube excited by surface waves of surface plasmon polaritons (SPPs) located in the tube. Several discharge streamers are immediately produced at the end of the copper wire when incident power reaches 20 W. From simulations, the wavelength of the surface wave was found to be approximately 5.7 cm. Although the developing streamers induce E-field enhancements favoring discharging, more streamer bifurcations requiring additional energy to maintain discharging diminish the resonant enhanced E-field. The underlying mechanism of the proposed plasma jet is resonant excitation of SPPs and its interaction with plasmas. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4738779]

I. INTRODUCTION

Microwave discharges at atmospheric gas pressures have been investigated for a wide variety of industrial purposes.1 Several applications, such as metal surface nitriding, medical instrument sterilization, and high-velocity fuel ignition, have been developed and/or improved.2–8 Among the various plasma devices, surface-wave plasma (SWP) sources are showing great promise in satisfying certain requirements for plasma processing in air. Several SWP jet devices have been investigated experimentally and theoretically.1–13

To address these issues on SWP sources, much research has focused on optimizing microwave-driven plasma sources. At low gas pressure, the uniformity of plasma below the dielectric slab over the largest area possible is one of the most important factors. Many trials are normally performed or empirical methods are used to obtain optimal uniformity.14–19 In air, an important factor is the efficient discharging of the system because of the difficulty in ionizing at higher gas pressures.1,6–9 A possible means to obtain efficient discharge control is to use a plasma-dielectric resonator, i.e., the surfatron, the surfaguide, and the waveguide surfatron.1

A surface wave of surface plasmon polaritons (SPPs) is an electromagnetic excitation existing at the interface between a metal (or over-dense plasma) and a dielectric material. The resonant interaction between electromagnetic radiation and the SPPs at the dielectric–plasma interface results in a remarkably enhanced E-field.18 Using SPPs to heat plasma and its features to produce over-dense plasma has been proposed.16,17 However, designs of the microwave plasma jets or torches based on the principles of SPPs in over-dense plasmas have not been clearly described. The purpose of this study is to establish an effective design for a microwave plasma jet excited by SPP surface waves in air.

II. EXPERIMENTAL SETUP AND DISCHARGE RESULTS

A. Experimental setup and operations

This study involved experimenting with an atmospheric pressure jet device. Figures 1(a) and 1(b) show a photo of the discharge setup and a schematic of the jet structure, respectively. Microwave radiation at 2.45 GHz, operated in mode TE10, is transmitted through in a narrow rectangular waveguide of length 200 mm and height 10 mm. Two tapered rectangular waveguides, 236 mm long and each connected at their 10-mm-high end to either side of the narrow rectangular waveguide, taper out to 50 mm in height at their other ends, which are connected with an R22 rectangular waveguide. The width of all waveguides is 110 mm. A 4-mm-radius hole is drilled in the center of the top side of the narrow rectangular waveguide to direct microwaves into the quartz discharge tube. A stainless steel sleeve (Fig. 1(b)), 36 mm long, 4-mm outer radii, and 3-mm inner radii, is placed above the hole. The quartz tube (dielectric permittivity εd = 3.78), of length 250 mm with 3-mm outer radius and 2-mm inner radius, passes through the metal sleeve and the waveguide. A copper wire, of length 42 mm and radius 0.55 mm, is fixed along the inner surface of the quartz tube and extends 10 mm below the narrow rectangular waveguide (see Figure 1(b)).

Microwave radiation transmitted through the R22 rectangular waveguide is provided by a 2.45-GHz magnetron with variable input power from 0 to 800 W, equipped with a water
circulator to avoid power reflection damage. A D07-7C/ZM
controller (Jianzhong Machinery, Beijing) with a maximum
flow limit of 1000 sccm controls the working gas, high-purity
argon (99.999%). The gas flow in the discharge tube is main-
tained at a specific flow rate of 0.5 slm. When argon gas is
injected at atmospheric pressure, an input power of 20 W
is applied in the discharge tube (quartz tube + metal sleeve
+ internal copper wire) and filamentary streamer discharges
are generated throughout the interior of the quartz tube
(Figure 2(d)). In view of incident power and discharge condi-
tions, this is a more efficient surface-wave discharge jet com-
pared with those reported in the literatures.4–13 The plasma
parameters, i.e., the length of the plasma plume, the electron
density, the electron temperature, and the temperature of the
plasma plume, can be adjusted by gas flow rate and applied
power. Besides argon, other gases such as helium, nitrogen,
oxogen, or even air can also be used (see Figures 2(e)–2(h)).

