Hardware Report #4
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EEE202-03

Hardware Report 4

Introduction

In this lab assignment, we are expected to design two passive circuits, in which we can maximize the power to a load resistor of 200Ω from a voltage source of source impedance 50Ω at any chosen frequency between 10MHz – 20MHz. The software section of the report investigates how we can achieve the goal, then in the hardware section, we implement the circuits physically and discuss whether the designed circuits were successful enough. Hence the designs are finalized within simulation on LTSpice and then the circuits are physically built.

Software Report (Design and Simulation)

The circuit that we will be working on can be found below.

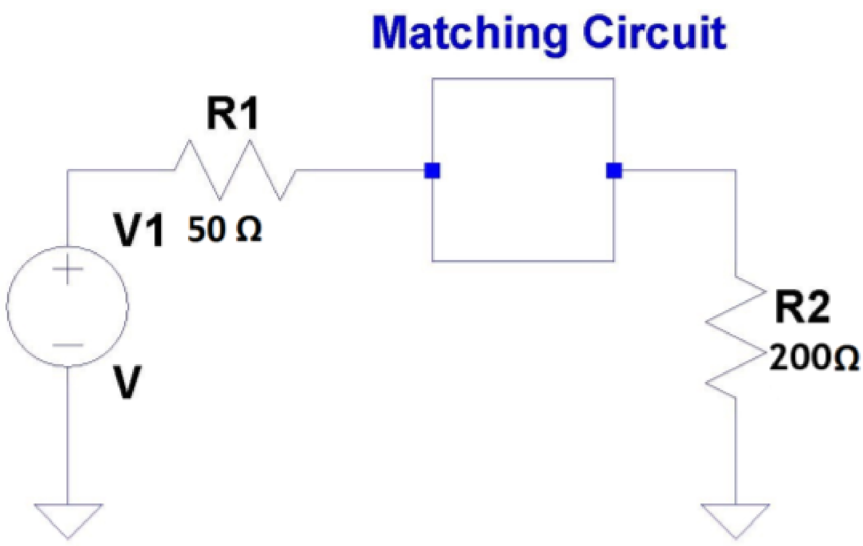

Figure 1: Matching Circuit

As seen from the schematic, this is called a matching circuit. The objective of this circuit is to match the impedances of the source and the load in order to obtain maximum power transfer. Although there are many separate ways to match impedances, I will only be using two of them as requested. Important note to mention, I will be setting the frequency as 10MHz in both occasions in order to make the results easily comparable

Before picking our methods, I will be describing how of maximize the power transfer. In a circuit with just a real voltage source and a load resistor, we can calculate the transferred power by the equations down below,

$$I_L = \frac{V}{R_S + R_L}$$

$$P_L = \frac{R_L\,|I_L|^2}{2} = \frac{R_L\,|V|^2}{2(R_S + R_L)^2}$$

where in the equations, I_L represents the current on R_L, the load resistor. R_S represents the source resistor and V represents the voltage of the source and finally P_L represents the power transferred to the load.

As we have been thought in the Analog Electronics (EEE211), in order to achieve maximum power transfer, we should equalize the source and load impedances. If we equate them, the equation turns into the one below.

$$R_L = R_S$$

$$P_L = \frac{|V|^2}{8 * R_S} = \frac{|V|^2}{8 * R_L}$$

In order to equalize the impedances, we will be using the matching circuits. Moving further, we will be discussing only two of the many matching circuits.

Through this lab assignment, we will be using the T-Section and Π-Section matching circuits. As the circuits to be used are chosen, the next step is to calculate the elements that we will be using and then simulate the circuits on LTSpice.

T-Section Matching Circuit

The schematic of a general T-Section matching circuit is given below.

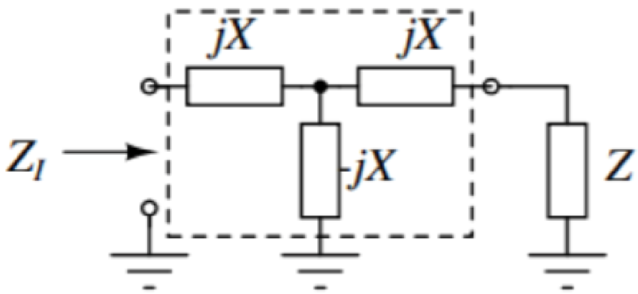

Figure 2 – T-Section Impedance Matching Circuit

In this schematic, Z is the load impedance and Z_L is the impedance that the source detects. Z, in our lab assignment is 200Ω. Since our purpose is to equalize the source and load impedances, we need to make Z_L 50Ω to maximize the transfer. Now, we will be calculating X which will be determining the type and value of the circuit elements. When that is done, I will be simulating the circuit on LTSpice.

