Simplified portable 4 MHz RF plasma demonstration unit

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Abstract. This paper documents the design of an RF plasma demonstration unit. The paper shows that there are significant challenges associated with the generation of high frequency plasma under atmospheric pressure, but it yields some interesting results and a simple and elegant design. The generator makes use of a standard power MOSFET in a modern switching amplifier design to produce the required RF power and drive the resonator to produce the high frequency discharge.

1. Introduction
Over the last decade, the interest in plasmas generated at atmospheric pressure has increased. Atmospheric plasmas offer high excitation selectivity and energy efficiency in plasma chemical reactions. They are sources of UV, Vis and IR radiation, free radicals such as O, OH and ozone that can play important roles in various techniques. This simplified RF plasma unit was built for several reasons: to prove that it could be done, despite many technical difficulties, to see how the appearance and behaviour of the electrical discharge differ at MHz frequencies, compared to “traditional” DC or low frequency corona discharge, to make the system compact and portable, easy to set up and use for demonstrations. The operating frequency of 4 MHz was chosen because it is sufficiently far into the RF spectrum so that the generated discharge will have a different behaviour than the low frequency corona.

2. The RF plasma source
Conventional power amplifiers for use at several MHz usually employ specially designed RF power semiconductors and operate in class A or class C. These devices typically use special fabrication techniques that reduce the stray capacitances down to acceptable levels to permit efficient operation at such high frequencies. The plasma unit presented in this paper was built using only general purpose components that are easily available. However, there are real challenges associated with getting standard switch-mode power MOSFETs to switch efficiently at 4 MHz. At this frequency it is difficult to drive the gate with fast edges due to its large capacitance. Large die power MOSFETs typically have gate capacitances of several nanofarads. It takes a considerable power to quickly charge and discharge this capacitance 4 million times every second. The “Miller effect” adds to this difficulty due to capacitance from drain to gate if the device is operated from a high voltage supply, such as in this particular application. Another problem are the high switching losses when the switching time represents a significant portion of the total period. A typical switching time of 50 ns is acceptable at 200kHz where the switching time only represents 1% of the total period. However the same 50 ns
switching time represents 20% of the period at 4 MHz. This means that the device would spend a considerable portion of the total period passing through the linear region dissipating a lot of power. Also, there are switching losses due to repeated discharging of the MOSFETs output capacitance. Every time a MOSFET is switched on the energy stored in its output capacitance is discharged into the MOSFET channel. This is particularly bad for devices being operated at high voltage and high frequencies, when the stored charge can be considerable.

2.1. The circuit explained

The system diagram can be broken down into the following functional blocks: power supply, 4 MHz crystal oscillator, high current MOSFET driver, MOSFET power stage and the Tesla resonator, tuned at 4 MHz. The diagram is shown in figure 1.

The power supply has three outputs: +5 V for the crystal oscillator, +12 V for the driver stage and +300 V for the MOSFET power stage. The two low voltage outputs are filtered and stabilized. The high voltage output is filtered by an LC cell. The crystal oscillator module is based on the SN7405 TTL integrated circuit (hex-inverter with open collector outputs) and provides a highly-stable square wave at 4 MHz. It was decided to drive the circuit from a fixed frequency oscillator because such a small Tesla resonator will not produce enough corona even at full power to greatly detune itself. Also, the circuit should be less sensitive to the surrounding environment detuning the resonator. The system can always be tuned by adding or removing a turn from the Tesla resonator, or fine adjustments made by raising or lowering the breakout point.

Figure 1. The system diagram.

Figure 2. Generator schematics.
The high current MOSFET driver module is based on the TPS2814P integrated circuit and it is capable of delivering peak currents of 2 A into highly capacitive loads. The power stage is built around the IRF740 power MOSFET transistor. Figure 2 shows the full schematics.

