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Reproducing continuous radio blackout using glow discharge plasma

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A novel plasma generator is described that offers large-scale, continuous, non-magnetized plasma with a 30-cm-diameter hollow structure, which provides a path for an electromagnetic wave. The plasma is excited by a low-pressure glow discharge, with varying electron densities ranging from $10^9$ to $2.5 \times 10^{11}$ cm$^{-3}$. An electromagnetic wave propagation experiment reproduced a continuous radio blackout in UHF-, L-, and S-bands. The results are consistent with theoretical expectations. The proposed method is suitable in simulating a plasma sheath, and in researching communications, navigation, electromagnetic mitigations, and antenna compensation in plasma sheaths. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4823526]

I. INTRODUCTION

When a spacecraft leaves orbit and reenters the atmosphere as it travels to a landing site, there is a critical period of time when all communications between spacecraft and ground control are lost. This period is also known as “radio blackout” or “reentry blackout,” which is caused by an envelope of ionized air surrounding the craft, created by the tremendous heat from air compressing around the craft. 1-3 The ionized envelope, called the “plasma sheath,” shields the electromagnetic (EM) signals and ultimately causes communication failure.

Radio blackout has puzzled the aerospace industry for decades and has not yet been completely resolved, although there are many methods and plans proposed to mitigate the problem. 4-7 Moreover, the plasma sheath is difficult to simulate in a laboratory environment because the requirements to combine many extreme conditions such as vacuum, hypersonic flow, and high temperature are difficult to establish.

From the 1960s to the 1970s, the shock-tube was used to simulate hypersonic flows as well as the plasma induced by them. 8 To date, it is still an important method in the study of EM wave propagation in plasma of high-speed airflows. 9, 10 While this approach reproduces almost exactly the same mechanism of real plasma sheaths, the drawback is that the duration of the plasma is very short, typically no more than several hundred micro-seconds. The EM-wave-related experiments must be completed within this short duration, and require a complex trigger and capture mechanism in testing. Naturally, only the simplest of EM-wave experiments, such as the measurement of the attenuation characteristic in carrier waves in plasma, are able to be conducted using the shock-tube.

Recently, a helicon plasma source, with a high ionization efficiency and large electron density, was used to simulate the continuous plasma environment. 11 Since then, many other investigations requiring long-lasting plasma have been conducted, for instance, the mitigation of the blackout by E×B cross-fields, 4, 6, 7 measuring the reflection coefficient of antennas under plasma, and adaptive tuning of the antenna. 12 However, the helicon plasma is excited from a cyclotron resonance chamber under a strong magnetic field; thus, the plasma is magnetized when generated. To avoid this magnetization in the experimental area, the plasma must be blown away from the source region and injected into the magnetically isolated experimental area, much like a plasma torch. During this process, the density of plasma declines rapidly because of the composite effect, resulting in a gradient distribution of plasma in the experimental area. Its size is also limited by the non-uniformed plasma distribution, being only for example, a few inches in length and width. 6

This work proposes a novel structure for generating large-scale, continuous, non-magnetized plasma simply by a glow discharge, which enables continuous blackout to be simulated and EM-wave-related experiments to be conducted. The remainder of this paper is organized as follows: Sec. II discusses the novel structure of the plasma generator; in Sec. III, we analyze the density and the distribution of the plasma; and in Sec. IV, the EM-wave propagation experiments in UHF-, L-, and S-bands are demonstrated to verify the proposed method. A detailed discussion, conclusion, and possible extensions appear in Sec. V.

II. THE PLASMA GENERATOR

To reproduce a continuous radio blackout in the laboratory, the first step is generating the plasma in a manner similar to that during reentry. Basically, the plasma generator should satisfy the three following characteristics.

First, the plasma scale should be large enough to cover the antenna area, and any metal obstructions should be removed from the EM-wave propagation path. The electrodes must be carefully arranged to avoid blocking the EM-wave propagation, and the diameter of the plasma window should
also be large enough to prevent the appearance of the cutoff waveguide effect.

Second, the electron density of the plasma should be sufficient to produce a strong attenuation of radio signals. The decay of the radio signals occurs when the plasma frequency $\omega_p$ is higher than the signal frequency $\omega$. The plasma frequency $\omega_p$ is given by

$$\omega_p = \frac{n_e q_e^2}{\varepsilon_0 m_e}, \quad (1)$$

where $n_e$ is the electron density, $q_e$ is the electron charge, $m_e$ is the electron mass, and $\varepsilon_0$ is the dielectric constant in vacuum. For instance, to reproduce the blackout of the GPS signals (1.57 GHz), the required $n_e$ is calculated to be approximately $3 \times 10^{10}$ cm$^{-3}$, which is within the range of glow discharge.

