Microwave Gas Breakdown in Tunable Evanescent-Mode Cavity Resonators

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Microwave Gas Breakdown in Tunable Evanescent-Mode Cavity Resonators

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Abstract—Microwave gas breakdown in strongly-coupled evanescent-mode cavity resonators in atmospheric pressure and room temperature is investigated both numerically and experimentally. This high-Q resonator is widely tunable by changing the gap between its loading post and top wall. In this letter, we study the effect of different gap spacings on breakdown characteristics of this resonator. Good agreement is observed between measured breakdown powers and ones by plasma simulations for resonators with gaps of 14.8–51.2 μm, working in the 6–8.25 GHz frequency range with input breakdown power in the range of 45–48 dBm.

Index Terms—Evanescent-mode cavity resonator, gas breakdown, high power, micro-plasma.

I. INTRODUCTION

POWER handling of microwave filters is of particular importance since many applications such as satellite communication systems, macro base-station transmitters, and radar transmitters require high transmitting powers. On the other hand, most of the current wireless systems require widely tunable with narrow instantaneous bandwidth filters due to the limited spectrum. These narrowband filters are usually implemented with high-Q resonators due to their low in-band insertion loss. Evanescent-mode (EVA) cavities have been extensively utilized to realize narrowband filters for their easy tunability, high-Q and forgiving Q-size compromise [1].

Microwave gas breakdown has been recognized as one of the major limiting factors in power handling of the filters especially in those including micro and nano-scale gaps [2]. Gas discharge is primarily due to three main mechanisms of electron-impact ionization (EII), secondary electron emission (SEE), and field emission (FE) [3], as indicated in Fig. 1. EII is a gas phase process while the two others are boundary mechanisms. The gap size, gas type and pressure determine the relative importance of each of these mechanisms [4], [5]. In atmospheric pressure, FE is the dominant breakdown mechanism in nano-gaps. However, EII and SEE have important roles in micro-gaps breakdown. The effect of FE is almost negligible for gaps larger than 10 μm [4].

Since gas breakdown depends strongly on both gap size and frequency, in continuation of [6], this letter presents computational and experimental investigations on high-power RF gas breakdown in tunable evanescent-mode cavity resonators in the range of 6–8.25 GHz. Plasma modeling is performed to understand the air micro-gap discharge behavior. High-power experimental characterization is also performed which validates the simulated observations.

II. MICROWAVE GAS BREAKDOWN

Generation mechanisms of charged particles include EII, SEE and FE. While, losses of particles are due to recombinations and attachments, as well as diffusion and drift to the electrodes. When generation rate of particles exceeds their loss rate, gas breakdown occurs. Although gas breakdown is desirable in several applications including micro-plasma generation [7], it may result in performance degradation or even failure in devices and circuits with micro and nano-gaps.

Since direction of RF electric field is changed every half cycle, different RF discharge regimes exist [8]. This makes microwave discharge problems much more complicated than dc ones. Although both the initial Paschen curve [3] incorporating just EII and SEE and modified Paschen curve [9] which also considers the effects of FE have been presented for calculating of breakdown voltage \( V_{BD} \) as a function of pressure-gap \( (p_d) \), these are mainly for dc breakdown. It has also been shown that the \( V_{BD} \) obtained by Paschen/modifed Paschen curves are good approximations at low frequencies [8]. However, beyond the critical frequency in which electrons can’t reach the electrodes anymore, the RF breakdown voltages become much lower than the dc ones [8]. A few theories for calculating microwave \( V_{BD} \) exist in literature [10], [11]. However, these are usually for specific cases and not accurate enough for micro-gaps. Therefore, performing RF plasma simulation considering all details related to a specific problem is the most accurate way for finding breakdown conditions.

In this study, we use the one-dimensional particle-in-cell/ Monte Carlo collision (PIC/MCC) technique [12] to solve the atmospheric pressure RF discharge problem in micro-scale gaps over the post of evanescent-mode cavity resonators. The XPDP1 code [13] was developed at the University of California, Berkeley and it is used here after including also the effects of FE. Since the post surface is sufficiently large compared to the gap size, we study the problem in its simplified...
one dimensional (1D) form. Nitrogen gas at room temperature and atmospheric pressure is assumed. Since about 80% of air is formed of nitrogen, this seems a reasonable assumption. It is to be noted that due to the presence of oxygen atoms and related negative ions, plasma simulation of air is more complicated than the pure nitrogen. Also, copper electrodes with work function equal to 4.7 eV are considered according to the fabricated resonator. The magnitude of local electric field on the surface of the cathode is enhanced by a factor which is called the field enhancement factor and is a strong function of the surface roughness. In this study, the average value of $\beta$ is found to be equal to 185 as a fitting parameter. According to the nitrogen ionization energy and copper work function, the secondary electron emission coefficient is calculated to be 0.08 [3]. The time step is considered equal to $10^{-15}$ sec to meet the stability conditions of PIC/MCC [12]. The number of cells is adjusted to keep their lengths to 10 nm. Also, the initial densities of both electrons and ions are considered equal to $10^{15}$ m$^{-3}$. In the PIC method, a group of particles is represented by a single simulation particle, which is called a superparticle. In this work, the superparticle ratio is set to $10^8$. In order to minimize the total number of simulations, the simulated $V_{RD}$ values are obtained with about 2% uncertainty.

