Letter

Plasma generation by dielectric resonator arrays

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Abstract

Arrays of dielectric resonators—illuminated by an antenna—are used to ignite and sustain multiple microwave plasmas in parallel. Calcium titanate cylindrical resonators were arranged in a linear array with separation distances between 0.5 and 5 mm. The operating frequency was near the HEM\(_{111}\) resonance of 1.1 GHz. Paschen curves of the breakdown field and voltage in argon atmosphere are consistent with parallel plate microwave breakdown except within discharge gaps of 1 mm or less. Sustaining of argon plasma between 0.5 Torr and 1 atm within the array is found to alter the electromagnetic scattering from the dielectric resonators, suggesting applications in plasma-reconfigurable metamaterials and photonic crystals.

Keywords: microwave plasma, microwave breakdown, high-\(k\) dielectric resonators, plasma metamaterials

(Some figures may appear in colour only in the online journal)

Introduction

Many gas discharge devices use resonance in order to ignite the plasma and to maintain stable steady-state operation. Prior to plasma ignition, the unloaded resonator structure produces strong electric fields necessary for gas breakdown. After ignition, however, the plasma impedance will interact with the resonator, quenching the quality factor and shifting the resonant frequency [1]. In this manner it is often possible to use resonators as so-called ballasts to avoid plasma instability such as the glow-to-arc transition [2]. This principle is used in plasma lighting devices [3, 4], RF capacitive- and inductively-coupled plasmas [5, 6], and many microwave plasmas [7]. As a counter-example, quasi-optical microwave beams that are focused with dielectric lenses or concentrating reflectors are essentially without ballast and result in interesting streamer formation [8].

In the stable glow discharge examples above, the plasma devices all contain electrical conductors that form the resonators. These elements include electrodes as well as capacitors, inductors, microstrip transmission lines, and resonator cavities. We demonstrate that it is also possible to use resonators consisting entirely of dielectrics to ignite and sustain a stable, nonequilibrium microwave plasma. By eliminating all conductive elements from the plasma device, one may enable plasma-reconfigurable electromagnetic surfaces [9, 10] without interference from conductors such as electrodes and wires [11].

In this work, we introduce dielectric resonators [12] excited by incident electromagnetic radiation as a means for gas breakdown and stable production of plasma. Fields are strongly confined within a single dielectric resonator (DR), but two adjacent resonators can couple to produce a breakdown electric field in the space between them. The breakdown
field and breakdown voltage are investigated as a function of pressure \( (p) \) and DR separation \( (d) \) in the canonical \( pd \) formulation. In addition, the electromagnetic backscattering from an array of dielectric resonators is compared with and without plasma.

**Experimental method**

Dielectric resonators are positioned within a stainless steel vacuum chamber (50 cm in diameter by 25 cm high) using a Teflon holder. The DRs are excited by microwave radiation emitted from a broadband antenna (1–18 GHz) positioned outside the chamber. The waves pass through a glass vacuum window (19 cm dia.) in the side of the chamber wall as illustrated in figure 1. A nominal 1.1 GHz signal is amplified by a linear 30 W amplifier which is connected to the antenna through a directional coupler. The power of the forward and reflected waves of the antenna is monitored by power sensors attached to the directional coupler. Argon gas is flowed into the chamber to achieve a desired static gas pressure as measured by a capacitance manometer \( (p < 10 \text{ Torr}) \) and a piezoelectric pressure transducer \( (p > 2 \text{ Torr}) \).

Cylindrical dielectric resonators were fabricated from CaTiO\(_3\). Commercially pure (Alfa Aesar, 99.5% purity) CaTiO\(_3\) powder was ball-milled with acetone (VWR International, >99.5%) and a binder (Acryloid, Conservation Resources International, VA) for 24h using a Teflon pot containing Y stabilized zirconia (YSZ) balls. The constituents were dried and prepared into powder form with micron size using a laboratory sieve. The resultant powder was uniaxially pressed into circular green pellets and underwent a binder removal process at 500 °C for 3h. The green pellets were then sintered at 1238 °C using a conventional furnace for 5h. The sintered pellets have a dimension of 28.55 ± 0.069 mm in diameter and 14.724 ± 0.0764 mm in height. The completed DRs were analyzed using the Hakki–Coleman resonance method [13]. The dielectric material was determined to have a high relative permittivity \( (\varepsilon_r = 172.47 \pm 0.900) \) and low loss tangent \( (\delta \sim 5 \times 10^{-4}) \) which results in a quality factor of the DR exceeding 1800. The large discontinuity in \( \varepsilon_r \) at the free-space boundary of the resonator causes internal reflections which result in modes that resemble a cylindrical cavity resonator. Unlike cavity resonance, however, there are fields external to a DR which we leverage for plasma formation. We chose the HEM\(_{111}\) hybrid electromagnetic mode [12] for this work which has a resonant frequency of 1.11 GHz at room temperature.