Finally, the plasma in the experimental area should be non-magnetized because the actual plasma sheath around the spacecraft is non-magnetized and wave propagation in magnetized plasma is very different from that in non-magnetized plasma. The residual magnetic field from the plasma generator must be sufficiently weak that it can be ignored.

Our realization of a plasma generator that fulfills all three requirements is based on the following idea. First, the experimental area is located as close as possible nearby the source region, so as to reduce the density losses caused by the composite effect. Second, a large experimental area is obtained by a combination of multiple plasma sources. Finally, the elimination of the magnetic field is achieved by a symmetrical configuration of discharge electrodes, in which the magnetic fields cancel each other.

With these in mind, the structure proposed, sketched in Figure 1, consists of a metal chamber, built of 18-cm-thick stainless-steel, which provides a container to withstand a vacuum. Two watch windows, 30-cm in diameter, are mounted symmetrically on both sides of the chamber, to provide a free propagation path for EM waves. The windows are made of quartz glass or Teflon (PTFE). Teflon provides a smoother wave impedance transition to air and plasma; the windows would only be replaced by quartz glass when optical diagnostics are needed. The boundary sheaths form near both watch windows, in which the electron density decreases rapidly, and their typical thickness are less than 1 cm, equal to a minor thickness loss. As sketched in Figure 1, the thickness loss is compensated by moving both watch window outward by approximately 1 cm.

The annular electrode is the critical part in the plasma chamber that also assumes the role of a cooling tube to transport heat away from the chamber. The annular electrode is fixed in the chamber by insulating pillars and insulated from the external cooling system by plastic pipes and non-conductive cooling oil (dimethyl silicone). Glow discharge occurs between the annular electrode and the inner wall of the metal chamber, excited by a RF power source connected between them.

The annular discharge gap is the source region of plasma, in which the density of plasma is relatively higher than that of the experimental area. The electrons and ions will diffuse from the source region to the inner experimental area through the spaces within the electrode tubes. This procedure is similar to many annular-installed plasma torches ejecting ions simultaneously towards the center, yields a plasma cluster with more uniformity and larger scale than that of a single torch (Fig. 2).

The proposed discharge structure has the following advantages:

First, the discharge occurs only between the annular electrode and chamber, leaving a totally metal-obstacle-free propagation path for EM waves and a passage that is larger than the main lobe of most horn antennas.

Second, the annular electrode forms a complete shielding ring (a Faraday cage), in which the electric potential is equal at all times. Therefore, the magnetic field generated by the symmetrical configuration of currents vanishes in the center of the experimental area.

III. DIAGNOSE THE PLASMA DISTRIBUTION

A diagnostic method combined with the microwave and optical analysis is adopted to test plasma uniformity in the EM-wave experimental area (Fig. 3). The electron density
in the central area of the watch window is analyzed using microwaves; microwaves, with angular frequency of \( \omega_d (\omega_d \gg \omega_p) \) propagating in plasma through length \( l \) yield an additional phase shift of \( \Delta \varphi \), which is related to the electron density \( n_e \).\(^{13} \)

\[
n_e \approx \frac{2\varepsilon_0 m_e \omega_d c}{e^2 l} \cdot \Delta \varphi = \frac{1.185 f_d}{l} \cdot \Delta \varphi \quad \text{(m}^{-3}\text{)}, \quad (2)
\]

where \( f_d \) is the frequency of the diagnostic microwaves and \( c \) is the speed of light.

The additional phase shift \( \Delta \varphi \) is determined by a network analyzer (N5230A, Agilent) in the phase measuring mode. Simultaneously with plasma diagnosis, the luminosity from the central area and the image of the whole watch window are obtained using a luminance meter and a digital camera, respectively. The relationship between the electron density and light intensity can be established running various experiments at different RF power injection levels using the camera, which can also be calibrated from the results. Finally, the distribution of the luminosity in the experimental area can be determined from the camera images captured, from which the electron density distribution can be estimated.