Looking on the circuit, we can write Z_L in terms of Z and X. As we know the values of Z_L and Z, we can find X.

$$Z_L = jX + \frac{1}{\frac{1}{-jX} + \frac{1}{jX + Z}} = \frac{X^2}{Z}$$

$$X = \pm\sqrt{Z_L . Z}$$

Using the equation above, we can find the value of X like,

$$X = \pm\sqrt{50 * 200} \approx \pm 100\Omega$$

The next thing to decide is the sign of the X that we are going to use. If we choose the positive value of X, then the jX elements are going to be inductors and -jX elements will be capacitors. However, intuitively we want to use more capacitors that inductors as winding is inductors is not easy. Thus, we will be using the negative value of X in order to get to the circuit with two capacitors and one inductor. Hence, we choose X as -100Ω. The next thing is to calculate the capacitance and inductance values. We equate the -jX with the capacitor's frequency domain representation.

$$-jX = \frac{-j}{2\pi f\ C}$$

$$C = \frac{1}{2\pi * f * X} = \frac{1}{2\pi * 10^7 * 10^2}$$

$$C = 159.2\ pF \approx 159\ pF$$

Then, the inductance is calculated.

$$jX = j\ 2\pi f\ L$$

$$L = \frac{X}{2\pi * f} = \frac{100}{2\pi * 10^7}$$

$$L \approx 1.59\ \mu H$$

As the calculations are over, we can now create and simulate the circuit we have chosen on LTSpice and see if the circuit maximizes the power transfer or not.

The circuit that is implemented on LTSpice is below.

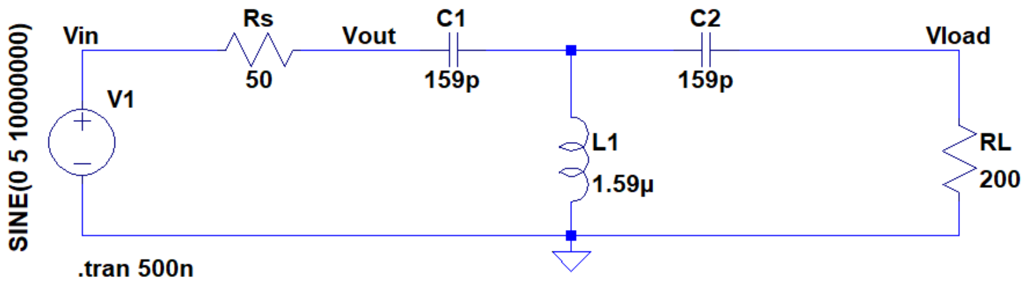

Figure 3 – The Circuit with T-Section Impedance Matching

As you can see, the capacitance and inductance values that we have calculated are embedded into the circuit. In order to see the power values on the graph, we observed the values V(vout,vin)*I(rs) and V(vload)*I(rl) which correspond to the source and load power values. The graph that we have obtained can be observed below.

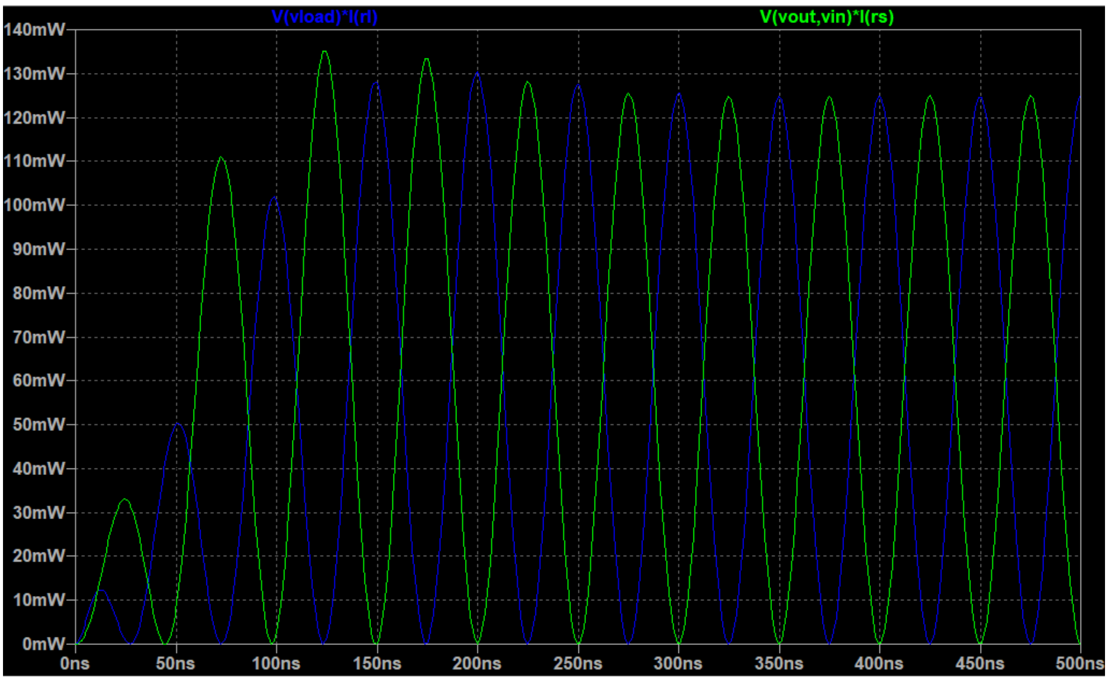

Figure 4 – Graph of the T-Section Circuit

Here, green line is the power on the source resistor and blue line corresponds to the power on the load resistor. As we can see the waveforms match with each other with some amount of phase difference that is originated by the capacitors and inductors. In order to be sure that the power is maximized, we can use the power transfer formula that we have defined in the introduction. Thus, the average transferred power is,