B. Discharge results and discussions

In this special plasma jet setup, influencing factors on
plasma parameters are the incident microwave power and the
gas flow rate. Figure 2 shows photos taken during discharg-
ing under different operating conditions. When argon is in-
jected at a rate of 0.5 slm with a discharge tube input power of
110 W, a bright plasma jet is generated within the entire
quartz tube interior (Figure 2(a)). The flame profile exhibits
several bifurcations at the tip. At the slower rate of 0.3 slm
with input power of 80 W, a bright plasma jet is also generated
throughout the entire quartz tube (Figure 2(b)). The profile
becomes less distinct, although several bifurcations are still
visible at the tip. Moreover, if the rate of 0.5 slm is returned
but now with input power of 20 W, a bright purple discharge
is seen in the tube (Figure 2(c)). The discharge image in
Figure 2(d) is an enlargement of the plume in Figure 2(c).
Several discharges emanate from the end of the copper wire
and each discharge bifurcates into several smaller branches.

In regard to the discharge mechanism, discharging for
this proposed jet source is based on SPPs resonant excitation
in over-dense plasma. The propagation constant $k_{spp}$ on the
dielectric–metal interface is given by15, 18

$$k_{spp} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}},$$

(1)

where $\omega$ is the angular frequency of the electromagnetic
wave, and $\varepsilon_m$ and $\varepsilon_d$ are the relative permittivity of metal
and dielectric, respectively. In over-dense plasma instead of
metal, Liang’s experiment15 has produced visible SPPs at the
dielectric–plasma interface in their cylinder setup at lower
pressure. Therefore, $\varepsilon_m$ in Eq. (1) should be replaced by the
relative permittivity for plasma $\varepsilon_p$. The propagation constant
$k_{spp}$ on the dielectric–plasma interface is given by15–18

$$k_{spp} = k_0 \sqrt{\frac{\varepsilon_p \varepsilon_d}{\varepsilon_p + \varepsilon_d}},$$

(2)

where $\varepsilon_p$ and $\varepsilon_d$ are the relative permittivity of plasma and
dielectric, respectively (gas, quartz, and plasmas with densi-
ties lower than the cutoff density of high-frequency waves); $k_0$
$= \omega / c$ is the wave number in free space. The expression for


FIG. 3. SPP wavelength as a function of plasma density, quartz tube with $\varepsilon_d = 3.78$ and incident wave frequency of 2.45 GHz. (b) Enlargement of the low plasma density regime of (a).

\[
\varepsilon_p = 1 - \frac{\omega_p^2}{\omega(\omega + i\nu_{en})},
\]

where, $\omega_p = (e^2 n_r(\varepsilon_0 m_e))^{1/2}$ is the angular frequency of the plasma. Substituting for $\varepsilon_p$ in Eq. (2) and taking the real part $k'_{spp}$ from $k_{spp}$, we derive the wavelength of SPPs from expression $\lambda_{spp} = 2\pi/k'_{spp}$. The value of $\lambda_{spp}$ is approximately constant at 5.7 cm when the plasma density is higher than $0.8 \times 10^{18}$ m$^{-3}$ (see Figure 3).

At atmospheric gas pressures, development of instabilities results in the formation of filamentary streamers. Such behavior results from increases in losses with increasing pressure. With the main purpose of understanding discharge evolution, microwave streamers in the field of a standing wave have been studied with the help of a numerical fluid model. Simulations performed by Chaudhury et al. show the formation of a plasmoid that extends in the direction of the incident field by a diffusion-ionization mechanism and becomes a plasma streamer. Therefore, microwave streamers can provide a theoretical interpretation of the discharging in experiments. Here, one crucial point must be stressed; the proposed discharge is excited by an ultralow input microwave power ($20 \text{ W} \leq P$), which encourages us to further study of the local enhanced electrical field of SPPs.

III. ANALYSIS OF SIMULATIONS ON THE ELECTRICAL FIELD OF SURFACE WAVES

A. Simulation without plasmas

In our simulations, we use the HFSS (a software program based on the FEM method produced by ANSOFT Company) CAD simulation programs for 3D numerical modeling based on Maxwell equations. All following simulations are operated with incident microwave power of 1 W. The electric field distribution in simulations, for which the model setup is the same as the experiment, is shown in Figure 4. Figure 4(a) shows the $E$-field distribution over the central horizontal plane of the waveguides; Figure 4(b) shows the $E$-field distribution over an axial cross section of the discharge tube. The amplitude of the $E$-field intensity appears to peak in the narrow rectangular waveguide and decays on both sides of the tapered rectangular waveguide. This is consistent with conclusions of previous reports and accomplishes our design goals. The electric field distribution in simulations along the quartz tube has yielded two peaks; the wavelength scale (about 6.0 cm) is consistent with the theoretical calculation based on the above analysis of SPPs.

Various simulations were performed to generate electrical field distributions using a model without the metal sleeve (Figure 5). The stronger spatial wave field distributions with the metal sleeve are obtained by comparing Figure 5 with Figure 4. Similarly, Figure 6 shows more simulations of electrical field distributions using a model without the metal sleeve and the cooper wire. Although these are sampled in the same way, spatial wave field distributions are produced if stronger wave field amplitudes are placed only near the narrow rectangular waveguide and its field value is two orders of magnitude lower than that of Figure 4 or Figure 5. Comparing Figures 4–6, one concludes that the existence of the cooper wire affords a stronger electrical field in the discharge tube and the metal sleeve only slightly enhances the $E$-field.
FIG. 5. (a) and (b) E-field distributions from simulations with model without a metal sleeve.