The experimental geometry is simulated using ANSYS High Frequency Structure Simulator (HFSS) as shown in figure 1. Simulations show that the peak internal electric field of a single resonator is the order of 1\( \text{ kV m}^{-1} \) for an incident antenna power of 1 W. This field is too low to breakdown the gas in the chamber, so we place at least two resonators in close proximity to enhance the electric field. If the resonators are nearly identical, the resonance fields of each will create a strong field in the free-space gap \( (d) \) between the resonators. The field in the gap typically exceeds 10\( \text{kV m}^{-1} \) for \( d \leq 1 \text{ mm} \). As we shall see, this is adequate to breakdown low pressure argon. While it is also possible to sustain a plasma on the surface of a single resonator, the electric fields are so confined to the internal volume of the cylinder that the single DR

![Figure 1.](https://example.com/figure1.png)
configuration needed to be started using a high voltage probe. As this defeats the goal of an all-dielectric system, the remainder of the work focuses on arrays of dielectric resonators.

Results

One motivation of this work is the generation of many simultaneous plasmas using larger arrays. Therefore, we first present an array of five DRs with \( d = 1 \text{ mm} \) spacing as shown in figure 2(a). The five DRs are held in place by a Teflon stand with their axes pointing toward the antenna. The contrast between the permittivity of Teflon (\( \varepsilon_r = 2 \)) and calcium titanate (\( \varepsilon_r = 170 \)) is so large that the Teflon has no measurable effect on the DR performance. The study of the microwave breakdown field is best suited to a single pair of dielectric resonators which is temporarily deferred to the next section. However, for illustration purposes the simulation of the electric field for an incident power of 1 W shows the concentration of field between the cylindrical resonators in figure 2(b). Scaling this model result (1 W) to the experimental power for breakdown (25 W), gives an approximate breakdown field of \( 30000 \text{ V m}^{-1} \).

The modeled fields assume perfectly identical DRs. However, the individually measured TE_{011} resonances of the five DRs from left to right are 1.096, 1.095, 1.095, 1.101, and 1.098 GHz in figure 2(a). The spread in resonance is due to variations in the manual fabrication of the DRs. With a quality factor of >1000, the bandwidth of each resonator is <1 MHz which means that two of these resonators fall somewhat outside the optimal excitation frequency range. Coupling among the resonators reduces this difference, but it was still necessary to ignite plasma first on a subset of the resonators and then slightly adjust the excitation frequency to ignite the remainder. With identical DRs, we believe the plasma array would start simultaneously. With slight adjustment of the frequency, we report in figure 2(c) that all five resonators ignite.
and support plasma at a pressure of 0.8 Torr using 25 W of net antenna power. Note that the free-standing DR array absorbs power and ignites at a frequency of 1.064 GHz which is lower than the individual HEM111 mode resonances (~1.110 GHz at 24 °C) likely due to coupled mode effects among the resonators [14, 15]. Once the plasmas were ignited, the pressure was continuously increased by flowing argon into the chamber. Figure 2(d) records the appearance of the plasmas near atmospheric pressure. The four regions of plasma are observed to shrink into stable microplasmas. As with other pure argon microplasmas, multiple filaments [16] are observed to form from DR to DR. These filaments are visible to the eye but their emissions saturate the camera in these photographs. After 15 min of plasma operation at atmospheric pressure, the peak local DR temperature was 55 °C at the point of plasma contact indicating that these are cold, non-equilibrium discharges. There was also no visible damage to the surfaces of the dielectrics.

We next present the breakdown characteristics for a pair of dielectric resonators. The resonators were oriented with axes pointed upward as depicted in figure 1. The distance between the two DRs was systematically varied from \( d = 0.5 \) to \( d = 5 \) mm. Due to the radius of curvature of the cylindrical resonators, we note that \( d \) represents the minimum discharge gap distance which is located in the region where the electric field is greatest. Unlike the parallel plate electrodes used for conventional breakdown studies, however, there is no unique path for breakdown in this cylindrical geometry.