$$P_L = \frac{|V|^2}{8\,R_S} = \frac{25}{8 * 50} = 62.5mW$$

In order to compare the theoretical value with the simulation data, we find the average transferred power in LTSpice using the interval between 120ns and 500ns. As the graph becomes stable after 120ns. The average value can be seen in the screenshot below.

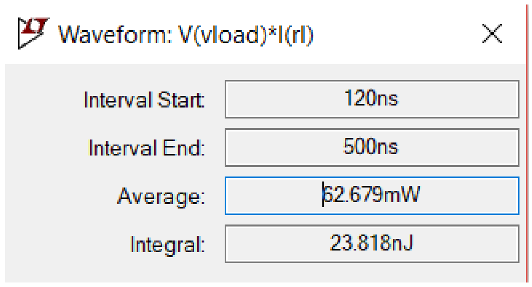

Figure 5 – The Average Power on the Load (T-Section)

$$P_{avg} = 62.679mW \approx 62.7mW$$

The value that we have obtained from the calculation and simulation are very close, hence we can stay that this method that we have used holds true and we can use T-Section impedance matching to achieve our goal.

Π-Section Matching Circuit

The second method that we have chosen to maximize the transferred power is the Π-Section impedance matching. Π-Section is also an impedance inverter like the T-Section. We will follow the same path that we have covered through the T-Section, using the value of X and then finding the capacitance and inductance values. The general form of Π-section is below.

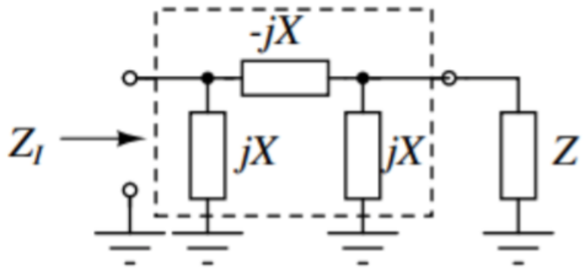

Figure 6 – The General Schematic of Π-Section Impedance Matching

The reason that we have chosen to use the Π-section matching is because, it has a relation with the T-Section. They get the same X values when they are inverting the same impedances both on the source and load. Therefore, we needn't calculate anything. Again we can choose the positive or negative X as well. Again, we will choose the same negative X value to use capacitors rather than inductors. Hence, the X, C and L values that are chosen are below.

$$X \approx -100\Omega$$

$$C \approx 159\, pF$$

$$L \approx 1.59\, \mu H$$

As we have all the needed values, now we can create and simulate the circuit. The implemented circuit is shown below.

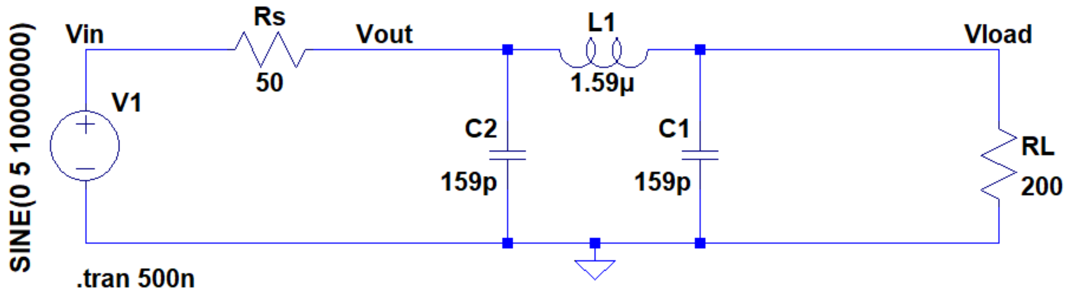

Figure 7 – The Circuit with Π-Section Impedance Matching

As we can see, we used the same inductance and capacitance values. Again, we followed the same syntax that we did previously to view the power graphs of source and load. The graph can be seen below.

