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Plasma Antennas

Theodore Anderson

Abstract

We have demonstrated that one or two plasma tubes can be used to focus, spread, and steer antenna beams. We have also shown that we can simulate convex and concave plasma lenses by using cylindrical plasma tubes. Focusing by a plasma is useful because it can be used to increase the gain of an antenna, and to quickly reconfigure the beamwidth as needed without physically moving the antenna. With this technology, there is no need for phased arrays to steer and focus an antenna beam. Beam steering with a plasma allows tuning to different frequencies which is a difficult task for standard antennas. Our experimental results with 44 GHz showed a dramatic improvement in beam steering and focusing characteristics compared to beam focusing and steering at 24 GHz. The shorter wavelength compared to the spatial variation in plasma density over the radius of the plasma tube, the easier it is to steer and focus antenna beams. These results have been incorporated in a new smart plasma antenna design.

Keywords: plasma antenna, antenna beam focusing, antenna beam steering, physics of refraction through a plasma

1. Introduction

Plasma antennas use partially or fully ionized gas as the conducting medium instead of metal to create an antenna. The advantages of plasma antennas are that they are highly reconfigurable and can be turned on and off. Hence research to reduce the power required to ionize the gas at various plasma densities is important and this has been achieved by various techniques including pulsing techniques. The power requirements for plasma antenna operation continue to decrease.

The same geometric resonances apply to plasma antennas as metal antennas. Plasma antennas of the same shape, length, and frequency of corresponding metal antennas will have the same radiation patterns. Plasma antennas have the advantage of reconfigurability.

High frequency antennas can transmit and receive through lower frequency plasma antennas eliminating or reducing co-site interference. Because of this principle, higher frequency plasma antennas can be nested inside lower frequency plasma antennas and the higher frequency plasma antennas can transmit and receive through the lower frequency plasma antennas. Higher frequency plasma antenna arrays can transmit and receive through lower frequency plasma antenna arrays. Co-site interference occurs when larger frequency antennas block or partially block the radiation patterns of smaller higher frequency antennas. With plasma antennas, co-site interference can be reduced or eliminated. The interference among plasma antennas can be reduced or eliminated by turning all the plasma antennas off (extinguishing the plasma) except the plasma antennas that are

transmitting and/or receiving. This is not possible with metal antennas. A general rule is that when an incident electromagnetic wave upon a plasma antenna is such that the frequency of the incident electromagnetic wave is greater than the plasma frequency of the plasma, the incident electromagnetic wave passes through the plasma without attenuation. If the incident electromagnetic wave has a frequency much less than the plasma frequency, the plasma behaves similar to a metal. The frequency at which plasma behaves like a metal or a dielectric is reconfigurable. The plasma frequency is a natural frequency of the plasma and it is a measure of the amount of ionization in the plasma. It is defined and used throughout this book. Both plasma antennas and metal antennas increase in size as the frequencies they operate goes down to maintain geometric resonance and high efficiency. However as the frequency of operation of the plasma antenna decreases, the density of the plasma needed to operate the plasma antenna also goes down. A rule of thumb is that the plasma frequency should be about twice the operating frequency of the plasma antenna. Hence the plasma frequency goes down as the frequency of the plasma antenna goes down. As the plasma frequency decreases, the plasma antenna becomes transparent to a greater bandwidth of electromagnetic waves. In short as the plasma antenna increases in size, the RCS of the plasma antenna goes down whereas for the corresponding metal antenna, the RCS goes up as the metal antenna increases in size. This gives the plasma antenna some great advantages at low frequencies over the corresponding metal antenna. In addition plasma antennas do not receive electromagnetic noise greater than the plasma frequency since these frequencies pass through the plasma antenna.

Related to plasma antennas, plasma frequency selective surfaces, plasma waveguides, and plasma co-axial cables have been developed. Unlike metal frequency selective surfaces, plasma frequency selective surfaces have the properties of reconfigurable filtering of electromagnetic waves. This could have tremendous advantages to radome design. Plasma frequency selective surfaces can be reconfigured by varying the plasma density, varying the shape of the elements, or tuning any number of the plasma FSS elements on or off. Plasma wave guides and plasma co-axial cables can be stealth like plasma antennas, and they can operate at low frequencies, and be invisible at high frequencies. Plasma waveguides and co-axial cables can be feeds for plasma antennas. Plasma feeds as well as the plasma antennas have reconfigurable impedances. If the impedance of the plasma antenna is changed, the impedance of the plasma antenna feeds can be changed to maintain impedance matching.

Thermal noise in a plasma antenna is less than the thermal noise in a metal antenna at the higher frequencies. Higher frequencies mean that there is a point in the RF spectrum in which the thermal noise of plasma antennas is equal to the thermal noise of metal antennas. At higher frequencies than this point, the plasma antenna thermal noise decreases drastically compared to a metal antenna. Below this point the thermal noise of the plasma antenna is greater than a metal antenna. For a fluorescent tube which has been built as a plasma antenna, the point where the thermal noise of the plasma antenna is equal to the metal antenna is about 1 GHz. This point can be decreased in frequency by decreasing the plasma density and/or gas pressure. The plasma in the plasma antennas are inert gases that operate at energies and frequencies in which Ramsauer Townsend Effects apply.

Ramsauer Townsend Effects mean that the electrons in the plasma diffract around the ions and neutral atoms in the plasma. This means that the collision rate of the unbound electrons in the plasma with ions and neutral atoms is small and much smaller than in a metal. This phenomenon contributes to the lower thermal noise plasma antennas have over corresponding metal antennas.

