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Plasma antennas for the undergraduate student

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Abstract – We describe the theory, practical construction, and experiments of a plasma antenna to radiate VHF wireless signals. The results show that a plasma antenna can be an effective radiator of RF signals with characteristics that favorably compare with a comparable metal antenna. Furthermore, when de-energized, the plasma antenna effectively disappears and thus can be useful when an object equipped with this antenna requires stealth (i.e., undetectable to RADAR). This paper provides a gentle introduction to plasma antennas for undergraduate physics and electrical engineering students who are studying general electromagnetic theory and basic antenna design. Building, measuring and characterizing a plasma antenna will enable experiential learning of not only the plasma antennas, but will also enhance the students' knowledge of electrical conductivity, dielectric breakdown and quantum mechanics.

Introduction

When students take their first electromagnetic (EM) course using a textbook such as Ulaby, et al. [1] they learn how materials such as metals with free electrons are conductors and those that lack free electrons are dielectrics. They also learn that if enough energy is applied, almost any dielectric will break down to enable free electrons, and thereby allow electric current conduction. Gasses are one example whereby if enough energy is applied, the breakdown in gas manifests itself as phenomena such as lightning, the arcing associated with automotive spark plugs or arc wielders, and florescent lights. The conductive gas is referred to as a *plasma*. The amount of energy required for breakdown depends on the gas type or element, and the frequency of the applied voltage. For example, neon has a relatively low breakdown voltage as compared to nitrogen. The breakdown voltage may be further reduced if the frequency is increased. By creating an arc or gas discharge, the gas which was formerly a dielectric becomes a conductor. As students' progress in their EM course, they also learn how a metal device can radiate or receive RF energy. Therefore, at some point, the student could synthesize these two concepts to create a plasma antenna that will radiate or receive wireless signals. They might also conceive the concept of a hidden antenna that is only electrically visible when the plasma is energized such as in stealth aircraft.

In subsequent sections of this paper, we describe plasma antennas to undergraduate physics and electrical engineering students with the goal of removing the mystery associate with these antenna types. This will be experiential, where our learning vehicle will be to construct a plasma antenna using widely available, low-cost materials and then conduct experiments to characterize the antenna's characteristics such as voltage-standing-wave ratio (VSWR), and radiation characteristics. As a benchmark, we compare our results using a similarly sized wire antenna. In the process of studying the plasma antenna, previously learned topics such as dielectrics, conductors, dielectric breakdown, quantum mechanics and electrical noise will be reinforced.

Literature review - Gaseous conductors, gas discharge tubes, and plasma phenomena have been known for a long time. Cobine [2] describes the physics of gaseous conductors; Anderson's book [3] has a comprehensive treatment of plasma antennas; Raynor et al. [4] and Alexoff et al. [5] describe the physical characteristics of plasma antennas as well as the various ways they can be constructed and reconfigured to achieve a particular electrical characteristic; Zhao et al. [6] and Alexeff et al. [7] describe the design and characteristics of various plasma antennas.

Theory

Ionization – Ionization is a process whereby an atom or molecule becomes charged either by losing or gaining electrons and is initiated by a sufficiently strong external energy source. In the case of a gas molecule, a *plasma* is created whereby its electrons go to a higher orbit, and then when returning will release photons which manifest themselves as light with spectral lines at various wavelengths. Because each element has a unique electron orbital structure, the photon spectrum will have multiple and unique wavelength lines. Thus, each element has a unique spectral fingerprint, and an element could therefore be identified based on its emission spectrum. Incidentally, each element having its own unique light spectrum is the basis for Atomic Emission Spectroscopy [8] and elemental detection. For example, neon's two strongest light wavelengths are 585 nm and 640 nm, whereas argon's two strongest wavelengths are 696 and 707 nm. The ionization process is initiated by either a high voltage, DC, RF waves, microwaves, ultra-violet rays, gamma rays, x-rays, etc. Visible examples of ionization would be an electrical arc across an air gap as occurs in an automotive spark plug or electric arc wielder, fluorescent bulb, or neon bulb.

Antenna theory – If RF energy is coupled onto a metallic element whose length is a half-wavelength, a dipole antenna is created that can radiate RF energy. By adding an additional conductor(s), such as a reflector we can enable the antenna to be directional. Examples, include the Yagi and parabolic dish antennas. Instead of using metallic elements we could use a various plasma devises to radiate and direct the RF energy. Alexeff et al. [5] creates a "dish antenna" where both the radiating element and reflector are plasma devices. Similarly, by adding various plasma sections to the antenna, and by lighting up the various sections, one could change its characteristics (i.e. radiation pattern, resonant frequency, etc.). See [1, 9] for more information on antenna theory.