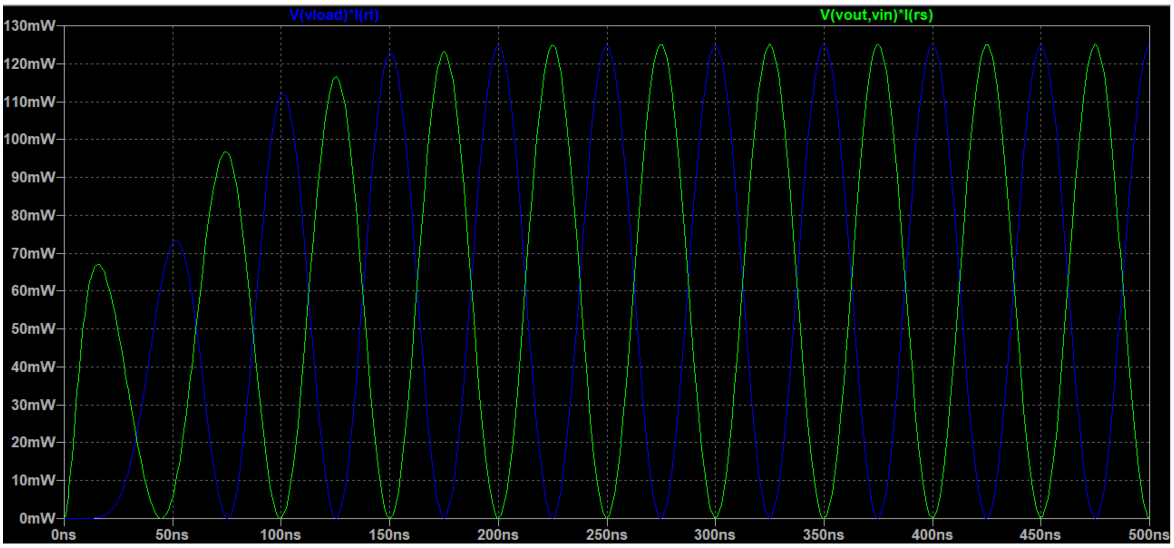

Figure 8 – Graph of the Π-Section Circuit

As it can be observed, Figure 8 shows great correspondence with Figure 4. The power on the load (blue line) is maximized with the given source power with only a phase difference. Both of the values go up and down

As it can be seen from the graph the power transferred to the load resistor, green graph, is maximized and shows similar behavior with the power of the voltage source with internal resistance, blue graph. Both graph goes up and down to the same peak values but they have a phase difference just like they are in the graph for T-section circuit. To prove that the power transfer is maximized, we will again use the maximum power transfer formula. The maximum average power transferred from this voltage source is,

$$P_L = 62.5mW$$

We have already found the maximum power transfer in the T-section part. To compare, we again take the average of the graph of the power on the load resistor.

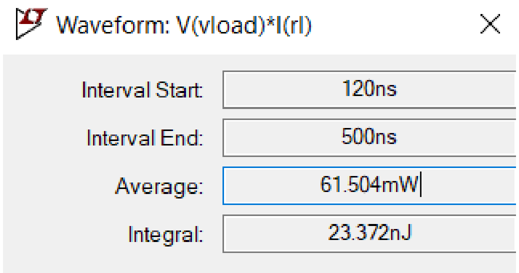

Figure 9 – The Average Power on the Load (Π-Section)

$$P_{avg} = 61.504mW \approx 61.5mW$$

As the values are very close, we can easily say that we successfully implemented Π-Section impedance matching to maximize the power transfer.

Hardware Section (Implementation and Analysis)

T-Section Matching Circuit

As discussed in the software section, we have decided to implement the T-Section impedance inverter as our choice of circuitry. In order to implement the circuit, I have used in total seven components, namely capacitors, inductor and resistances, and built the circuits by soldering them together. The built circuit can be seen below.