Satellite plasma antennas benefit from the lower thermal noise at the frequencies they operate. Ground based satellite antennas point at space where the thermal noise is about 5° K. A low thermal noise, high data rate satellite plasma antenna system is possible with low noise plasma feeds and a low noise receiver. Satellite plasma antennas can operate in the reflective or refractive mode. Satellite plasma antennas need not be parabolic but can be flat or conformal and effectively parabolic. The effective plasma parabolic dish antenna is part of the scope of future work. Electromagnetic waves reflecting off of a bank of plasma tubes get phase shifted as a function of the plasma density in the tube. This becomes an effective phase array except that the phase shifts are determined by the plasma density. If the plasma density in the tubes is computer controlled, the reflected beam can be steered or focused even when the bank of tubes is flat or conformal. In the refractive mode, the refraction of electromagnetic waves depends upon the density of the plasma. In the refractive mode, steering and focusing can be computer controlled even when the bank of tubes is flat. This eliminates the problem of the blind spot and feed losses caused by the feed horn and receiver in front of a metal satellite antenna.

Pulsing techniques instead of applying continuous energy were developed to increase the plasma density and decrease the amount of energy to maintain the plasma.

In the history of antennas, it has been difficult to develop low frequency directional and electronically steerable antennas that fit on land vehicles and aircraft. Low frequency means the wavelength is on the order or larger than the vehicle. With plasma antennas this is possible with multipole expansions of clusters of plasma antennas that are all within a wavelength of each other. This depends on the ability of turning plasma antennas on or off (extinguishing the plasma) to create reconfigurable multipoles of plasma antennas that can be rotated in time creating directional and steerable antenna beams. This is not possible with metal antennas because they cannot be turned on and off.

Several groups have done work in using numerical techniques to plot plasma antenna radiation patterns. Zhou et al. [1] used FDTD Method techniques. Bogachev et al. [2] predicted radiation patterns for plasma asymmetrical dipole antenna. Zhivko Kiss'ovski [3] calculated the radiation pattern of miniaturized plasma antennas. Golazari et al. [4] did measurements and simulations of a loop plasma antenna in UHF band Barro et al. [5] did simulations to get the radiation patterns of cylindrical plasma antennas. Kumar et al. [6] have done simulations of a plasma antenna array. Melazzi et al. [7] have developed a plasma antenna numerical code called ADAMANT. An overview of experimental and numerical research is Anderson et al. [8]. Mansutti et al. [9] have done numerical work on metal-plasma L band antenna.

The phase speed of electromagnetic waves in a plasma is given by:

$$v_p = \frac{c}{\sqrt{1 - \omega_p^2/\omega^2}},$$

Where the plasma frequency is given by:

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}$$

In this paper, we are experimenting in the region where the antenna frequency is greater than the plasma frequency:

$$\omega > \omega_p$$

In this region refraction and not reflection takes place.

The phase speed of electromagnetic waves in a plasma is greater than in free space. The greater the density of the plasma the greater the phase speed. Since the plasma density can be reconfigured, the steering and focusing of antenna beams by the physics of refraction through a plasma is reconfigurable [10, 11]. The amount of refraction through a plasma depends on the path length through a plasma and the change in plasma density over that path length [12]. This physical process can also be considered as a plasma lens [13].

Refraction in a plasma depends on:

1. Plasma density
2. Path length
3. Gradient of plasma density

We have very good results at 24 GHz and above using COTS plasma tubes. We made custom plasma tubes with larger diameter and refraction that worked well at 10 GHz.

At 24 GHz, two plasma tubes were used to get antenna beam focusing and one plasma tube was used to get antenna beam spreading. Antenna beam steering was achieved with one and two plasma tubes at 24 GHz. In another case our beam steering experiments from using the physics of refraction through a plasma were done at 44 GHz.

2. Focusing antenna beams with the physics of refraction through plasma

In the following sections we show our work on antenna beam focusing, beam spreading, and beam steering using refraction of RF waves in a plasma. This is our first iteration of the plasma lens work and it can only improve. We found it was easier to show the lensing effects of plasma at 24 GHz since the size and shape of COTS plasma tubes are amenable to a 24 GHz. These effects all scale according to wavelength, but cylindrical annular rings of plasma are the best way to control the plasma density variations of plasma to optimize the engineering effects of plasma refraction to control beam focusing, beam spreading, and beam steering.

We have demonstrated the ability to use a plasma for manipulation of a microwave signals by focusing a wide beam into a more narrow beam and also by steering the beam.

Figure 1 shows the experimental set-up for beam steering and lensing. A narrow-beam 24 GHz signal is directed into the side of two 1.5 inch diameter plasma tubes which focuses the antenna beam into higher directivity, gain, and range.

This change in velocity of the signal inside the plasma results in a lensing effect if the beam passes through varying lengths of plasma similar to light passing through glass of varying thickness to make a lens. But there is an important and interesting difference between an ordinary lens made of glass or plastic and a plasma lens: The glass lens slows-down the signal while a plasma lens speeds-up the signal. Therefore

a convex glass lens focuses a signal to a point while a convex plasma diverges the signal similar to a concave glass lens that diverges the signal while a concave plasma lens focuses to a point.

We have built converging and diverging plasma lenses using plasma tubes as shown in **Figures 1** and **2**. A single plasma tube with the beam passing through its diameter acts as a diverging plasma lens (**Figures 2** and **3**) and two plasma tubes side-by-side form a converging (focusing) lens (**Figures 1** and **4**).

