AN RF VOLTAGE DIVIDER FOR AN INDUCTIVELY POWERED PLASMA SOURCE

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ELECTRONICS RESEARCH LABORATORY

College of Engineering
University of California, Berkeley
94720

An RF Voltage Divider for an Inductively Powered Plasma Source

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Abstract

The goal of the project was to develop an accurate radio frequency (RF) voltage divider to measure the voltage drop across an inductive coil. The primary obstacle to overcome was the large radio frequency interference, specifically at 13.56 MHz, generated by the matching network.

1 Introduction

The apparatus is an RF power source used to drive an argon plasma. A three turn coil is used to inductively couple the RF power source across a quartz dielectric window to drive the plasma; see Figure 1. A voltage V_{actual} is applied over the coil, and a matching network composed of capacitors C_1, C_2, and C_3 is tuned to 50Ω of impedence in order to provide optimum power flow from the power supply to the inductive coil to the plasma. The voltage divider is designed to measure the voltage drop across the coil. However, the use of a high power RF inductive coupling introduces a large amount of RF interference which makes the measurements from the unshielded voltage divider used previously and shown in Figure 2 unreliable and creates a need for shielding.

The voltage measurement is very important because together with a measurement of the root-mean-square current I_{rms} it yields the inductance of the coil:

$$L_{coil} = \frac{V_{rms}}{\omega * I_{rms}}$$

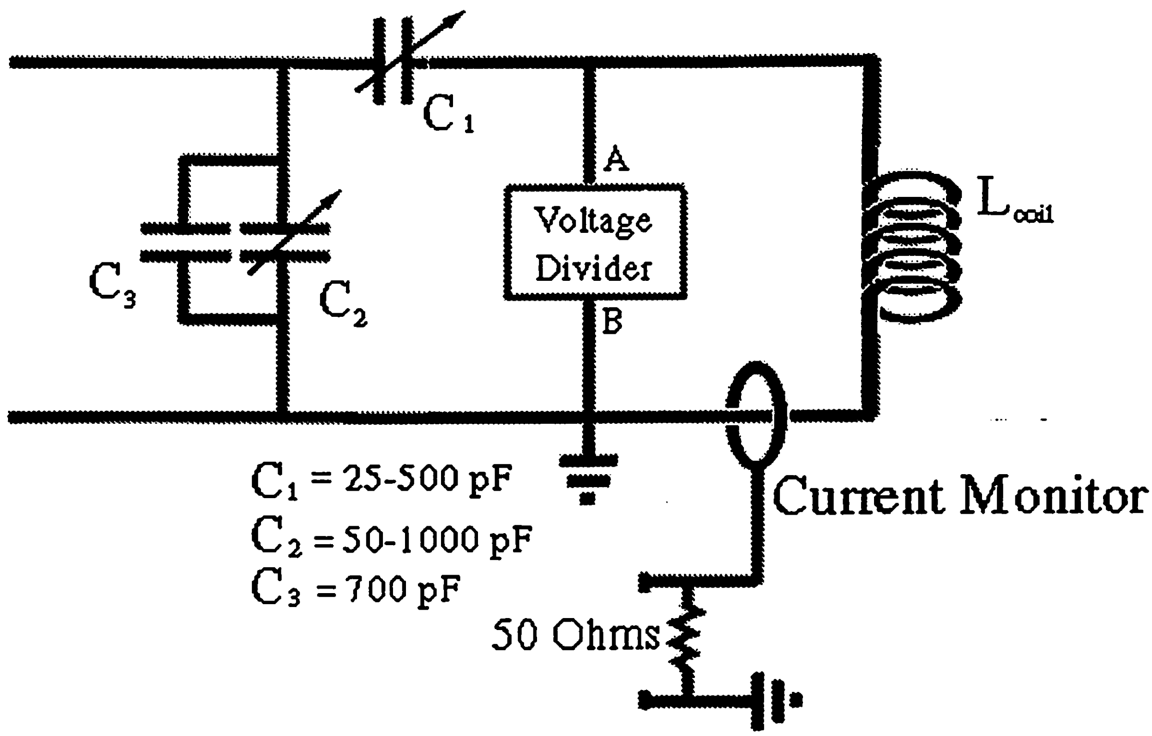

Figure 1: The matching network circuit. Points A and B correspond to A and B in Figures 2 and 3.

where

$$\omega = 2\pi * 13.56\text{MHz}.$$

The change in coil inductance in the presence of plasma, in turn, is a good indicator of the amount of current flowing through the plasma. Thus, a reliable and accurate voltage measurement is vital.