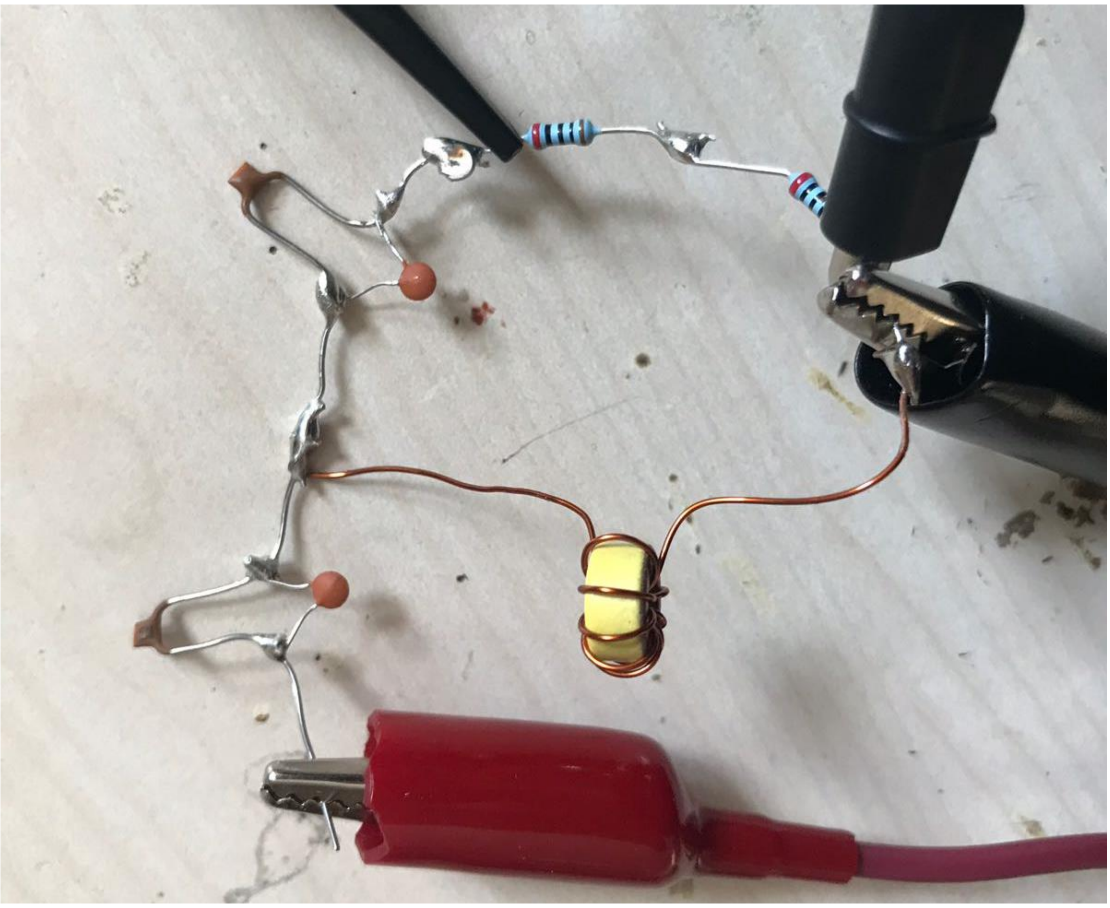

Figure 10 – T-Section Impedance Inverter

If we examine the circuit and correlate between the theoretical circuit that we have designed, we see the theoretical circuit uses 159pF of capacitance in each of its arms. In order to obtain a nearly similar result, I have used the standard values of 150pF and 10pF and soldered them in parallel in order to obtain 160pF which is nearly equal to 159pF.

Then in order to find a similar inductance value, I have done calculations in order to find the right number of windings. I have used a T38-8/90 core which has $20nH/n^2$ as its A_L value. Using the equations below, I have calculated the winding.

$$L = 1.59 * 10^{-6} = 20 * 10^{-9} * n_p^2$$

$$n_p^2 = 79.5$$

$$n_p = 8.916 \approx 9\ turns$$

$$L = 20 * 81 = 1620nH \approx 1.59\mu H$$

We could not exactly obtain the desired value; however, we have obtained a value that will be close to the theoretical values. These values will definitely create errors which will be discussed in the further parts.

Also, in order to see the output of 200Ω, I have serially connected two 100Ω resistors. Since the circuit is complete, we can connect it to the elements and analyze the outputs.

As mentioned in the previous sections, I have designed this circuit with the initial input of 10MHz on 5Vp-p in the range of the assignment description. Hence, the signal generator used is given below.

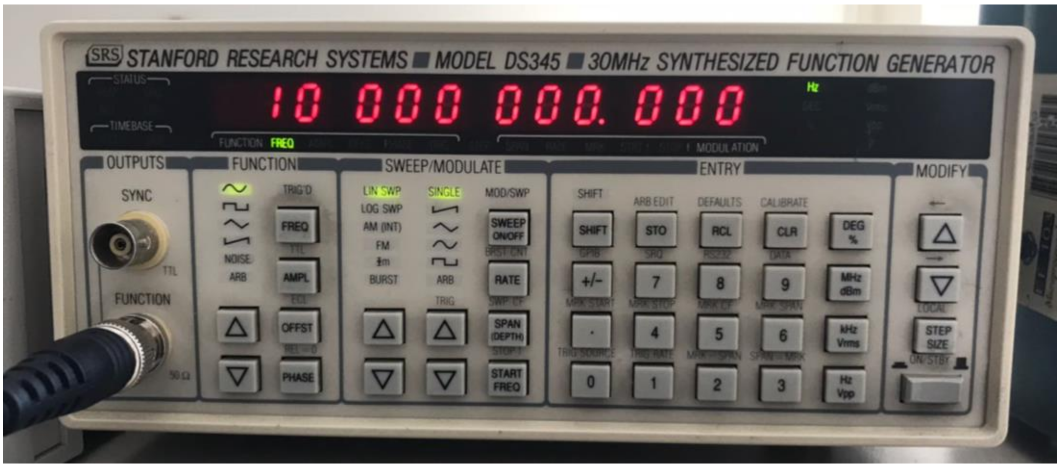

Figure 11 – The Signal Generator

Then in order to compare the circuits to the given power value, I have prepared a comparison circuit, which has nothing but 50Ω of resistor, built with two 100Ω parallelly connected. The circuit is implemented on breadboard, which is below.

