RF Power Measurements and Control

First Semester Report
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ABSTRACT

RF power measurements take special care and equipment to measure accurately. In our case we have slightly increased this difficulty by designing a circuit with a high-Q. An LC load is used in conjunction with an argon stream to generate a highly parasitic atmospheric plasma. The high Q load is operated at 13.56MHz which makes any power measurement of a traditional probe both inaccurate and parasitic to the point that the plasma will not ignite. Furthermore, the use of Z-scans consumes power and also adds to the size of the circuit. It is our goal to replace the use of parasitic and bulky equipment with physically small components that are controlled by a dynamic feedback network. The current system is simply too large and is not an acceptable design for its broad range of applications (surgical plasma, for example.) If plasma is to remain a flexible technology then it must be redesigned using available off-the-shelf components.

For a successful ignition of the plasma the LC circuit must be a standard 50Ω load. The most accurate approach is unfortunately the most costly and time consuming: a network analyzer measuring a manually adjusted load capacitor. Furthermore, a signal generator and amplifier must be used to generate the desired output waveform at the resonant frequency, which also adds to the cost. Our goal is to replace all specialized equipment with physically small components. The end result will be a self-matching design that does not require the use of external test equipment and eventually will be reduced in size from taking up a tabletop to fitting in one’s hand. To date we have identified our circuit topology and are testing individual sections of our block diagram (fig. 2). The signal generator will be replaced with a Voltage Controlled Oscillator (VCO) with appropriate filters, the amplifier with an on board equivalent, and the matching network controlled with a Programmable System on a Chip (PSOC). Our ambitious goal is to have a working prototype this spring.

A special note must be made to emphasize the extremely parasitic load. Because we must use a high-Q load any object that interrupts the field surrounding the plasma has an adverse effect on the intensity of the plasma. Since our ultimate goal is a surgical plasma special care and attention must be made to always keep the plasma at its peak efficiency regardless of changes in the environment. This criterion requires us to plan for an exceptionally reliable design.
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Chapter I – INTRODUCTION TO A PLASMA CIRCUIT

Plasmas are used in various ways in modern devices and have plenty of room to grow. A quick internet search on plasmas will return dozens of companies offering products that vary from thin film deposition to plasma-based lighting systems and display systems to switches, relays, and antennas. Despite its flexibility and usefulness, plasmas require a considerable amount of peripheral equipment and labor costs to successfully operate. Our goal is to reduce both of these factors by adding value to plasma technology. Our approach is to re-design the circuit that generates the plasma in an effort to ease plasma ignition and operation. Chapter one outlines the current approach and its drawbacks.

The problem has been that almost all plasmas require bulky equipment and fine-tuned equipment to operate. Even then they do not operate predictably and are not tunable within a changing environment. This makes for an inefficient circuit with unnecessary power losses in the 10’s or even 100’s of watts. Our goal is miniaturize the circuit’s components and deliver only the proper amount of power to the load. Our final design must meet the above criteria as well as have the entire circuit’s physical size reduced.

Despite the relative simplistic circuit design the current approach to ignite the plasma requires considerable labor and cost. The LC load is typically disconnected from the circuit and fine tuned using a network analyzer’s Smith Chart. To do this we used a large span of frequencies to identify the various resonant frequencies along the spectrum. The goal with this step is to create a match. We do this by judiciously building our
inductor and tuning the capacitor with a target of 13.56 MHz: resonant frequency = \(1/\sqrt{L*C}\)

The inductor is built using copper with typical inductor equations in mind. The radius of the turns, number of turns, and length of the inductor all play a role: \(L=\mu*\text{Area}*N^2/\text{length.}\) Since high Q is desirable, we also must consider its equation: \(Q=(1/R)*\sqrt{(L/C)}\). In other words, we must build the inductor with the trade-off of physical size for Q. To date we have built dozens of inductors, all with different gauge wires and overall inductance values. For the purposes of this experiment and based on our design restrictions we can assume a range of inductor values on the order of hundreds of milli-Henry’s (mH) and Q\(\approx\)300-500. Such a high Q requires special care as any within a few centimeters will attenuate the plasma’s intensity.

Since our inductor values are basically fixed the capacitor is the tunable component. The load is tuned to minimize the complex impedance of the circuit until a match is achieved \((X_L = X_C)\). On the downside the capacitors are rather large and must be manually tuned using a knob. But these capacitors are not without their benefits as they are cheap, available, and most importantly offer a huge voltage tolerance. In a high Q circuit this is invaluable as the high tolerance allows us to
operate a range of frequencies around the resonant frequency without damaging the load. The load is then tuned until the Smith Chart indicates a $50\Omega$ match. We note the resonant frequency and reattach the load to the circuit.

The circuit’s waveform is generated by a signal generator that outputs a sinusoid at the resonant frequency. Typically our $V_{\text{sig}}$ is between 1v and 3v peak to peak. Our particular signal generator has a sufficient frequency range and waveform generator to meet our needs but also takes up about 5 cubic feet on a table top and is not easily portable. The signal generator’s frequency tuning plays a huge role in the power delivered.