The frequency of the diagnostics microwave is set at 10.4 GHz; other testing conditions and procedures are described as follows. First, we hold air pressure at 10 Pa, then inject RF power from 65 W to 2950 W. The results for the RF power and luminosity, plotted against electron density, are shown in Figs. 4(a) and 4(b), respectively. The digital camera (model: EOS 5D-II, Canon), set 1.2 m away from the watch window, has a CMOS image sensor with 5618 \times 3744 pixel resolution. The aperture and shutter speed were set at \( F = 8 \) and 1/50 s, respectively. Finally, we fixed the RF power at 170 W, stopped the vacuum pump, and injected a trickling flow of air to raise the pressure from 14 Pa to 56 Pa. During this period, several images was captured, the plasma distribution at different pressures were obtained (Fig. 4(c)). The 2D electron distribution in the experimental area at RF power of 1300 W is given in Fig. 4(d).

The test results indicate that the plasma spreads over the entire experimental area as expected, yields a large-scale plasma dielectric layer for the EM-wave propagation experiments. The plasma uniformity can be defined as follows:

\[
U = \frac{n_e(\text{max}) - n_e(\text{min})}{n_e(\text{max}) + n_e(\text{min})} \times 100\%.
\]

At lower air pressures, the composite effect is weaker during plasma diffusion; therefore, the plasma is more uniform and the electron density at the center of the chamber is higher. The uniformity was evaluated as 97.3% at \( P_{\text{air}} = 21 \text{ Pa} \) and \( P_{\text{E}} = 1300 \text{ W} \). The plasma density in the center of the chamber rises to \( 2.5 \times 10^{11} \text{ cm}^{-3} \) at \( P_{\text{E}} = 2950 \text{ W} \) and \( P_{\text{air}} = 24 \text{ Pa} \), meanwhile the uniformity was evaluated as 96.1%. According to Eq. (1) the corresponding \( \omega_p \) is \( 2.82 \times 10^{10} \text{ rad/s} \), which means radio signals below 4.49 GHz will be blocked.

**IV. REPRODUCING THE RADIO BLACKOUT**

**A. Experimental setup**

Most telemetry systems typically have 15–30 dB of link budget. To reproduce radio blackout, an extra attenuation greater than 30 dB must be introduced by the plasma. To prevent diffraction propagation, a shielding chamber is mounted on one side of the watch window, and microwave absorbing foam is affixed to its inner wall to reduce reflections, as illustrated in Fig. 5.

The plasma chamber is the only EM-wave propagation path, and two pairs of antennas are installed on both sides of
the chamber. One pair, for plasma diagnosis, uses horn antennas with narrow beam-width; the other pair, for signal transmission, uses patch antennas which are similar to those used on actual space vehicles. The frequency of the microwave for diagnostics is set at 10.4 GHz, which is much higher than the maximum plasma cut-off frequency. The signal frequency is selected from 455 MHz (UHF Band), 1 GHz (L-Band), and 2.49 GHz (S-Band), which are representative of the respective bands. The transmitted signal power is 10 mW and the attenuation is measured by a spectrum analyzer (N9030-MXA, Agilent).

With the air pressure kept between 15 and 20 Pa, RF power is then injected and varied from 100 W to 2500 W. During this period, the electron density and the signal atten-

FIG. 4. (a) RF power vs. electron density, measured using microwaves at 10.4 GHz; (b) luminosity vs. electron density, $P_{air} = 14$ Pa; (c) electron density distribution vs. air pressure, $P_{air} = 170$ W, $n_{e\text{max}} = 14-56$ Pa; and (d) electron density distribution in the experimental area, $P_{air} = 21$ Pa, $P_{E} = 1300$ W.

FIG. 5. Experimental setup to reproduce radio blackout.
ulation are recorded simultaneously. If the measured attenuation is greater than 30 dB, it is believed that a continuous radio blackout is reproduced for most of the communication systems.

B. Theoretical expectations of signal attenuation

To theoretically predict the signal attenuation, the plasma chamber and the experimental system is simplified to a three-layer dielectric model (see Fig. 6). The metal container and electrode is omitted, as the scale of the wave-transparent window is large enough. The axial distribution of the plasma layer is assumed uniform, although the free diffused plasma in the central part of the cylindrical chamber satisfies the cosine law in theory. However, for low air pressure, most of the plasma region corresponds to the flat top of the cosine curve. The plasma diffusion effect renders a homogeneity of up to 97% over a 30 cm span (radial direction), so one can assume that it also has acceptable homogeneity over the smaller span of 18 cm (axial direction).