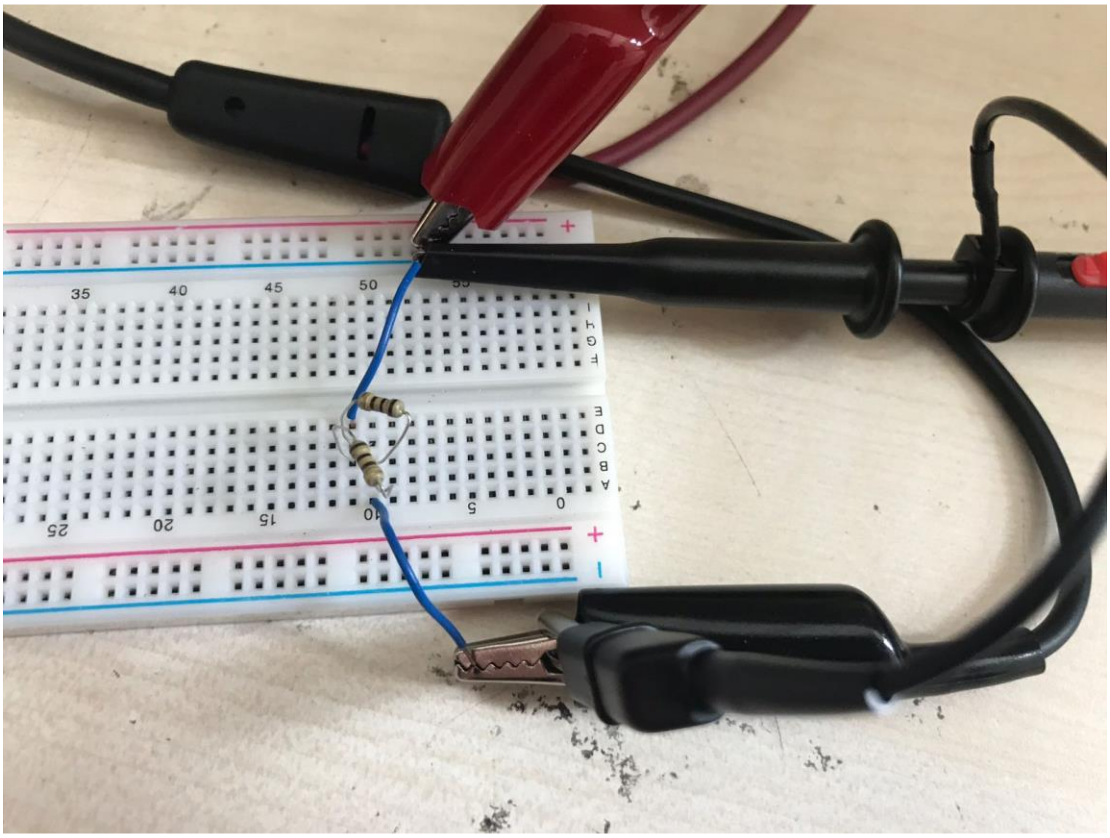

Figure 12 – The Comparison Circuit

Then when I put the voltage that is configured, the oscilloscope screen becomes;