Experimental setup

Construction – The plasma antenna and its RF source is shown in Figure 1. Our goal with the plasma antenna is to emulate the conventional metallic half-wave dipole. The antenna consists of a 1.1m long, 25 mm diameter, U-shaped florescent tube where the gas discharge is created by a 50 kHz signal from a commonly available florescent ballast transformer.[1] If this were an ideal thin wire half wave dipole, the resonant frequency would be 125 MHz.

The signal source comes from an Agilent 9912A Field Fox and was capacitively coupled to the plasma tube via the copper rings as shown in Figure 2. Figure 3 is a diagram of the system. Shielding of the antenna's circuitry was to minimize leakage of RF energy when the plasma is turned off. Put another way, we wanted the antenna only electronically visible when the gas was energized. Placement of the coupling rings was to minimize both the VSWR and RF leakage.

[1] The ballast transformer is an electronic type that outputs a signal between 42 and 52 kHz. The manufacturers use this type of device to avoid interference with infrared devices, and eliminate visible flicker.

Figure 1. Plasma antenna using fluorescent tube with 122 MHz signal source.

Figure 2. Construction details of plasma antenna showing 50 kHz ballast transformer and how the RF source is capacitively coupled to the gas tube via a copper rings. The leftmost ring is grounded and the right most ring receives the RF energy via the coaxial center conductor.

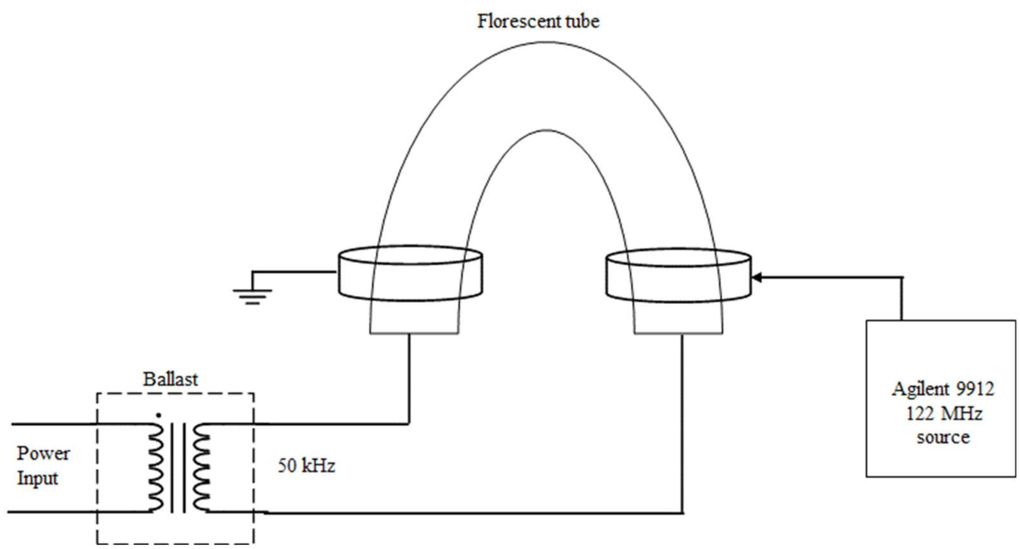

Figure 3: Diagram of plasma antenna system. Note, shield on right most ring is not shown.

As Figures 2 and 3 indicate, both ends of the florescent tube have copper rings that are used to capacitively couple RF energy from the RF source. The coaxial center conductor goes to one ring, and the shield is connected to the other ring. There is no direct connection from the RF source to the plasma. To minimize RF radiation (i.e., leakage) when the plasma is turned off, the copper ring that connects to the coax center conductor is also shielded by a third copper ring (not shown in Figure 3). To further minimize leakage when the plasma was turned off, we added additional aluminum foil to the box containing the florescent tube as shown in Figure 1. The two copper rings that supply the RF energy could be moved around to minimize the VSWR. In the end, however, the feed points were located at opposite ends of the tube and inside the aluminum box.

Procedure and results

Resonant frequency and VSWR– We used an Agilent 9912 RF analyzer and an RF source and to measure the resonant frequency and VSWR. Our measurements indicated a resonant frequency of 122 MHz with a corresponding VSWR of 2.3. We used a 122 MHz signal for all our subsequent testing. At other frequencies, the VSWR was in excess of 10. The measured resonant frequency of 122 MHz is relatively close to the theoretical half-wavelength value of 125 Mhz. The difference is likely due to the thickness of the plasma conductor and other effects.