The first attempt was a one-stage voltage divider without shielding, Figure 2. The inductance was measured to be roughly 440 nH. Unfortunately, this measurement is suspect because of the lack of shielding.

2 Circuit and Design

The circuit of the shielded, two-stage voltage divider is shown in Figure 3. The circuit consists of two dividers rather than one in an attempt to reduce the measurement's sensitivity to stray impedence. The original divider's second capacitor, C_2 in Figure 2, has an impedence of $X_2 = 1/\omega * C_2 \simeq 4\Omega$. At 13.56 MHz, stray inductance in the wire can contribute a substantial enough fraction of 4Ω to create an error in the voltage measurement.

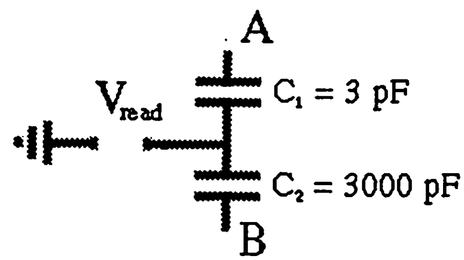

Figure 2: Unshielded, one-stage divider.

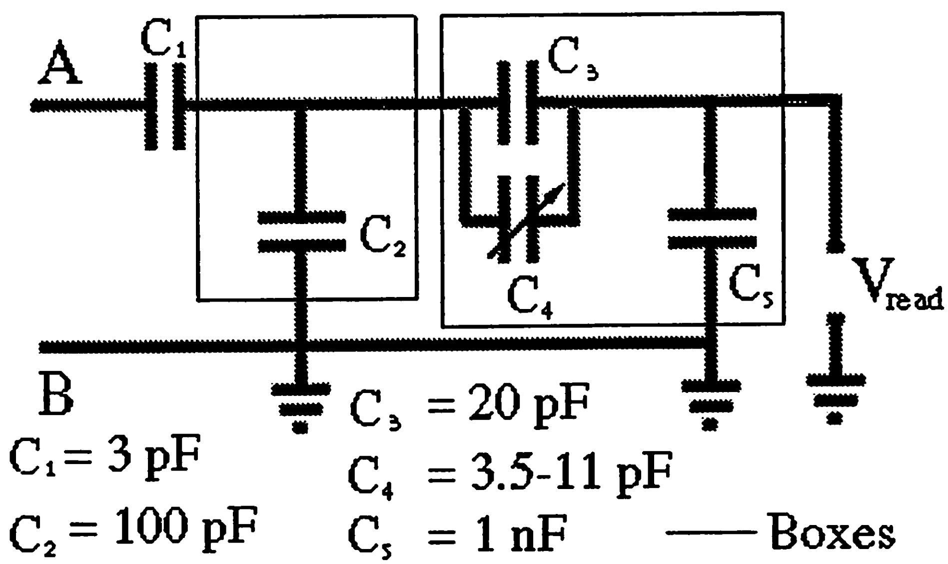

Figure 3: Shielded, two-stage voltage divider.

Thus, a two-stage divider was designed; the first stage of this divider has a 100 pF capacitor, C_2 in Figure 3, with $X_2 \simeq 120\Omega$ of impedence, making the divider less sensitive. The second stage of the divider is added to increase the division. The factor of division is given by

$$V_{actual} = D_1 * D_2 * V_{read}$$

where

$$\frac{1}{D_1} = \frac{C_1}{C_1 + C_2'}$$
$$\frac{1}{D_2} = \frac{C_3 + C_4}{C_3 + C_4 + C_5}$$

and

$$C_2' = C_2 + \frac{(C_3 + C_4)\, C_5}{C_3 + C_4 + C_5}$$

The expected voltage on the coil is on the order of one kilovolt. As the output from the voltage divider may later be wired to the inputs of a data acquisition card, which cannot tolerate more than a few volts of input, the values of the capacitances were chosen to give a division of roughly 500:1 or -54.0 dB. C_3 was added in parallel to C_4 in order to allow for a small amount of tuning of the divider. Tuning allows the user to achieve a specific voltage division or, if desired, to compensate for additional capacitance on the readout wire, if desired.