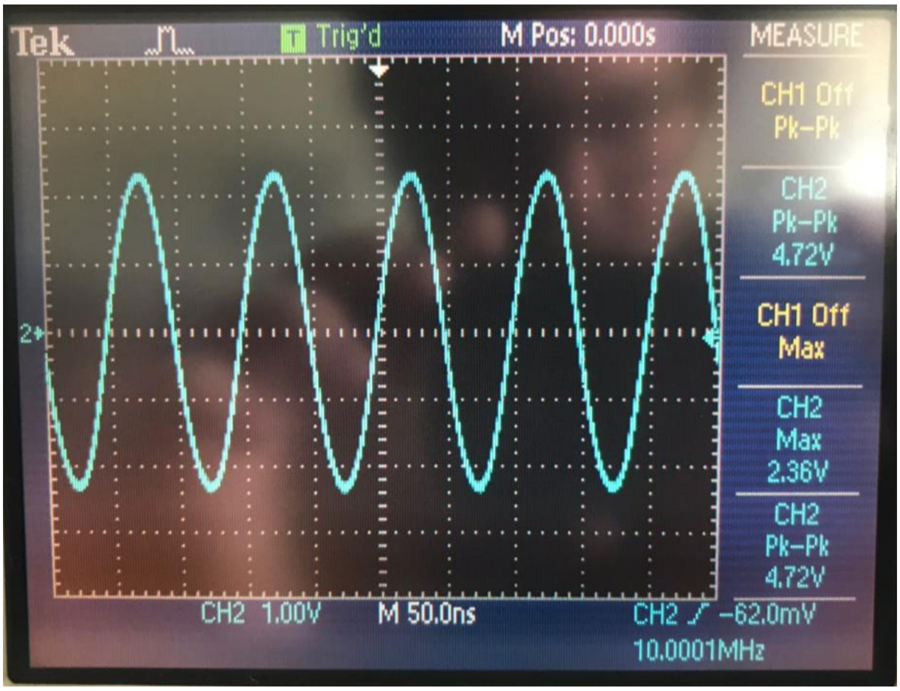

Figure 13 – Comparison Waveform

This shows that the expected voltage from the impedance matching circuit is nearly two times the Vp-p which is 2*4.72 = 9.44V. Of course, we know that the results will show up lower as the inductance values are lower than what it should be. Also, as the soldering process increases the overall resistance in the circuit we assume that the voltage drop can be even in the range of 2V.

As we now know the value that we should be comparing, we look the voltage through the oscilloscope and observe voltage relations. The oscilloscope view of the T-Section circuit is given below.

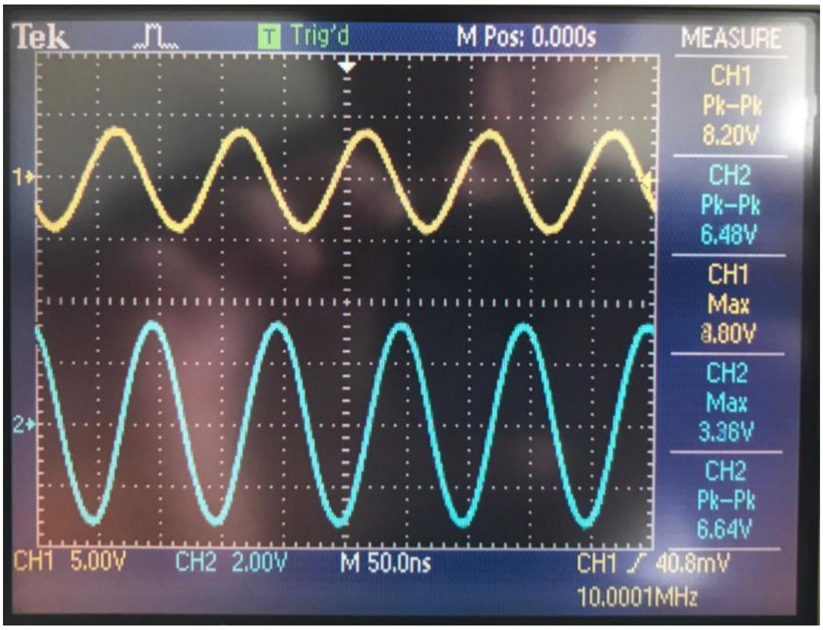

Figure 13 – The T-Section Circuit Waveforms

Here blue line represents the input and yellow line represents the output. As we can see the output becomes 8.2Vp-p which is in the range 9.4±2V. This is not a very close value to what is expected however, we can say that it is logical. The next thing to do is to also do the same analysis for the Π-Section impedance inverter and discuss the results.

Π-Section Matching Circuit

The circuit is given below, as the values and components are the same, except the fact that the parallelly connected inductor is now in series and serially connected capacitors are now in parallel.