From the signal generator the sinusoid goes into the amplifier. From here we can deliver 10’s of watts to the load. Since the amp is fixed gain we can tune the power delivered by tuning the frequency on the signal generator. Our specific set up allows us the flexibility to see the power output of the amplifier change with frequency. In other words, when we reach minimum power delivered we are at the resonant frequency. The more out of resonance the load is tuned, the more impedance is seen by the amplifier so more power is delivered.

Now that our equipment is tuned we need to turn on the argon gas flow. The argon will be the medium for which the plasma will ignite and operate. The tube carrying the argon is placed on the load, turned on, and the plasma is then ignited. Upon ignition the power usually peaks and then immediately drops to an operating level. A few months ago this configuration had a minimum delivered power of about 20 watts. Now that we have practiced and studied we can operate the plasma at less than one watt.
From here there is only so much fine tuning we can do. Our measuring capabilities are severely hindered by the parasitics involved with traditional VI measurements with a probe. We are limited to measuring reflected power, utilizing a directional coupler or a Z-scan. Almost any direct capacitive intrusion will prevent a high Q therefore also prevent the plasma from lighting.

The directional couplers offer us a chance to place a planar inductor close to the load and measure the current with little intrusion. The problem here is that it takes a considerable amount more power for the directional coupler to produce a sufficient measurement. Along the same line a Z-scan offers better results but is not exactly accurate as it requires more power than the plasma by itself. Our best guess based on our experiments is less than 1.0 Amps and 0.5kv-1.5kv, depending on the load’s resonant frequency and corresponding impedance.
Chapter II – IDEAL CIRCUIT WITH FEEDBACK

We have decided that since the load is extremely susceptible to outside stimuli that our approach should be something that reacts faster than or as fast as the environment. Our solution is to monitor changes in the resonant frequency. By monitoring changes in the frequency we have an indication of how the load’s impedance changes. Based on this indicator we can change the frequency of the input signal and maintain a relatively constant output intensity by always staying at the changing resonant frequency.

To accomplish dynamic control we need to have a little more information about what is happening within the circuit as well as control over the input signal to adequately control the output. Our solution involves a few circuit modifications. First, notice that the capacitor is no longer variable and we have to settle on a capacitor value using the equations from above.

The feedback loop starts with a small VI pickoff before the load but after amplification. This allows us a few opportunities. We can be less intrusive on the load by being allowed to design and build our own directional coupler. We have the advantage of not needing to know the exact values at the load, but rather only the changes. More specifically, we utilize Analog Device’s 8302 chip. This chip can tell us the phase difference between two inputted signals, in this case the voltage and current.
Since the phases should be equal when the load is resonating this should be enough information.

The 8302 then sends its output to the Programmable System on a Chip (PSOC), which accepts the analog output and makes a corresponding digital signal. Ideally, the signal is captured and data is gathered about the changes in the phase of the output. The signal is then run through our program and then converted back to analog. This analog signal is the control voltage for our VCO. It is our sole means to control the input frequency. Then, the cycle starts again but with a programmed offset. The PSOC registers the new phase shift and compares it to previous value. This way the PSOC knows which way to adjust the frequency. Once more the PSOC will register and compare the values while the programmed offset jumps to the “other side” of the resonant frequency and again compares. This cycle continues, all the while, gathering data within its registers.

Further reduction in size comes in choosing our new amplifier; Darlington Pair and has 18dB of constant gain. Power control is offered in the form of the pre-amp. Our preamp design limits the gain from 0 to 1. In this configuration we can control our amplifier’s constant gain without putting unneeded stress on the device. The preamp circuit consists of two op-amps in follower configuration connected by a serially controlled potentiometer. Ideally, we should be able to control the potentiometer with the PSOC. This will allow us to deliver only the necessary power to the load without harsh Vdd changes to our amplifier.
Chapter III – PRINTED CIRCUIT BOARD MAKING

Unlike in our labs so far, we operate at levels above 30MHz. We can no longer use our proto boards and consideration has to be given to every connection as most devices cannot take a 30MHz input. This led us to design and fabricate our own Printed Circuit Boards (PCB). Even then it is extremely difficult as any conductor around may contribute a decent amount of capacitance to the circuit to affect our measurements.

For every PCB that was fabricated, excess copper was always etched away as the design’s spacing and style contributed to the circuit’s capacitance. One example that we realized in our experiments is that RF sources conducts better on copper strips than on copper wire. We also had to leave as much ground plane on the opposing side as possible, which allowed us the benefit of less cross-talk and interference from adjacent runs.

Another aspect where we utilized our PCB’s was the design of a planar inductor. For a planar inductor, an RF source is conducted through a copper strip in parallel with a squiggly copper strip. Previous experiments performed indicates that, $V_{out} = K \times V_{in}$.

For the design of the planar inductor, the width of copper strips, length, and number of squiggly edges all plays an important role in determining the value of $K$. This is a huge concern when dealing with our specific load. We had tried about a dozen types of planar inductors to “pickoff” the current’s phase, all made by etching away copper on a circuit board.