The shielding was accomplished via two small grounded Pamona boxes and BNC-type connectors. The Pamona boxes are simply grounded, conducting boxes used to eliminate RF interference inside the box. The boxes were grounded via a connection to the matching network ground. The BNC connectors are similarly shielded and grounded.

The first, 3 pF capacitor C_1 in Figure 3 was kept just outside of the first box because it carries high voltage on its anode. Unlike the the previous, unshielded divider, a long, high inductance lead was required to connect this capacitor to the coil. However, this inductance is tolerable becuase the inductive impedence is in series with the much higher impedence ($\simeq 4000\Omega$) of the 3 pF capacitor.

The two stages were shielded in separate boxes as an extra precaution. Otherwise, the relatively high voltage on the first stage, which is on the order of 30V, may have the effect of a slight capacitive coupling on the second stage, which has a voltage on the order of one volt.

3 Calibration

The voltage divider was initially tuned to roughly 500:1, or −54.0 dB. The tuning was accomplished with the voltage divider not yet affixed within the matching network. The output from a signal generator set to 13.56 MHz was amplified and measured and the signal was then fed through the voltage divider and measured again.

When the divider was soldered into the matching network, a network analyzer was used to determine the actual division, which at 13.56 MHz is affected by the capacitance of the wires and matching elements. A voltage was applied over the inductive coil, and the response of the divider was measured.

The analyzer determined the division to be −55.8 dB or 617:1. Unfortunately, the error in the measurement is rather large - the reading from the analyzer fluctuated from −55.5 dB to −56.2 dB, though the large majority of the values fell between −55.7 dB and −56.0 dB. The best estimate of the division is the average value, -55.8 dB. The error, based on the deviation of the values, is .2 dB or $\simeq$3% .

The division of the analyzer was almost independent of frequency in the neighborhood of 13.56 MHz, especially at lower frequencies. Above 30 MHz, the division varied greatly from its value at 13.56 MHz.

4 Data and Error Analysis

The matching network, along with the voltage divider, was inserted into the chamber and an argon plasma was initiated. The plasma length was approximately 7 cm.Voltage measurements with the new voltage divider in place are shown in Table 1. The root-mean-square voltage is given by

$$V_{rms} = \frac{V_{read} * D_1 * D_2}{2^{\frac{3}{2}}}$$

where V_{read} is the measured peak-to-peak voltage.

A Pearson coil model 411 was used to monitor the current (see Figure 1). It produces a voltage output, from which the root-mean-square current is given by

$$I_{rms} = \frac{V_{monitor} * Cal}{2^{\frac{3}{2}} * K}$$

Volts	10 mTorr	30 mTorr	50 mTorr
50 W	3.83e2	3.46e2	3.12e2
100 W	4.59e2	4.14e2	3.94e2
200 W	5.75e2	5.27e2	5.09e2
300 W	6.73e2	6.25e2	6.12e2
400 W	7.68e2	7.14e2	7.14e2
500 W	8.47e2	8.10e2	8.12e2

Table 1: Root-mean-square voltage as a function of power and pressure.

Amps	10 mTorr	30 mTorr	50 mTorr
50 W	9.28	8.40	7.61
100 W	11.1	10.2	9.67
200 W	14.1	13.0	12.7
300 W	16.6	15.5	15.3
400 W	20.1	18.9	18.9
500 W	22.14	21.3	21.4

Table 2: Root-mean-square current as a function of power and pressure.

where $V_{monitor}$ is the peak to peak voltage output and

$$Cal = 10 * 2 = 20\frac{\text{A}}{\text{V}}$$

and

$$K = 1.616$$

The calibration coefficient is the product of the current monitor specification and a factor of two due to a 50Ω terminator that was used during measurements. K represents the high frequency response and is designed to compensate for a shift in calibration at high frequencies; the value of K was obtained from a calibration chart produced by Pearson. The values of the RMS current are shown in Table 2.