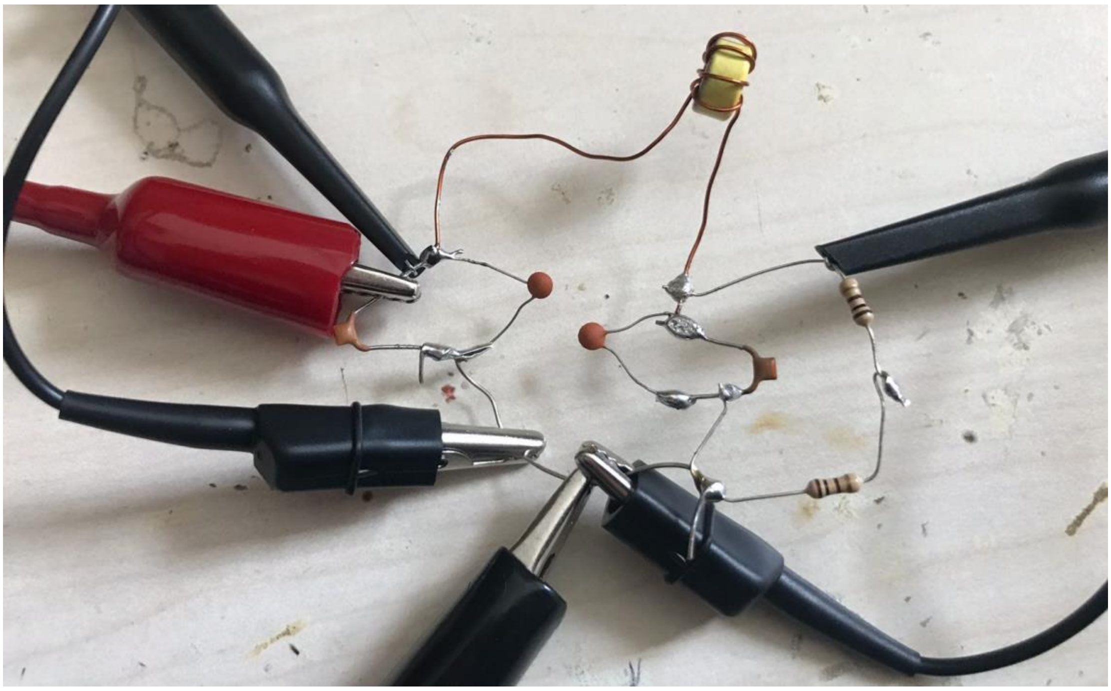

Figure 14 – The Π-Section Impedance Inverter Circuit.

Then, the only thing to do is to observe the outputs on the screen.

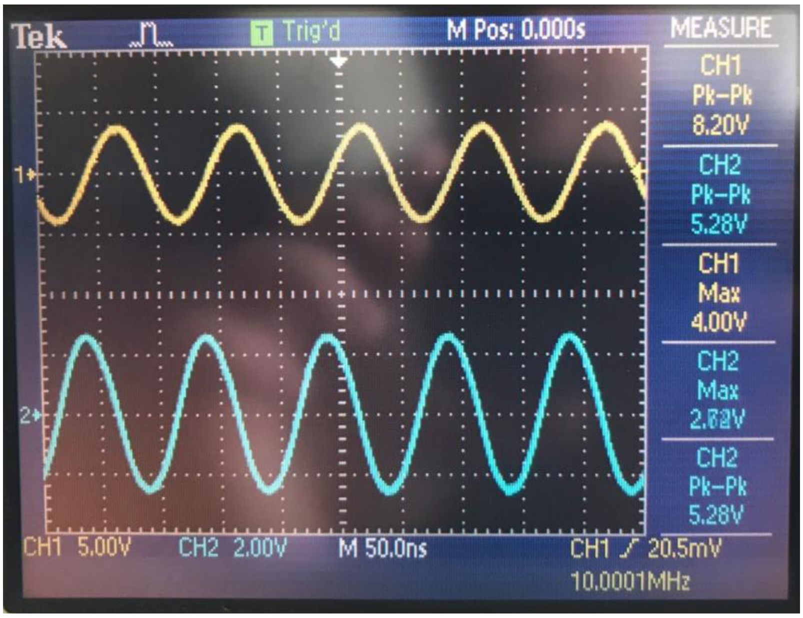

Figure 14 – The Π-Section Circuit Waveforms

As we can observe again, the output form is shaped as 8.2V which is exactly the same value that we have come up when dealing with the T-Section Circuit. Thus, we can conclude that, even though not perfectly, this circuit has accomplished what is asked. The next step is to calculate the percentage error in the output values.

$$\left|\frac{L_{theoretical}-L_{calculated}}{L_{theoretical}}\right| * 100 = \ \% \ Percentage\ Error$$

$$\left|\frac{9.44-8.2}{9.44}\right| * 100 = \%13.136$$

13% error shows that the experiment was not done perfectly, however it was sufficient to be presented. The next and final thing to do is to move on to the conclusion.

Conclusion

In this lab assignment, we were given the directive to maximize the power transferred to a load resistor of 200Ω from a voltage source that produces 10MHz 5V sinusoids with 50Ω source impedance. We discussed that we should equalize the source and load impedance to make this possible. Then to do that, we implemented the T-Section and Π-Section impedance matching circuits that we have learned in the EEE211 Analog Electronics course.

Finally, we can say that we have achieved transferring the possible maximum power to the load resistor by using two types of impedance matching circuitry. It can be seen that we have achieved a power of 62.7mW by using T-section and 61.5mW by using Π-section. Since the maximum power transfer for a voltage source with 5V, 10MHz and 50Ω is 62.5mW. By looking at these values, we can finalize that the circuits are acceptable despite the negligible errors. These errors have occurred as we haven’t used the exact values and rounded them, also the average is taken from t=120ns which the circuits may not have been fully stabilized.

In the hardware part, there were more notable errors when compared with the software. As we could not achieve the perfect values and soldered the components together, creating extra resistance, the experimental values differentiated from the expected values by 13.3%. However, getting the same outputs from the different circuits, we can see that the two circuits were consistent with each other. Also, we looked at the equivalent voltages and compared them rather than comparing the power directly, which differentiated this part from the software a further. Overall the hardware lab is done successfully with minor discrepancies.

At the end, we can say that this lab assignment was very useful as we have gone through the concepts “impedance matching” and using capacitors and inductor in our circuitry. Also, our knowledge on maximum power transfer has improved significantly.