We have built the “concave” set-up for beam shown in **Figure 1**, and **Figure 4** is a 24 GHz, 5 mW Gunn diode is used as the microwave source with the signal

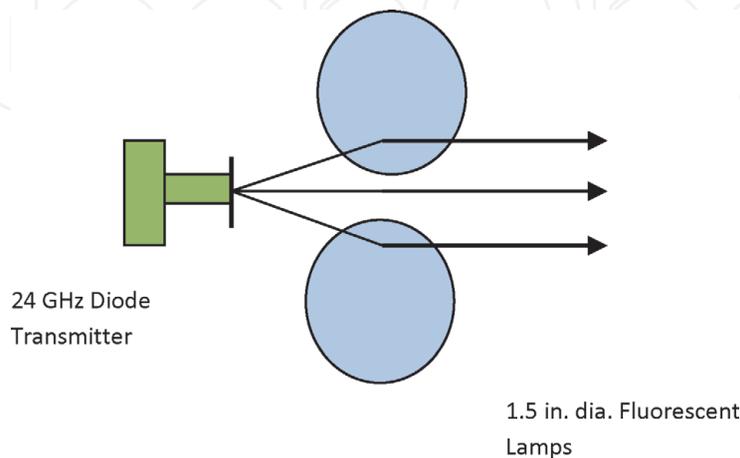
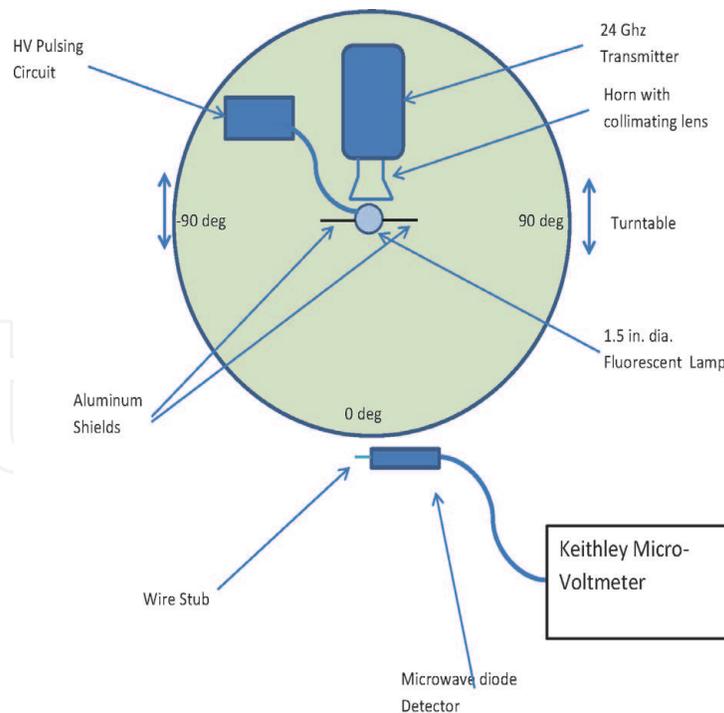


Figure 1.
 Schematic for experimental setup of antenna beam focusing with tubes with plasma using two COTS (commercial off the shelf) tubes.



Set-up for measuring plasma lensing effect

Figure 2.
 Schematic for experimental setup for antenna beam spreading with tubes with plasma in one COTS (commercial off the shelf) tubes.

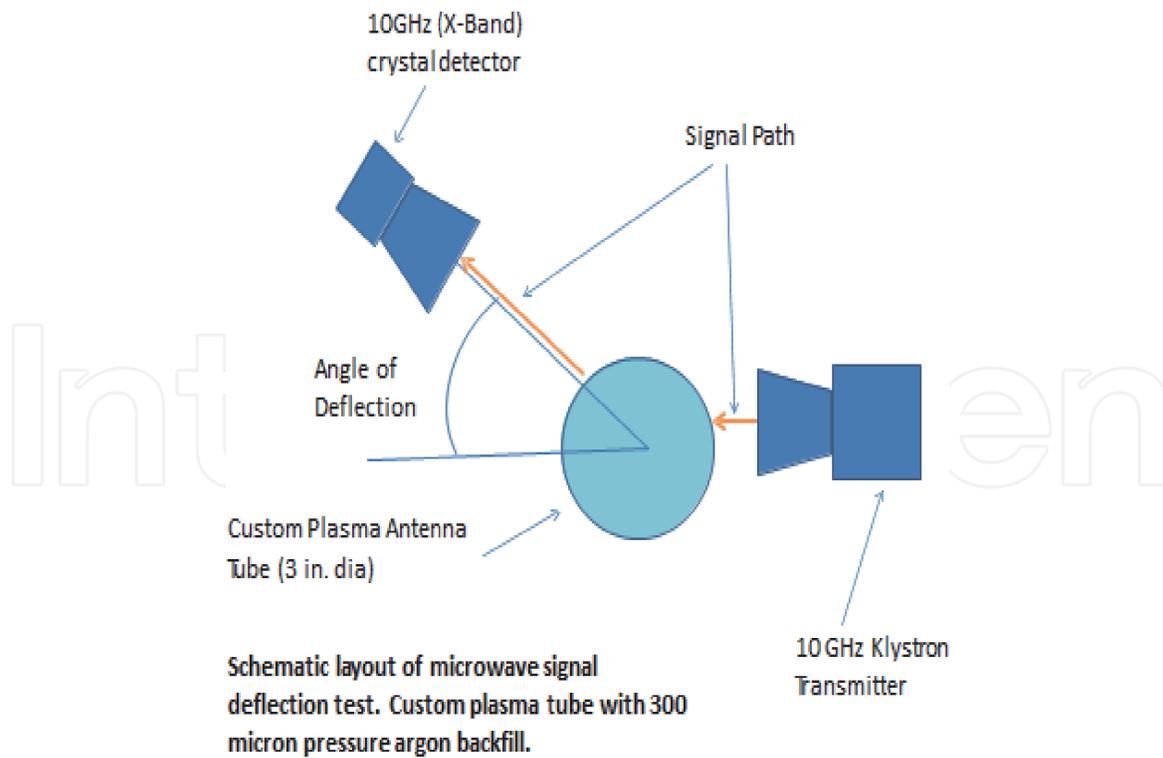


Figure 3. Schematic showing antenna beam spreading with one 3-inch diameter custom made plasma tube at 10 GHz.