The error in the voltage measurement is

$$(\Delta V_{rms})^2 = (\Delta D)^2(\frac{\partial V_{rms}}{\partial D})^2 + (\Delta V_{read})^2(\frac{\partial V_{rms}}{\partial V_{read}})^2 + (\Delta P)^2(\frac{\partial V_{rms}}{\partial P})^2$$

and the error in the current measurement is

$$(\Delta I_{rms})^2 = (\Delta V_{monitor})^2(\frac{\partial I_{rms}}{\partial V_{monitor}})^2 + (\Delta Cal)^2(\frac{\partial I_{rms}}{\partial Cal})^2 + (\Delta P)^2(\frac{\partial I_{rms}}{\partial P})^2$$

where we estimate

$$\Delta V_{monitor} = \Delta V_{read} \simeq 1 * 10^{-1}\mathrm{V}$$

based on fluctuations in the readings.

$$\Delta Cal \simeq 1 * 10^{-2} * Cal$$

$$\Delta D = \Delta(D_1 * D_2) = 3 * 10^{-2} * D_1 * D_2$$

The values of power were measured with a Bird Wattmeter 4522; the error in the measurement is 5W. Unfortunately, the dependence of the voltage and current on the power is not known, so it is difficult to arrive at an accurate measurement of error. However, these dependencies can be estimated by adjusting the power values by ±5 W, and recording the change. The dependencies, accurate only to within an order of magnitude, are

$$\frac{\partial V_{read}}{\partial P} \simeq 5 * 10^{-2}\frac{\mathrm{V}}{\mathrm{W}}$$

and

$$\frac{\partial V_{monitor}}{\partial P} \simeq 4 * 10^{-2}\frac{\mathrm{V}}{\mathrm{W}}$$

These values are roughly correct over a range of 10 mTorr to 50 mTorr and 50 W to 500W. These dependencies in turn gives us an approximation of the dependencies of I_{rms} and V_{rms} on the power. Therefore,

$$(\frac{\partial V_{rms}}{\partial P})^2 = (\frac{\partial V_{rms}}{\partial V_{read}}\frac{\partial V_{read}}{\partial P})^2 = (\frac{\partial V_{rms}}{\partial V_{read}} * 5 * 10^{-2}\frac{\mathrm{V}}{\mathrm{W}})^2$$

and

$$(\frac{\partial I_{rms}}{\partial P})^2 = (\frac{\partial I_{rms}}{\partial V_{monitor}}\frac{\partial V_{monitor}}{\partial P})^2 = (\frac{\partial I_{rms}}{\partial V_{monitor}} * 4 * 10^{-2}\frac{\mathrm{V}}{\mathrm{W}})^2$$

Finally, the uncertainties are

nHenrys	10 mTorr	30 mTorr	50 mTorr	Average
50 W	484	484	481	483
100 W	485	476	478	480
200 W	479	476	470	475
300 W	476	473	470	473
400 W	449	443	443	445
500 W	449	446	445	447
Average	470	466	465	467

Table 3: Coil inductance (nH) as a function of input power and pressure.

$$(\Delta V_{rms})^2 = \left(\frac{D_1 * D_2}{2^{\frac{3}{2}}}\right)^2 \left[9 * 10^{-4} V_{read}^2 + 7.3 * 10^{-2}\right]$$

and

$$(\Delta I_{rms})^2 = \left(\frac{Cal}{K * 2^{\frac{3}{2}}}\right)^2 \left[1 * 10^{-4} V_{monitor}^2 + 5 * 10^{-2}\right]$$

The values of I_{rms} and V_{rms} determine the coil inductance, shown in Table 3.

The error in the inductance is

$$(\Delta L_{coil})^2 = (\Delta V_{rms})^2 (\frac{\partial L_{coil}}{\partial V_{rms}})^2 + (\Delta I_{rms})^2 (\frac{\partial L_{coil}}{\partial I_{rms}})^2$$

$$(\Delta L_{coil})^2 = \frac{1}{\omega^2 I_{rms}^2} \left[(\Delta V_{rms})^2 + (\Delta I_{rms})^2 V_{rms}^2 I_{rms}^{-2}\right]$$

Using the average values for current and voltage,

$$\Delta I_{rms} = 9.8 * 10^{-1} \text{A}$$

and

$$\Delta V_{rms} = 2.4 * 10^{1} \text{V}$$

and therefore

$$\Delta L_{coil} = 4.2 * 10^{-8} \text{H} = 42 \text{nH}$$

5 Conclusions

The similarity between the inductance calculated from the voltage measurements of the previous unshielded and the shielded divider lend credibility to those measurements. Though it appears that the RF interference did not distort the values of the voltage significantly, the shielded divider is a more reliable source of data. The error in the measurement of the inductance is significant; a large part of that error is due to the uncertainty in the power measurement.