Abstract—This letter investigates the harmonic and intermodulation distortion behavior of a prototype plasma capacitor proposed for use as a radio-frequency control device. Experiments at a fundamental frequency of 900 MHz show second and third order harmonic output as high as $-29$ dBc and $-35$ dBc respectively for a 20 dBm input. Intermodulation distortion measurements are also performed at difference frequencies of 200 kHz and 1 MHz.

Index Terms—Capacitors, dielectric materials, plasma devices.

I. INTRODUCTION

The IEEE 802.11e mobile WiMax standard includes specifications for the use of adaptive antenna systems (AAS) to increase system capacity and range [1]. Implementation of such antenna systems will require the use of an increasing number of radio-frequency (RF) control devices and there are examples that use PIN diodes and RF microelectromechanical systems (MEMS) [2], [3]. Existing RF control devices, however, do not necessarily fulfill all performance requirements in such applications and there is scope to investigate a new type of device as an alternative.

Recent work proposed the use of the dielectric properties of a gas discharge plasma to create a continuously variable RF capacitor [4]. This work investigated the small-signal impedance characteristics of a prototype device at frequencies up to 2.4 GHz and results showed a 2–6:1 capacitance ratio with $Q = \infty$ at 600 MHz from a millimeter-scale device. The impedance characteristic shows promise with further development.

However, the potential for nonlinear behavior should also be considered. Nonlinearities will produce harmonic distortion and intermodulation distortion (IMD) that will cause interference between and within channels. This letter therefore investigates the harmonic and intermodulation characteristics of a prototype RF plasma capacitor.

II. THEORY

Nonlinearities in a plasma capacitor can arise for a number of reasons but are most likely due to the ion sheaths that separate the bulk plasma from the vessel walls. These are shown in Fig. 1(a) and their width is dependent on the voltage across them. Under small-signal conditions, they can be assumed stationary with a width approximated by $s_{DC} \approx 4\lambda_{De}[5]$ with the Debye length, $\lambda_{De}$, given by

$$\lambda_{De} = \sqrt{\frac{\varepsilon_0 k_B T_e}{e^2 n_s}}$$

where $n_s$ is the electron density at the sheath edge ($m^{-3}$), $e$ is the electron charge, $\varepsilon_0$ is the permittivity of free space, $k_B$ is Boltzmann’s constant and $T_e$ is the electron temperature in Kelvin.

However, as the voltage across the sheath increases, the motion becomes significant. The sheath becomes equivalent to a voltage dependent capacitance in parallel with a conductance resulting from electron movement to the vessel wall when the sheath is narrow. The sheath conductance becomes less important as the applied frequency increases and the nonlinear capacitance dominates.

Hilbish et al. [6] provide a simple step-wise model of the sheath that allows the dynamic capacitance to be determined. This is shown in Fig. 1(b). Poisson’s equation can be used to calculate the electric field, $E(x)$, and voltage, $V(x)$, at some time $t$ for, in this case, a planar sheath

$$\frac{dV}{dz^2} = -\frac{e n_s}{\varepsilon_0} \begin{cases} \frac{(1-\alpha) x + \alpha}{s_{RF}} & 0 < x < s_{RF} \\ \frac{1}{s_{DC}} x + (\alpha - 1) & s_{RF} < x < s_{DC} \\ 0 & x > s_{DC} \end{cases}$$

where $\alpha$ is some fraction that determines the ion distribution profile ($0 \leq \alpha \leq 1$) and $s_{RF}$ is the sheath width due to the
RF voltage (the ions are assumed to be too heavy to respond to changes in the applied field).

Requiring that the electric field in the bulk plasma be zero and that the voltage to be the plasma potential, \( V_p \), gives the boundary conditions \( E(s_{DC}) = 0 \) and \( V(s_{DC}) = V_p \). Further requiring continuity throughout the sheath allows calculation of \( E(x = 0) \) and \( V(x = 0) \) and subsequent calculation of \( s_{RF} \) and a dynamic sheath capacitance from \( dq/dV \) (where \( q \) is the charge).

\[
C_s(t) = \frac{\varepsilon_0 A_{RF}}{2 \left( \frac{\varepsilon_0 V_s(t)}{\varepsilon_{in}} + \frac{1}{6}(1 - \alpha)\varepsilon_{DC} \right)}
\]

where \( V_s(t) \) is the total voltage across the sheath and \( A_{RF} \) is the area of the capacitor plate. This nonlinear capacitance results in a distorted “sawtooth” shaped current waveform and, therefore, harmonics.

However, there are two sheaths in a plasma capacitor that are orientated back-to-back. If the capacitor were symmetric—such that \( A_{RF} \) and the magnitude of \( V_s \) were the same in both sheaths—distortion currents cancel and only odd-order harmonics would be produced [5]. This could be a positive in wireless communication applications.