For each gap size, the ideal resonant frequency was determined experimentally. Then the forward power to the antenna was slowly increased until the plasma was visible. This procedure was repeated several times to insure a consistent reporting of the minimum breakdown power. For each gap, the argon pressure was also varied (typically between 0.5 and 60 Torr) to create a series of Paschen-like breakdown plots as shown in figure 3(a). For discharge gaps of \( d \geq 2 \) mm the breakdown power is seen to have a minimum near 0.3–0.8 Torr-cm and resembles a Paschen curve. For smaller DR separations, however, there is no minimum power within the experimentally-possible range of \( pd \).

It should not be surprising that the microwave breakdown does not appear to strictly follow the DC Paschen law. First the breakdown volume is curved as previously discussed. Second, we report forward power to the antenna rather than voltage or electric field. Also relevant, however, is that the electromagnetic coupling between the two resonators and therefore the electric field in the gap is a complex function of DR separation (\( d \)). To remove this factor, we simulate the electric field in the discharge region as a function of experimental antenna power and \( d \) using the HFSS model of the entire experiment as shown in figure 1. The computed peak electric field at breakdown as a function \( pd \) is shown in figure 3(b). The breakdown field is the order of \( 10^4 \) V m\(^{-1} \) which is consistent with the microwave breakdown determined in a carefully controlled parallel plate geometry [17] and recent simulations in microgaps at high pressure [18]. Finally, we calculate the magnitude of the microwave breakdown voltage by integrating the breakdown electric field along the shortest line between the two resonators. The magnitude of the breakdown voltage is plotted in figure 3(c). For \( pd \) values larger than 1 Torr-cm, the breakdown voltage is fairly consistent among the various discharge gap distances. The minimum \( pd \) is still not apparent for the closest DR spacing, but this is possibly due to the discharge being initiated at a location where the effective spacing is greater than \( d \) due to the curvature of the surfaces. This corresponds to the known limit in which breakdown occurs in free space rather than within the confines of the gap [17].
Finally we examine changes in electromagnetic scattering from the DR system when plasma is present. The measurement of power in the reflected wave to the antenna is used to evaluate backscattering. The reflected power consists of two components: (1) the wave reflected due to the small impedance mismatch between the antenna and the 50 Ω power amplifier, and (2) the wave backscattered from the DR array. The ratio of reflection to forward power due to mismatch is typically around 5% for this antenna. In figure 4(a) we show that two dielectric resonators produce little additional backscatter above the mismatch threshold value since the cross section of these two elements is rather small compared to the aperture of the antenna. Once a plasma is formed between the two resonators, however, the backscatter jumps to approximately 30%. These data are taken at low argon pressures for which the plasma is diffuse and occupies a large volume as shown in figure 2(c). Therefore the plasma enhances the cross section of the two DR system and causes more reflection of the wave.

The backscatter from the five element DR array is quite large prior to plasma ignition, in part because the length of the array is the same as the antenna aperture. As plotted in figure 4(b), more than 30% of the forward power is backscattered to the antenna by the five DRs (no plasma). In this case, the ignition of a low pressure plasma reduces the scatter due to absorption of power to sustain the large plasma volume shown in figure 2(c). As the pressure increases, we observe that the 5-element DR-sustained plasma absorbs most of the incident wave with almost no backscatter. The plasma volume is radically smaller at atmospheric pressure, so we speculate that the highly collisional plasma is acting as an electromagnetic absorber. While these results are of interest for an initial report, a greater understanding of the entire electromagnetic system is the subject of future studies and will require self-consistent models of the plasma and the electromagnetic radiation.

Conclusion

In this communication we have described a plasma source consisting of entirely dielectric materials that can ignite and sustain microwave plasma from a low-power electromagnetic wave. The breakdown electric fields are consistent with previous measurements of microwave breakdown within a planar electrode geometry [17]. Initial results show that the plasma can strongly reconfigure the electromagnetic properties of the dielectric resonator array.

Additional electromagnetic simulations show that larger arrays of dielectric resonators should also be capable of sustaining plasma. For example a 2D planar array consisting of 5 × 5 DRs has similar electric field patterns to the five element linear array described above. Scaled array sizes and spherical resonators are the subjects of future studies.

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