III. EVANESCENT-MODE CAVITY RESONATOR

The analyzed and measured heavily loaded EVA cavity resonator is depicted in Fig. 2. This type of cavity is constructed by placing a loading post at the center of a regular cylindrical cavity, leading to a much lower resonant frequency. Here, the electric field is concentrated in the small gap between the post and the top wall, which forms the effective quasi-static capacitance of the resonator. This capacitance is adjustable by changing the gap size $g$, which gives the structure tunability factor and is a strong function of the surface roughness. In this study, the average value of $g$ is found to be equal to 185 as a fitting parameter. According to the nitrogen ionization energy and copper work function, the secondary electron emission coefficient is calculated to be 0.08 [3]. The electric field strength decreases with the gap.

Ansys High Frequency Structure Simulator (HFSS). The final geometrical dimensions of the designed cavity as well as other critical parameters are summarized in Fig. 2(b) and Table I. The resonant frequency is experimentally controlled by finely polishing the copper surface of the center post. No integrated tuning mechanism, e.g., MEMS, is included in this study in order to exclude the effect of high-power-induced mechanical deflection. Fig. 3 shows the simulated relation between the gap distance and the resonant frequency of the designed EVA resonator, indicating a frequency variation from 6 to 8.25 GHz when the gap is changed from 14.8 to 51.2 $\mu$m. Fig. 3 also shows the simulated strength of electric-field at resonance frequencies in the gap as a function of the gap distance (with a standard 1 W incident RF power), indicating that the E-field strength decreases with the gap.

Fig. 4 shows the schematic of the experimental characterization setup. The key part of this setup is a traveling-wave-tube (TWT) power amplifier (IFI T186-100), which is capable of generating 100 W RF power within a wide frequency range of 6–18 GHz. A wideband circulator is placed between the device and the PNA to maintain a constantly small VSWR when the frequency is swept and/or when the gas breakdown occurs. Since the RF power can be as high as 100 W, it is received by Port2 of the PNA after being sufficiently attenuated by a 30 dB directional coupler and 20 dB attenuator.

IV. BREAKDOWN RESULTS

High-power measurements for finding the breakdown power are performed by measuring the transmission coefficients, $S_{21}$, of the resonators by an input power sweep with steps of 0.05 dB at center frequencies. The value of $S_{21}$ remains approximately constant with the input power until gas breakdown occurs. Beyond this level, the transmission of the resonator is sharply reduced because the ionized gas reduces the electric field between the post and the top wall. This measurement is shown for a sample resonator with 19 $\mu$m gap as an inset in Fig. 5.
Fig. 4. High-power measurement setup.

The high-power measurement is conducted using the sample devices with various gap distances \((g)\) and resonant frequencies. The measured input breakdown powers for different resonant frequencies are shown in Fig. 5, indicating that more RF power is required to result in the breakdown as the \((g)\) increases. The measured breakdown power can be transferred to the respective breakdown field strength \((E_{BD})\) and \(V_{BD}\) over the gap based on the HFSS simulation results (illustrated in Fig. 3), given by

\[
E_{BD} = E_{Sim.\ 1W} \times \sqrt{P_{BD}}, \quad V_{BD} = E_{BD} \times g. \quad (1)
\]

The calculated \(V_{BD}\) as well as the PIC/MCC simulated \(V_{BD}\) versus different gaps (equivalently frequencies) are plotted in Fig. 6. Very good agreement between simulated breakdown voltages and those extracted from the measurements are seen. The observed differences may be due to several phenomena such as recombination of positive ions, attachments of electrons to the oxygen atoms to form negative ions and variations of gas temperature which have not been considered in the employed PIC/MCC code. The presence of water vapor in the experimental work can also affect the results.

V. CONCLUSION

This letter presents numerical and experimental investigations into high-power RF gas breakdown in strongly-coupled high-Q tunable evanescent-mode cavity resonators. Gas discharge is simulated using the PIC/MCC technique and the simulations results are in good agreement with high-power measurements conducted at 6–8.25 GHz. This shows the capability of the PIC/MCC technique to also simulate the high frequency gas discharge phenomena. The breakdown voltage increases almost linearly with frequency (gap size) which means almost constant breakdown fields in this regime. This is similar to the behavior of breakdown voltage in the right-side of Paschen’s curve for the dc case.

REFERENCES