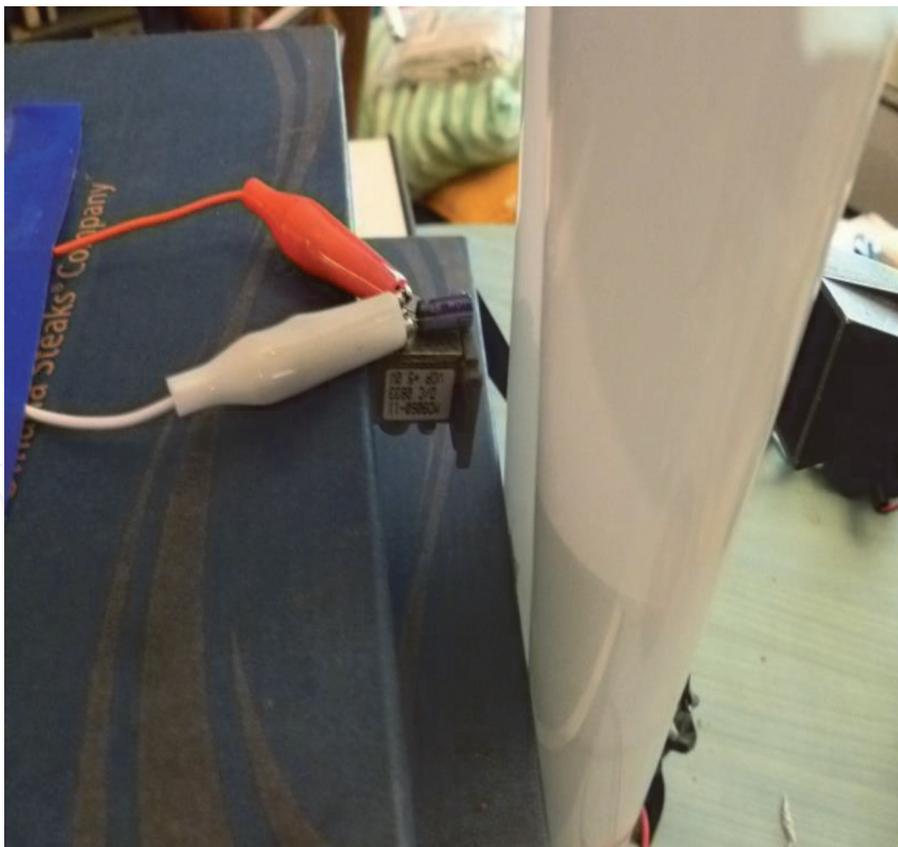


Figure 4. Plasma focusing experimental setup from a different angle. Gunn diode 24 GHz transmitter with fluorescent tubes used for plasma beam focus.

radiating from the open waveguide, which gives a directional but unfocused microwave output. This setup allows us to focus the beam in the forward direction resulting in a gain of 2 (3 dB). This can be seen in **Figure 5**.

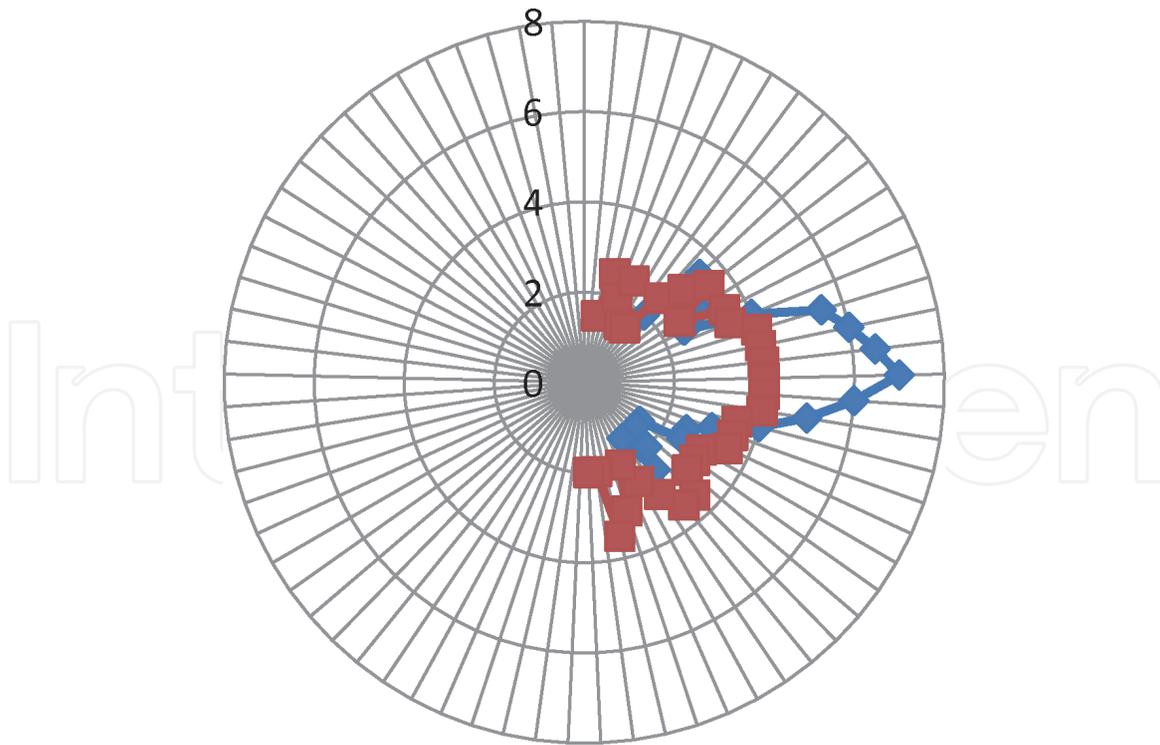


Figure 5.
24 GHz beam focus with plasma. Red line is with no plasma. Blue line is with plasma. Note that the plasma focus increases beam amplitude by a factor of two compared to no plasma (~ 3 dB gain). A crystal waveguide detector was used as a receiver. Amplitude numbers are relative voltage readings from the crystal detector.