2.2. Tesla resonator and the corona discharge

The Tesla resonator is a high frequency air cored resonant transformer consisting of two windings, named primary and secondary. The primary winding is where the RF power developed by the power stage is coupled into the Tesla resonator. The dimensions, number of turns, and coupling coefficient to the resonator are critical to correct operation. Both the coupling and the inductance of this primary winding determine the power throughput of the system. The value of the coupling coefficient also effects the tuning of the resonator. The reason for this may not be immediately apparent, but increasing the coupling coefficient ties up more of the lower turns of the resonator in transformer action by magnetic coupling to the primary. As the coupling coefficient is increased there is less of the resonator's total inductance free to resonate, and so the apparent resonant frequency increases. The secondary winding – the resonator, has to be build so that it self-resonates at the desired frequency. This means that its inductance and stray-capacitance forms a series-resonant LC circuit, “tuned” at exactly 4 MHz. For this application the support for the coil was chosen a 50 mm diameter PVC tubing pipe. The coil was wound with 0.4 mm copper-enameled wire. At 4 MHz the skin depth in copper is only 0.033 mm. The 0.2 mm radius of the wire represents 6 skin depths so there would be little benefit in using a thicker wire, as the largest portion of the current is already flowing in the outermost skin of the wire. The parameters of the resonator coil were calculated using the following equations:

\[
L = \frac{(N \cdot R)^2}{9R + 10H} \quad \text{(air cored solenoid inductance)} \quad (1)
\]

where: \(L\) is the inductance in \(\mu\)H, \(N\) is the number of turns, \(R\) is the radius of the coil in inch, \(H\) is the length of the coil in inch.

\[
C = (0.29 \cdot H) + (0.41 \cdot R) + 1.94 \frac{R^2}{H} \quad \text{(Medhurst self capacitance)} \quad (2)
\]

where: \(C\) is the self capacitance in pF, \(R\) is the radius of the coil in inches, \(H\) is the length of the coil in inches. The resonance frequency is given by Thompson’s equation:

\[
f = \frac{1}{2\pi\sqrt{LC}} \quad (3)
\]

where: \(f\) is the frequency in Hz, \(L\) is the inductance in H, and \(C\) is the capacitance in F.

The correct number of turns was chosen by a series of approximations. Table 1 presents the final specifications of the Tesla resonator. Figure 3b presents the Tesla resonator and the corona appearance. The corona is a silent flickering orangey-lillac plasma flame, with a length of about 20mm, at an input power of 100 W.

**Table 1.** Tesla resonator specifications.

| Specification        | Value          |
|----------------------|----------------|
| Diameter             | 50 mm          |
| Length               | 60 mm          |
| No. of turns         | 150            |
| Wire gauge           | 0.4 mm         |
| Wire length          | 23.2 m         |
| Inductance           | 690.18 \(\mu\)H |
| Selfcapacitance      | 2.35 pF        |
| Natural res. freq.   | 3.95 MHz       |
| DC resistance        | 2.84 \(\Omega\) |
Figure 3. a) Generator coupled to Tesla resonator. b) generated corona discharge at 100W input power.

Figure 3a presents the generator-unit being coupled to the Tesla resonator. Weight no more than 3 kg, the unit is compact, portable and easy to set up for demonstrations. The setting up procedure is very easy, consisting of supplying the unit with 230 VAC and connecting the Tesla resonator to the output. The unit has two control buttons on the front panel. The red button is the main power switch and the green button controls the driver module, turning on or off the corona discharge.

3. Future development – amplitude modulated RF corona and applications
The nature of the corona discharge at these high frequencies makes it the ideal candidate for low frequency modulation. The modulation of any high frequency plasma is possible by varying the RF output power proportionally with an incoming signal. This varying power causes the air around the discharge to vary in temperature, expand and contract producing waves. Modulation of the system is best implemented using high level modulation of the +300 V supply to the final power stage. An interesting effect which will be studied is the modulation of a microwave signal by a low frequency modulated RF plasma. When microwaves propagate through a plasma in which electron density and electron collision frequency periodically vary, the propagated wave is modulated in amplitude and phase. An interesting application of the modulated RF corona discharge in experimental physics is a method for making superhydrophobic substrates on polymeric or non-polymeric articles.

4. Conclusions
This 4 MHz RF plasma unit was built to study the behaviour of the corona discharge at high frequencies compared to traditional DC or low frequency corona discharge. It was built using only general purpose components that are easily available. The generator is driven by a stable crystal oscillator working at 4 MHz. The overall characteristics are: simplicity, elegant design, high portability and easy set up for demonstrations.

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