Propagation of microwave surface-wave-sustained discharge in air

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Abstract. The propagation dynamics of the gas microwave discharge front in a quartz tube filled with air is studied experimentally. The discharge is initiated and sustained by the dipolar mode (m = 1) of the propagating surface electromagnetic wave (SEW). The discharge front propagation regime was experimentally discovered, which is characterized by the arrest of propagation of the discharge front, the plasma decay and the subsequent resumption of the translational motion, but at a lower propagation velocity. The distributions of the SEW electric field and the integrated discharge luminosity along the plasma column are measured. The mean plasma density in the tube was estimated using data on the measured SEW wavelengths and the dispersion relation.

1. Introduction

Propagation of the ionization front of the surface-wave-sustained discharge [1] in air is studied. In most of the papers concerning these discharges [2, 3], short pulses with duration of 100–300 µs are considered. In the presented experiments, pulse durations are 25–50 ms. The experiments were performed in the pressure range from 0.02 to 0.4 Torr, for which the relation $\nu_{en} << \omega$ is satisfied ($\nu_{en}$ is the electron-neutral collision frequency, and $\omega = 2\pi f$ is the wave circular frequency). It was experimentally ascertained in [4] that, if the relation $R \geq 2$ GHz cm is satisfied ($R$ is the inner tube radius), then the discharge will be sustained by the SEW dipolar $m = 1$ mode. The experimental conditions of the presented experiment satisfy this relation. In contrast to the azimuthally-symmetric SEW mode, the electric and magnetic field components of which correspond to the TM wave, the dipolar $m=1$ mode is a hybrid wave with all six non-zero wave field components $E_r, E_z, E_\phi, B_r, B_z$ and $B_\phi$.

The discharge is formed as the ionization front propagates and leaves behind the stable plasma column sustained by the surface wave [5]. The discharge propagation is slowed down as the SEW propagates along the tube, until its velocity becomes zero. After that, under certain conditions, the discharge partially decays and then resumes its propagation at a lower velocity.

2. Experimental setup

Figure 1 shows schematic of the experimental facility that was designed to study the propagation of the surface-wave-sustained discharge.
Figure 1. The experimental setup: (1) vacuum pump, (2) surfaguide, (3) magnetron, (4) photodiode, (5) modulator, (6) trigger pulse generator, (7) oscilloscope, (8) microwave probe with photodiode, (9) camera, (10) vacuum gauge, (11) leak valve, and (12) quartz tube.

The discharge is initiated in the quartz tube (12) with a length of 2 m, an inner diameter of 21 mm and an outer diameter of 27 mm. The SEW is excited by a waveguide launcher (2) [6] connected to the magnetron (3). The magnetron with power of 800 W operates at a frequency of 2.45 GHz. The magnetron operation is controlled by the trigger pulse generator (6). The magnetron generates single rectangular pulses with duration of 25–50 ms. The backing vacuum pump (1) is used to pump out air from the tube. The gas flow is controlled by a leak valve (11), and the pressure was measured with a digital vacuum gauge (10).

The discharge propagation is fixed by photodiodes (4) and (8) as well as by the high-speed camera (9). The photodiode (4) with the collimator was also used for the local intensity measurements of the discharge glow. Relative measurements of the $E_z^r(z,t)$ radial component of the electric field at different coordinates along the tube are performed using the microwave probe (8). The microwave probe is installed in the same section as one of the photodiodes (8). The photodiode and microwave probe signals are recorded using the oscilloscope (7).

In order to create primary ionization, the quarter-wave electrode [7] is installed in that part of the tube, which is inside the surfaguide.