We are the only group utilizing a pulsed high voltage power supply to give a much higher average plasma density and much lower average power to ionize the gas into plasma. This ability to tune the focusing of a RF beam is very useful because the same lensing structure can be used with different frequencies and to vary focal length as needed.

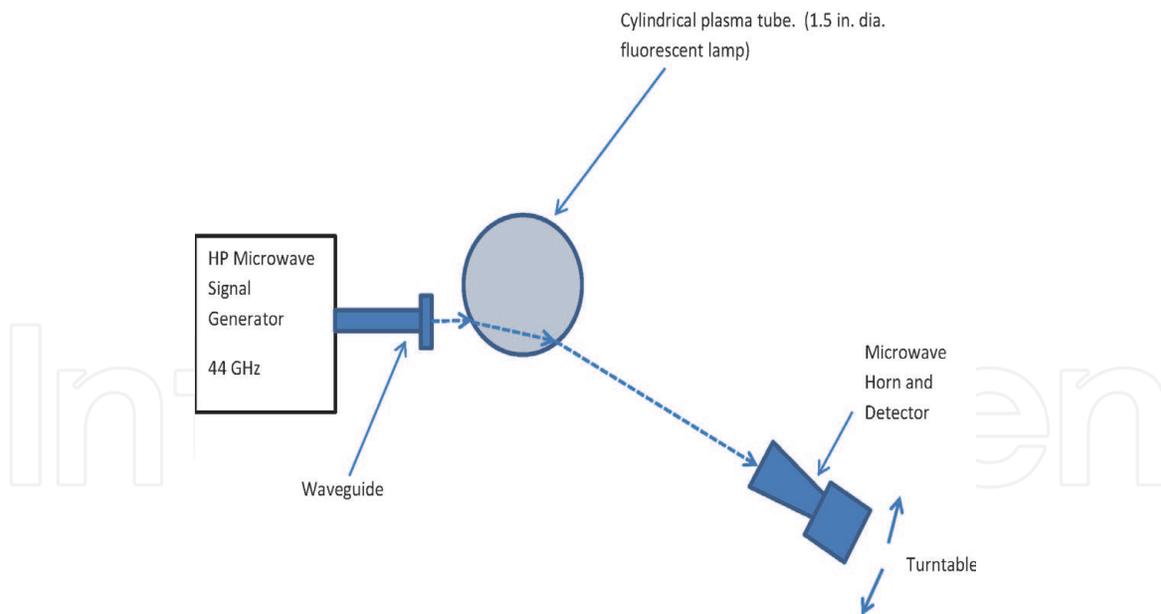
3. Steering antenna beams with the physics of refraction through plasma

We have done microwave beam steering using a cylindrical plasma tube. Those tests were done using fluorescents lamps with a diameter of 1.5 in (3.8 cm); and with a 24 GHz microwave beam. A shortcoming of the set-up was that the 24 GHz signal has a wavelength of 1.25 cm, which is 1/3 the diameter of the tube. For a properly working lens, the wavelength should be small compared to the physical dimensions of the lens, or in our case the plasma tube.

This work involved using a much higher frequency (44 GHz, 0.68 cm) and therefore shorter wavelength. This wavelength is a factor of 5.6 smaller than the 3.8 cm tube diameter which should result in a more ideal lensing action. Our testing has confirmed this and has shown significantly narrower beam steering and less signal loss.

Of course all the dimensions scales with wavelengths used so going down to lower frequencies requires larger diameter tubes or other shaped plasma containers. This is why it is important to make custom made plasma tubes or other geometries.

Figure 6 is a schematic for the experimental setup, and **Figures 7** and **8** are photos of the setup. A 33–50 GHz HP Microwave Signal Generator is used to generate the incident microwave beam. The plasma tube (fluorescent lamp) is placed ~ 1 inch in front of the open-ended waveguide, and an aluminum shield is placed against the side the tube to ensure that most of the microwave signal goes



Schematic layout of 44 GHz beam steering experiment.

Figure 6.
Schematic for antenna beam steering using one COTS tube with plasma.



Figure 7.
Plasma beam steering experiment. Antenna rotator with holder (green) and receiver horn/detector is in the foreground. The oscilloscope used to monitor the signal waveform is on top of the HP signal generator. The solid state pulsing circuit is to the right of the signal generator.

through the plasma and is not bypassed to the side of the tube. A 33–50 GHz microwave horn with HP crystal detector is placed on a rotating arm that is scanned in an arc around the plasma tube by an antenna rotator. The arm places the horn

receiver about 16 inches from the plasma tube. This corresponds to 60 wavelengths between the steering plasma tube and the detector and clearly qualifies as far field.

In order to generate a plasma with a density high enough to interact with RF signals in microwave frequencies, we use short current pulses ($\sim 1 \mu\text{s}$) that quickly ionize the plasma; then rely on the plasma ions rather slowly migrating to the wall of the plasma tube. Using this technique (developed by Dr. Theodore Anderson and the late Professor Igor Alexeff) we generate a much higher average density plasma with a low average current and power.

Our high current pulses have so far had a period of 1 ms. With this time separation between pulses, the plasma density decays by about a factor of two



Figure 8.
Fluorescent plasma tube is located in front of the output waveguide on the HP signal generator. Aluminum shield on left of tube prevents stray RF from bypassing the plasma. High voltage pulser is on the right.