Unlike before, when we could simply crank up the amplifier, we are limited to our on board amplifier’s design so the parasitic effects of the planar inductor must be minimal. So, the use of an additional inductor is simply too parasitic.
Chapter IV – PROGRAMMING PSoC IN C

In our project, we use the PSoC microcontroller to read the output from AD8302 chip. This signal will be our feedback to the voltage controlled oscillator to control the magnitude and phase of our load, refer Figure 2.

For the programming of the PSoC microcontroller, the precision and optimization of the results is our top priority. As we are operating the circuit at MHz range, a slight fluctuation will produce a large error in our measurements. For every step of our design with the microcontroller, we remind ourselves of precision. One example would be the selection of the A to D converter’s bit value for accuracy.

The PSoC has 4 registers that are dedicated to A to D and D to A conversion. Since we will need to utilize both for our circuit, we are limited to 256 bits over a 5 volt range. To further complicate the issue, we can only expect to use our VCO in a small range of the full five volts. Basically, we have limited resolution but it should be enough. By our calculations we can expect about a 600Hz jump in input frequency for every mV change from the PSoC.
Chapter V – ENGINEERING THE NEW CIRCUIT

To date we have advanced with the outlined goals in mind. Getting everything to work together has proved difficult. We have been taking it one step at a time and have hit several roadblocks along the way.

First, the VCO I researched from Texas Instruments did not work the way I thought it would. The 13.56MHz range was not in the linear range we were after. Then, I replaced this VCO with a simple VCO from Emhiser. This VCO operated wonderfully but could only take 30µA and quickly failed. Now we have another chip from Texas Instruments that works well, but again is not fully linear. This complicates the PSoC issue as we have to make a look-up table within our program. Basically, the logic of the program must take the time to look up what voltage to output instead of increasing it by a certain amount.

Next, the preamp was not cooperating with my potentiometer. I had to replace the serial potentiometer with a manually adjustable one to get results. And even then we did not achieve the full range of 0 to 1 and we only achieved about half of this gain. It will work for our purposes but I do see room for improvement.

Then, we had to find inexpensive parts for the load that were readily available. It turns out that copper has gone up in price 200% from last year so making our own inductors is not without its drawbacks. As far as the capacitors go we have found that chip capacitors in the low pico-Farad (pF) range with a 0.5kV tolerance do not have the tolerance necessary. A minimum of 1kV is necessary to achieve and maintain ignition. Unfortunately, doubling the tolerance also doubles the price. Furthermore, capacitors
with low ESR are also mandatory as resistance is inversely proportional to our desired Q factor.

Finally, the PSoC; this is the brains of the feedback loop and it needs to be operating at its full potential for the system to work. It currently takes in the analog signal, converts and stores data, and then outputs a corresponding signal. What we need to add is a look up table for our specific VCO, make an output for the potentiometer, and fine tune our resolution to maximize our feedback loop. Additionally, the VI pickoffs are still of great concern. How do we get this information with minimal intrusion on the load? This and other factors of the feedback loop will be the focus of our second semester.

Below are pictures of our plasma:

Figure 3: Plasma, example 1

Figure 4: Plasma, example 2
Chapter VI – FUTURE WORK

Our progress will be greatly determined by how well we can integrate the PSoC into our circuit. Since it controls the gain at the preamp, limits the D to A and A to D resolution, and controls our dynamic frequency it is the cornerstone of our design.

We will begin the next semester by integrating our amplifier into one cohesive system. Then, we will fine tune our VCO, as it can be slightly adjusted with external resistors and capacitors. Once we have a better understanding of our VCO we can then change the PSoC code to include definite ranges of operation.

The final step will be to dynamically control the gain of the amplifier circuit. This will take considerable amount of time since we do not necessarily know how low the plasma will require before it extinguishes. We will have to write additional PSoC code to gather data on our behalf. Once we have this understanding, we can design a control loop that operates differently at ignition and operation.

Ideally, we should also look into a micropump to pump ambient air in lieu of argon. This part would take up our entire budget and may not even meet our needs. However, all things considered, this is a topic for another time.
- Appendix A

List of Abbreviations:

RF – Radio Frequency
LC – Inductor/Capacitor
Q – Quality Factor
VCO – Voltage Controlled Oscillator
PSoC – Programmable System on a Chip
PCB – Printed Circuit Board
Vdd – DC Voltage applied to a circuit
Vsig – Voltage from signal generator
D to A – digital to analog
A to D – analog to digital
ESR – Equivalent Series Resistance

Units of Measure:

MHz – Mega-Hertz
X_l - Inductive Reactance
X_c - Capacitive Reactance
VI – Voltage/Current
mH – mili-Henry
mV – mili-Volt
µA – micro-Ampere
pF – pico-Farad
kV – kilo-Volt
- Appendix B

Budget Summary:

$50 x 2 members =$100 total budget

We have 100% of our budget left thanks to the generous donations from:

Texas Instruments
AVX
Analog Devices
Digikey
Invotech
Linear
Sirenza
Emhiser
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