3. Experimental results and discussion

The discharge propagation velocity was measured in the pressure range of 0.02 ÷ 0.4 Torr using the high speed camera and photodiodes. Figure 2 shows the discharge velocity as a function of pressure. Measurements were performed at a fixed distance of $z = 5$ cm from the surfaguide wall ($z = 0$) corresponds to the surfaguide wall. At lower pressures, the electron losses are determined by the diffusion processes, while, at higher pressures, the attachment losses prevail: $v_{\text{loss}} = (v_a + v_d)$, where $v_d \sim p^{-1}$ and $v_a \sim p$ ($v_a$ is the attachment rate, and $v_d$ is the diffusion loss rate). It can be seen that the discharge propagation velocity reaches its maximum at pressures of $p = 0.1 \div 0.15$ Torr (figure 2) when the losses are determined by the attachment processes. The spatial distributions of the ionization front velocity are demonstrated in figure 3 for four different pressures. The front velocity can be estimated from the relation $v_f = v_i \Delta_f$ [7], where $v_i$ is the ionization rate, $\Delta_f$ is the characteristic front length.

The threshold ionization rate can be determined from the discharge existence condition: the front velocity becomes zero $v_f = 0$, when $v_i = v_a + v_d = 1.5 \cdot 10^4$ s$^{-1}$. These estimates are in good agreement with the experimental results.
Figure 2. The measured ionization front velocity $V_f$ as a function of pressure $p$.

Figure 3. The measured ionization front velocity $V_f$ as a function of the distance $z$ from a surfaguide wall.

The final stage of the discharge space-time evolution is plotted in figure 4. It can be seen that, after the arrest of propagation of the discharge front, the discharge partially decays and continues its propagation at a lower speed.

Figure 4. Spatio-temporal evolution of the SEW-sustained discharge under the pressure of 0.1 Torr. The final stage of discharge propagation is presented.

This effect most clearly manifests itself at pressures of 0.1 ÷ 0.15 Torr, which correspond to the maximum discharge propagation velocity (figure 2). This effect may be associated with the processes of the ionization-field instability type [8]. The wave reflected from the end of the plasma column interferes with the incident wave, forming the field modulation that causes unstable propagation of the discharge. This effect was simulated at a pressure of 0.1 Torr using a metal mirror installed at the end of the plasma column ($z = 40$ cm): if the mirror is displaced, then the region of instability will be also displaced. The mirror was also used to form a standing wave. The SEW wavelength measured in the coordinate range of $z = [15, 40]$ cm along the tube varies only slightly and can be estimated as $\bar{\lambda}_c \approx 10.5$ cm. That allowed us calculating the mean plasma density using the dispersion relation for the waves of this type [9], [6], and it turns to be $\bar{n}_e \approx 6.2 \cdot 10^{13}$ cm$^{-3}$. The plasma density at the end of the column can be obtained from the SEW existence condition [10]: $n_{min} \approx (1 + \varepsilon_j)n_c = 5n_c$, where the permittivity of quartz is $\varepsilon_j = 4$, and the critical plasma density is
$n_e = 6.6 \times 10^{10} \text{ cm}^{-3}$. It is assumed here that the measured luminosity distribution (figure 5 (2)) along the column characterizes qualitatively the distribution of plasma density.

One can calculate that the power needed to sustain the column with a length of $l = 60 \text{ cm}$ is approximately equal to $Q = \pi R^2 \theta n_0 (v_n + v_d)^{-1} l \approx 60 \text{ W}$ (where $\theta$ is energy spent on the creation of an electron-ion pair), while the magnetron power is approximately equal to 800 W. Thus, less than 10% of the initial power is spent on the maintenance of the plasma column.

![Figure 5. Axial distribution of radial electric field component $E_r^2(z)$ (1) and light emission intensity $I(z)$ (2). Pressure in the tube is $p = 0.1 \text{ Torr.}$](image)

Figure 5 (1) presents the measured distribution of the $E_r^2(z)$ electric field component along the plasma column. This curve demonstrates almost linear decrease in the intensity. Along the first $\approx 10–15 \text{ cm}$ of the surfaguide, the electric field growth can be caused by interaction between the surface wave field and the bulk of radiation. The proximity to the metal wall of the waveguide can also introduce additional distortions [6].

References

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