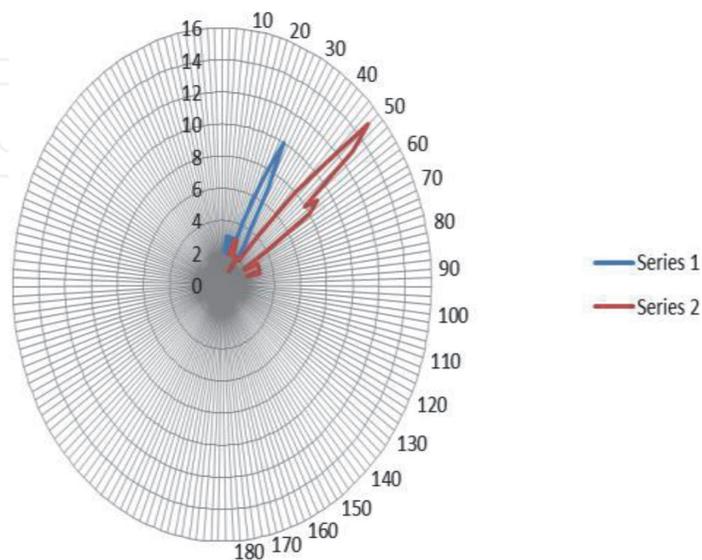


Figure 9.
Beam steering (44 GHz) for two different plasma ionizing currents. Blue line: 5 A peak. Red line: 8 A peak. A crystal waveguide detector is used as a receiver. Amplitude numbers are relative voltage readings from the crystal detector.

before the next pulse comes to refresh the plasma back to peak density. This has not caused a problem with the smart antenna because we are using the plasma to totally block the RF signal, like a shutter. But lensing and beam steering require a plasma of a specific density to get a consistent beam deflection angle.

We are avoiding this problem by recording the received microwave signal immediately after the current pulse; therefore measurements are taken at a constant plasma density, which is also the maximum density before significant decay of density occurs.

Our recent experimental results with 44 GHz show dramatic improvement in beam deflection characteristics compared to previous testing at 24 GHz. The shorter wavelength compared to tube dimensions has clearly resulted in cleaner and more consistent beam steering.

Figure 9 shows beam deflection at two peak ionization currents. The blue curve shows about 26 deflection with a current of 5 A peak. The red curve shows about 50 deflection with a current of 8 A peak.

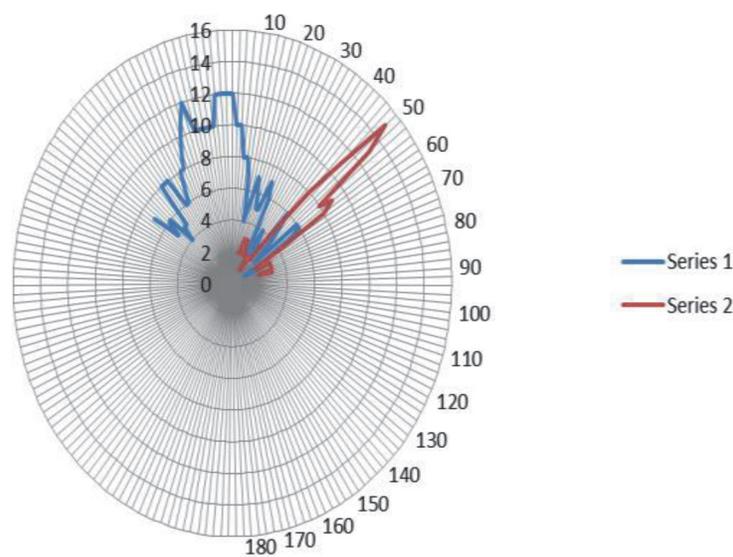


Figure 10. Plasma beam steering. Beam is steered $\sim 45^\circ$ clockwise. Blue line: No plasma. Red line: 8 A peak ionizing current. A crystal waveguide detector is used as a receiver. Amplitude numbers are relative voltage readings from the crystal detector.

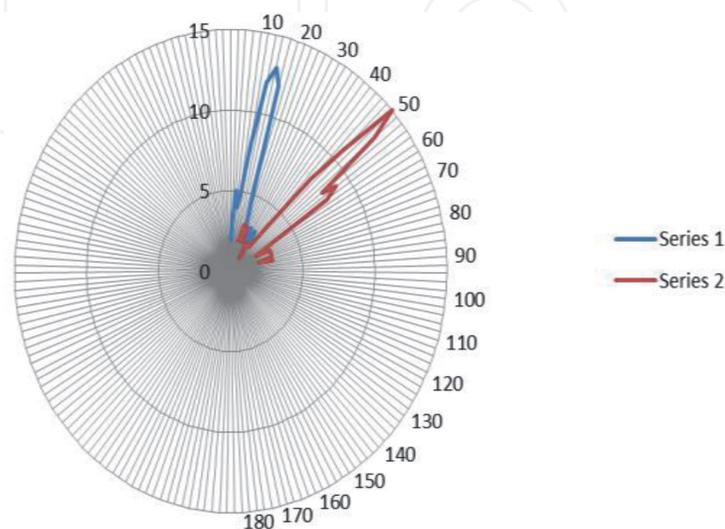


Figure 11. Beam steering for two different plasma ionizing currents. Blue line: 3 A peak. Red line: 8 A peak. A crystal waveguide detector is used as a receiver. Amplitude numbers are relative voltage readings from the crystal detector.

Figure 9 demonstrates that we can vary the angle of deflection by changing plasma ionizing current; but the most striking result shown in **Figure 9** is the very narrow beam-width of the deflected signals. This is quite surprising. **Figure 10** shows the 50 deflected beam (red line) along-side the un-deflected beam with no plasma. The incident un-deflected beam has a much wider beam-width compared to the deflected beam with plasma turned on.

Figure 11 shows the beam deflection (blue line) with a lower peak plasma current of 3 A with a beam deflection of 15°. For comparison the 50° beam deflection with 8 A peak is shown in red.

4. Pulsed plasma antenna circuitry

A plasma antenna operating in the microwave frequency range requires higher operating currents (Greater than ~ 1 A) and consequently can overheat when used continuously. Our plasma antennas are able to work CW at high frequencies (>1 GHz) because of a concept invented by Igor Alexeff and Theodore Anderson that uses fast high-current pulses; instead of DC current.

The plasma initiates quickly in less than a microsecond, but when plasma ionizing current is turned off, the ions take about a millisecond to recombine with electrons. Therefore plasma density stays high for almost a millisecond even though the ionizing current is no longer on. We use an even short pulse width (~ 1 μ s), and therefore less power is required to run the antenna.