Leakage – A second Agilent 9912A RF analyzer in Spectrum Analyzer mode was used to measure the RF energy from the antenna originating from the other 9912 RF source. To determine how “stealthy” our antenna was, we measured the radiation levels of the 9912 source with the plasma turned on then off. When the plasma was on, the 122 MHz level was -62 dBm and when off, the level was -96 dBm. Thus, the shielding reduced leakage by 34 db. Further reductions in RF leakage might result if we shielded the power cord.

Radiation pattern - The plasma antenna was set up in the middle of a field as shown in Figures 4 and 5. Measurement of the plasma radiation pattern consisted of encircling the RF source/plasma antenna at a distance of 80 feet and then tabulating the signal strength every 45 degrees. In Figure 4, the measurement points are marked with an "X." Measurements were such that the variation in RF energy varied by no more than +/- 4dBm. Therefore, we believe the radiation pattern to be omnidirectional. We attribute the signal strength variations to nearby metallic objects, lack of a perfect far-field source due to measurement distance, and other measurement errors.

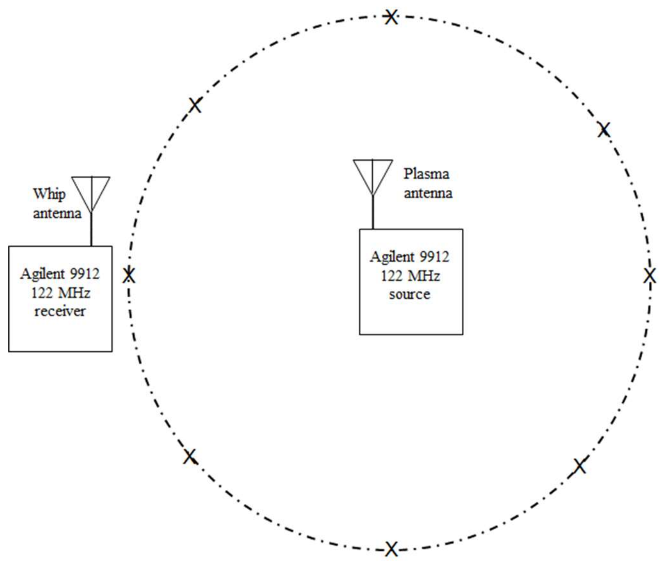

Figure 4. Test setup to measure the radiation pattern from the plasma antenna. Signal strength measurements were made at the spots marked "X."

Comparison to a metallic antenna – As a benchmark, we measured the emitted RF levels from a comparable metallic whip antenna. The metallic whip antenna had a signal of -52 dBm, versus -62 dBm of the plasma antenna. Thus, there is a 10 dB penalty with the plasma antenna versus the metallic one. We attribute most of the 10 dB difference in signal strengths due to greater radiation efficiency of the metallic antenna, since metal is a better conductor than plasma. More work needs to be done to properly quantify and attribute the differences between these types.

Figure 5. Measurement of the RF intensity on the football field.

Conclusions and further work

We have implemented a plasma antenna using commonly available components that can radiate a VHF signal and be relatively undetectable when the plasma is turned off. Students observe and experience the behavior of this unconventional type of antenna. It is expected that this project will further their interest in conventional and unconventional antenna types. While the antenna setup does not achieve the best performance, the project has removed the "mystery surrounding the plasma antenna", demonstrated that a conductive gas can indeed radiate RF signals, and was low cost (<100$ excluding RF source).

With respect to pedagogy, there are more questions to be answered. First, the more advanced students who have had communication systems and understand how conductors carrying colliding charges are also noise generators thus will then ask the question, "Given that a plasma is a gas with lots of collisions, how much more noise does the plasma antenna add to the system and will it be a major limiting factor?" Therefore, the next experiment would be to see how much noisier the plasma antenna is as compared to its metallic counterpart and to measure the signal-to-noise difference of signal received with a metallic versus the plasma antennas. Secondly, does the type of gas affect the ability of the antenna to radiate or receive RF signals? Thirdly, to what degree does the excitation frequency affect the antenna's performance? This could be done by switching out the 50 kHz ballast and substituting a 60 Hz ballast. Most of these questions have already been addressed in the existing literature. However, they are better answered by having the students themselves build the plasma antennas and then do the appropriate experiments.

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