### III. Distortion Measurement

Fig. 2 shows a schematic of the prototype device constructed to measure the nonlinear distortion output of a small-scale plasma capacitor. Two co-planar electrodes fire a direct-current (DC) glow discharge and two plane-parallel electrodes form an RF capacitor. The capacitor electrodes are each 4 \( \times \) 1 mm\(^2\), with an overlapping area of 2 \( \times \) 1 mm\(^2\). They are insulated from the gas discharge by thin layers of lacomitr varnish. Argon gas is pumped through the small chamber at a pressure of 2.6 mbar.

At the gas pressure used in these experiments, the discharge current (through the dc electrodes) is 50–550 \( \mu A \) with a resulting (calculated) bulk electron density \( (n_e) \) and temperature of the order of \( 10^{16}–10^{17} \) m\(^{-3}\) and \( T_e = 70–200 \times 10^3 \) K respectively. Further details on device construction, operation and characteristics can be found elsewhere [4], [7].

Fig. 3 shows the the setup used to measure harmonic distortion with \( Z_0 = 50 \Omega \). A fundamental frequency of \( f_0 = 900 \) MHz was used with a maximum power of 20 dBm presented to the device under test (DUT). Harmonic measurements were performed with a noise floor of approximately –90 dBm and second order harmonics due to the system that were, at worst, –82 dBc.

Measurement of IMD was a similar process to measurement of harmonic distortion but requires two input tones. This setup is shown in Fig. 3 and there is a total of 42 dB of isolation between the two input branches. The two signal tones are at \( f_1 = 900 \) MHz and \( f_2 = f_1 + \Delta f \) where \( \Delta f \) is the difference frequency. In these experiments a \( \Delta f \) of 200 kHz and 1 MHz is used.

### IV. Results

Fig. 4 shows the second and third order harmonic output along with the fundamental over three devices with \( n_e \approx 2 \times 10^{17} \) m\(^{-3}\). The increase in the fundamental with respect to the input power is very close to 1 dBm/dBm, indicating little if any absorption of RF energy by the discharge. Furthermore, second and third order harmonics increase at approximately 2 dBm/dBm and 3 dBm/dBm respectively as expected for conventional square and cubic nonlinearities.

At worst, second and third order harmonics are –20 dBc and –35 dBc respectively (at 20 dBm input). Importantly, these figures are dependent upon the electron density and improve as it is reduced.

Even though the plasma capacitor is geometrically symmetric, even order harmonics are present. However, true symmetry also depends upon the discharge. Fig. 5 shows a double Langmuir probe [5] trace from discharge characterization experiments [7] (with uninsulated electrodes) that was used to calculate the electron density and temperature. This
Up to six orders of IMD were observed. Fig. 6 shows the second and third order IMD output for $\Delta f = 200$ kHz and 1 MHz for $n_e \approx 10^{17}$ m$^{-3}$. Only IMD output at $f_1 + f_2$ is consistent over all experiments and, in addition, output at $f_2 - f_1$ is always of a much smaller magnitude than its second order counterpart. Second and third order output intermodulation intercept points (OIP2 and OIP3 respectively) can be estimated and result in OIP2$\approx 35$ dBm for both $\Delta f = 200$ kHz and 1 MHz and OIP3$\approx 29$ dBm for $\Delta f = 200$ kHz. No clear dependence on the electron density could be determined within the resulting error ranges.

Undesired behavior was also observed. During harmonics measurements, unstable and oscillatory discharge currents result in sidebands of the harmonics at frequency separations equal to the current oscillation frequency. Such an effect has been observed by Asmussen and Lee [8], who contend that it is caused by nonlinear coupling between electron plasma waves and ion-acoustic waves in the bulk region of the discharge plasma. Such behavior would create interference in neighboring channels. IMD experiments also showed that an oscillation is induced in the discharge current, with a frequency that is equal to $\Delta f$, in operating regions where stable discharges are otherwise expected. Further experiments are required to examine both of these effects more closely.

V. CONCLUSION

We have examined the nonlinear distortion output of a prototype plasma capacitor that has previously shown promise as an RF control device for use in wireless communication systems. Even and odd order harmonics are produced with second and third order output that are, at worst, $-29$ dBc and $-35$ dBc respectively for a 20 dBm input. IMD is also produced, but only output at $f_1 + f_2$ is consistent over all experiments. Some undesired behavior was observed during experiments that would be detrimental to the operation of the device in a wireless communications environment. Appropriate device design may alleviate some nonlinear effects by, for example, ensuring symmetry, but development of the prototype as an impedance device cannot occur without consideration of distortion behavior.

REFERENCES