We developed a pulsed voltage doubler circuit, allowing us to use a lower voltage DC power supply for the input power to the pulsing circuit using a modified Marx Generator. A Marx Generator is a pulsed voltage multiplier. A series of capacitors was charged in parallel and then discharged in series through spark gaps.

Figure 12 shows a two stage voltage doubler circuit. We have built and tested a modified Marx Generator that replaces the spark gaps with an IGBT electronic switch.

Keeping the second spark gap in the circuit results in a faster rise time than in our previous pulsing circuits. The voltage doubler allows the use of a lower voltage DC power supply than would otherwise be required.

A simple non-voltage multiplying IGBT pulsing driver circuit is shown in **Figure 13**. A CMOS timer IC is used to generate short 1 μ s pulses with a repetition time of 750 μ s. An IXYS brand 2500 V IGBT is the high voltage switch. This pulsing arrangement allows us to use a factor of 750 less DC current and power from the DC power supply.

We have been driving our plasma antenna tube with the fast, high-current pulses described here to allow operation at higher frequencies than is possible with CW current. Our pulsing circuit had required that the both electrodes of the plasma tube operate at high voltage; with the positive electrode at constant maximum DC voltage (2–3 kV). We have modified the circuit to allow the negative electrode to remain grounded while a positive 1 μ s pulse is applied to the anode electrode. This change offers several advantages:

Improved electrical safety because one electrode remains grounded and the other electrode is supplied with short pulses. Less capacitive loss in the current leads allowing the use of faster pulses; since one electrode is grounded and can be attached to a ground plane.

Eliminating the need for a negative lead wire means less high voltage wiring. Lower EMI caused by high current pulses in wiring.

Grounding one side of the plasma tube requires that the high voltage switcher (IGBT) be able to float up and down in voltage with the tube's anode. To do this we

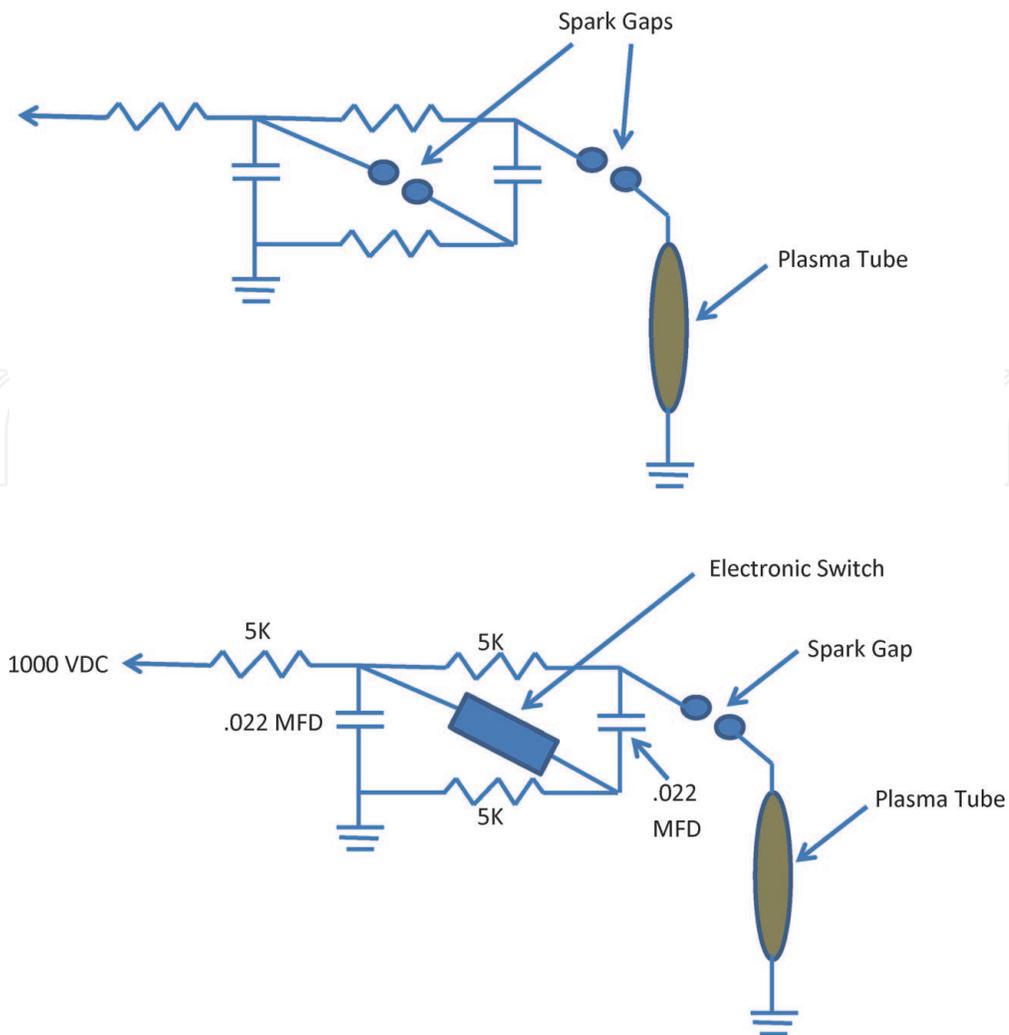


Figure 12. 1000 V DC to 2000 V pulse circuit using modified Marx generator with spark gaps in the top photo and with an electronic switch and spark gap in the bottom figure. Two electronic switches was also built but not shown.