The non-magnetized plasma layer is regarded as a dispersive, nonlinear dielectric, whose complex relative dielectric constant is equivalent to

\[ \bar{\varepsilon}_r = 1 - \left( \frac{\omega_p}{\omega} \right)^2 \frac{1}{1 - j \frac{v}{\omega}} = 1 - \frac{\omega_p^2}{\omega^2 + v^2} - j \frac{v}{\omega} \frac{\omega_p^2}{\omega^2 + v^2}, \]

where \( \omega, \omega_p, \) and \( v \) are the signal, plasma, and collision frequencies, repetitively; the wave impedance of plasma is given by

\[ \eta = \sqrt{\frac{\mu_p}{\varepsilon_0 \varepsilon_r}} \approx \sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_r}}. \]

Here, \( \mu_p \) is the permeability of plasma, which is approximately equal to that of a vacuum (\( \mu_0 \)). Both the plasma dielectric constant and the wave impedance vary with signal frequency, whereas those of the Teflon window are approximately constant (\( \varepsilon_r = 2.0, \eta = 267 \Omega \)). Based on these dielectric parameters and the estimated collision frequency of 1.0 GHz, the total transmission coefficient of the three-layer structure can be solved by multi-layer medium transmission method.\(^{14}\)

C. Experiment results

The experiment apparatus and results are illustrated in Fig. 7. With the increased density of plasma, the radio signals are attenuated as expected in UHF-, L-, and S-bands. The maximum attenuation reaches more than 50 dB, which exceeds the link budget of most communication or navigation systems, thereby, reproducing a continuous radio blackout. Moreover, the experiment results are consistent with theoretical expectations with acceptable error, which validate the proposed scheme and the simplification of the theoretical model.

A particular non-monotonic trend occurs at 2.49 GHz, which is not observed for lower frequencies (455 MHz and 1 GHz). The possible causes are described below. When the signal frequency is 2.49 GHz, the wavelength is \( \sim 12 \text{ cm} \) (in vacuum, \( \varepsilon_r = 1 \)), which is slightly shorter than the thickness of the chamber (18 cm). As the chamber fills with plasma, the equivalent relative permittivity \( \varepsilon_r \) decreases below 1, which means the wavelength in the chamber lengthens. When the wavelength is approaching the thickness of the chamber, resonance occurs, which causes a frequency-selective enhancement. However, at lower frequency (1.0 GHz and 455 MHz), the wavelength is much longer than the thickness of the chamber; therefore, no resonance will occur. As a result, the attenuation exhibits a monotonic trend.

V. DISCUSSION AND CONCLUSION

A. Discussion

This study reproduces radio blackout as encountered in vehicle reentry using a novel plasma generator that produces a large-scale, nonmagnetic plasma area. With a wide experimental window forming a metal-obstacle-free structure, the chamber has little influence on EM-wave propagation; the radio attenuations substantially match theoretical expectations. Nevertheless, no ground-based means can reproduce a real plasma sheath high up in the atmosphere; of course, the proposed method also has some limitations.

First, the plasma generator produces homogeneous plasma with a fixed thickness, whereas the thickness and distribution of real plasma sheaths vary with reentry conditions, such as flight speed, altitude, and vehicle angle. However, strong attenuation appears only when \( \omega_p > \omega \); thus, the peak electron density is the major contributor to signal attenuation. Therefore, by simulating peak electron densities with a thickness correction, radio blackout can be reproduced approximately.

Second, in glow discharge plasma, lower ion temperatures yield lower collision frequencies (typically no more than several GHz), which can be less than those of actual plasma sheaths. The denser atmosphere will cause greater collision frequencies during actual reentry periods. When simulating plasma sheaths at altitudes lower than 40 km, a further collision frequency correction to the experiment results is necessary.
Finally, glow discharge turns to arc discharge when the RF power is more than 3 kW. The arc can cause damage to the plasma generator and RF power system. As a result, the maximum electron density is limited to $2.5 \times 10^{11}$ cm$^{-3}$, which is lower than that of actual plasma sheaths (which can exceed $10^{12}$ cm$^{-3}$ outside the antenna window in the worst case). However, the density is sufficient to reproduce radio blackout below the S-band.

**B. Conclusion**

The proposed method provides a long-lasting, large-scale, non-magnetic plasma with a certain similarity to a plasma sheath and reproduces a continuous radio blackout in the UHF-, L- and S-bands. In addition, the plasma density can be easily controlled by RF power in an approximately linear relation, achieving an arbitrary variation of plasma density. Moreover, the proposed experimental apparatus is also suitable for studying the EM-wave propagation in plasma, testing antenna performance in a plasma sheath, and blackout simulations for radio systems under S-band, such as GPS navigation systems, telemetry, and tracking and control systems.

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