B. Simulation with the contracted plasmas

Although an abrupt enhancement in the electrical field is achieved for our specially designed sources, discharging is with over-dense plasmas in the quartz tube. Therefore, we will further need to investigate numerically the possible influence of the plasmas on the surface wave distribution. Accounting for the complicated character of the plasmas in air, the following simulations are performed with contracted plasma model of Drude model described by Eq.(3).

Figure 7 shows the electrical field distributions over central cross sections of (a) the waveguides and (b) the discharge tube. The plasma in Figure 7 is three cylinder bodies (of 0.4 mm radii) distributed irregularly in the interior of the quartz tube near the copper wire, with a uniform plasma density of $2.0 \times 10^{18}$ m$^{-3}$ (here other density values can also be used producing similar results in simulations). The amplitude of the wave field distributions in simulations is stronger than that without plasmas. The locations of peaks in the electrical field occur under the narrow rectangular waveguide, which suggests that jet generation should be downstream. The effect of the plasmas on the wave distribution can be attributed to wave interference, multiple reflections, and scattering$^{21,22}$ taking place between the corrugated channels between discharge bifurcations, the copper wire, and the inner surface of the quartz tube. These can be seen in Figure 7(b) as an absence of the two peaks of E-field seen in Figures 4(b) and 5(b). The role of the plasma on surface wave propagation is also under further investigation.

C. Discussion on simulation results

Regarding plasma discharging, the input microwave distribution in the narrow rectangular waveguide couples to that in the discharge tube. This in turn interacts with the copper wire to form SPPs surface waves over the copper surface. From these surface waves (Figures 4 and 5), local enhanced E-fields accelerate the electrons that ionize the Ar gas thus creating the plasma. Afterward, an increasing plasma density reflects the input wave from the cutoff layer, which thereby limits its energy input in the region near the interface, and attenuates by the plasma. The electrons, accelerated by surface wave, then collide with the neutral Ar atoms; the density of electrons and excited Ar atoms will increase simultaneously. From discharges occurring at atmosphere gas pressures, discharge instabilities develop and result in the formation of filaments or streamers.$^{10,11}$ The field at the streamer tip is significantly enhanced and is responsible for the quick propagation of the streamer in the direction of the incident field because of an over-dense plasma density in the streamer channel. Furthermore, the SPP waves distributed in the discharge tube present a uniform pattern except for a partial enhanced peak seen in Figure 7. When an enormous number of excited argon particles revert back to their original states, we can observe the light patterns characteristic of filamentary streamer discharges.

As is well known, when an electrical field reaches critical values for gas discharge, denoted $E_c$, the gas will ionize to produce a plasma. $E_c$ is given by the following expression:$^{23}$

$$E_c = 2.415 \times 10^{20} n_e (\gamma_{en}/n_N) \sqrt{2U_i/(eM)},$$  \hspace{1cm} (4)

where $\gamma_{en}/n_N = 24.0 \times 10^{-14}$ m$^3$s$^{-1}$, $U_i = 15.755$ eV and $M = 6.634 \times 10^{-26}$ kg are the respective momentum transfer collision rate, ionization energy, and atomic mass for argon gas in air, respectively; the critical electrical field is then approximately $3.0 \times 10^5$ V/m for Ar in air. In our proposed
plasma jet, the maximum value from the $E$-field simulation is $5.37 \times 10^5$ V/m at 1 W input power (see Figure 4). Nevertheless, the discharge experiment suggests that stable discharge actually occurs at an input power larger than 20 W, which might be due to energy dissipation in maintaining stable discharges and energy losses in microwave transmission. For an applied power of 20 W, several watts of power is lost in microwave transmission and a larger portion of power is dissipated in maintaining stable discharges aside from the 1 W for starting the discharge. In other words, argon gas discharges might start near the copper wire with 1 W of power, but that discharge will be extinguished unless extra energy is available for stable discharging. If plasma forms, the resonant coupling between electrons and SPP surface waves induces local enhanced electrical field efficiently. On the one hand, developing streamers induce enhancements in $E$-field distribution that favors discharging. On the other hand, more filament or streamer bifurcations need additional energy to maintain discharging but diminish the resonant enhanced $E$-field. This interaction between filamentary streamers and SPP surface waves is very complicated and further studies are also underway.

IV. CONCLUSIONS

In summary, SPP resonant excitations were used to produce a microwave plasma jet of argon in air when an appropriately arranged copper wire is placed in the quartz tube. Experiments using input power of larger than 20 W show that several discharges are immediately produced at the end of the copper wire in the quartz tube. The wavelength of the surface wave, calculated from electric field distribution on the simulations, is about 5.7 cm, which approximately reproduces the theoretical value from a calculation using the SPPs dispersion equation. Owing to very complicated interaction between filamentary streamers and surface waves of SPPs, further work on streamer bifurcations is required.

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