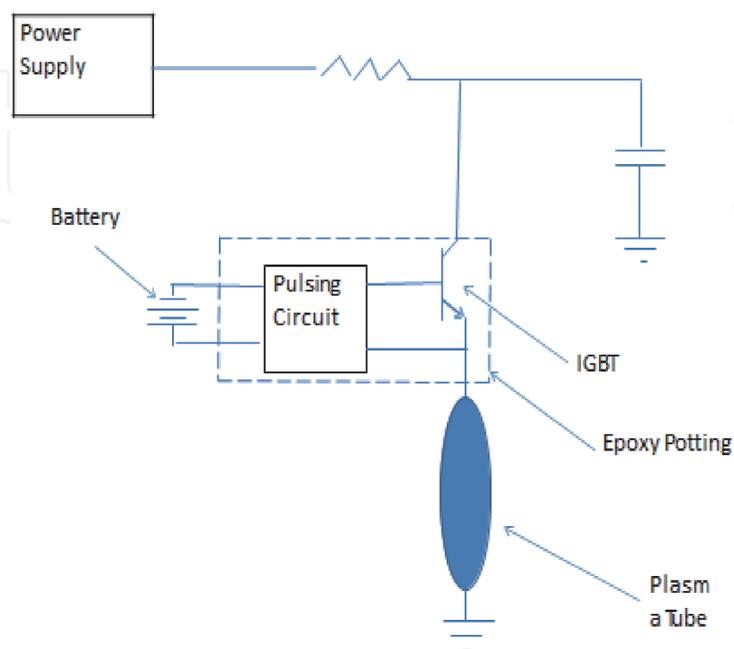


Figure 13. Basic pulsing circuit. A DC power supply charges the capacitor, the IGBT pulsed circuit switching delivers short $\sim 1 \mu\text{s}$ pulses to the plasma tube.

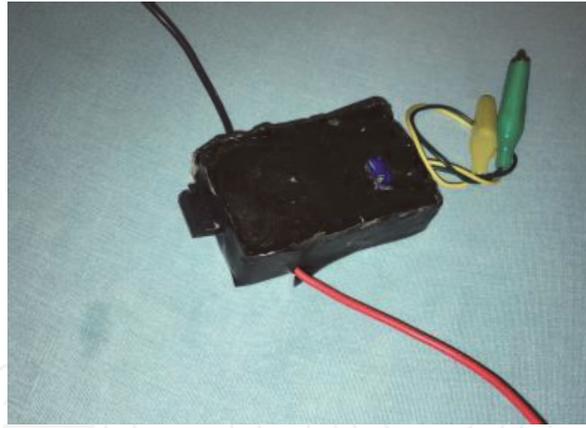


Figure 14.

Prototype pulsing circuit potted in epoxy. High voltage leads are at top and bottom, and the battery connection is on the right.

have electrically isolated the switcher by using a battery to power the electronics and by potting the IGBT and electronics in epoxy.

Figure 14 shows our first prototype with steel-filled epoxy; not the best choice of epoxy but one that is working quite well so far. Potting the circuit is advantageous for airplane and aerospace applications, providing mechanical ruggedness as well as electrical isolation. Epoxy has much higher thermal conductivity than air, but not as good as a metal heat sink. The steel filled epoxy has about a factor of 10 higher thermal conductivity than air. Highly thermally conductive epoxies can have a factor of 100 higher conductivity than air. Potting in epoxy in our case allowed operation without an additional metal heat sink, saving space and eliminating the need for electrical isolation between the IGBT and a metal heat sink. We tested the ruggedness of our epoxy-potted circuit by dropping it on a concrete floor from a height of 6 ft. without damage to the circuit.

We ran the circuit shown in **Figure 13** (with no additional heat sink) with peak current of 20 A and a pulse period of 1000 μ s.

After $\frac{1}{2}$ hour of operation, the epoxy and IGBT were warm to the touch but with no indication of over-heating.

5. Power, current, and voltage requirements in pulsing excitations

The plasma antenna requires a relatively high voltage, low current power supply.

Short pulses are applied to the terminals of the plasma tube. Peak current is about 1 A with 5 μ s pulse width and a time between pulses of about 1 ms.

This duty cycle of 1/200 results in an average power of about 5 W.

Overall average power drain from the battery driving the plasma antenna will be much less than 5 W. Two standard 9 V batteries and/or one 6 V.75 AH SLA battery can operate a plasma antenna. The smart plasma antenna can operate on a 12 V car battery which is enough voltage to ionize the plasma in 12 tubes and run the computer.

The power losses of the supply voltage connected to the plasma antenna are because the VSWR numbers in many cases indicate a very good match between the feeds and antennas.

Anyone trying to build a plasma antenna according should consult a licensed electrical safety expert before proceeding. After consulting a licensed electrical safety expert, proceed as follows. Use a three-wire grounded power cord and

securely attach the green ground wire to the metal enclosure. Install an appropriately sized fuse or circuit breaker to protect from short circuits or overloads. Always unplug the unit before modifying or working inside.

6. Conclusions

We have demonstrated that one or two plasma tubes can be used to focus, spread, and steer antenna beams. We have also shown that we can simulate convex and concave plasma lenses by using cylindrical plasma tubes. Focusing by a plasma is useful because it can be used to increase the gain of an antenna, and to quickly reconfigure the beamwidth as needed without physically moving the antenna. With this technology, there is no need for phased arrays. Beam steering with a plasma allows tuning to different frequencies which is a difficult task for standard antennas. Our experimental results with 44 GHz showed a dramatic improvement in beam steering and focusing characteristics compared to beam focusing and steering at 24 GHz. The shorter wavelength compared to the spatial variation in plasma density over the radius of the plasma tube, the easier it is to steer and focus antenna beams. These results have been incorporated in a new smart plasma antenna design which appears in another paper.

Driving the plasma with short high-current pulses allows CW operation at higher frequencies with a minimum amount of ionization power and higher plasma densities. Circuits for pulse forming and voltage multiplication are presented. The maximum frequency that a plasma antenna can operate CW has previously been limited by the high DC current needed to ionize the plasma. We minimize the average ionization power and increase the plasma density by using fast current pulsing with a short duty cycle. The average current is much lower but the average plasma density remains high than in the DC mode.

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