EE 221L Circuits II Laboratory #4

Inductors

By

Angsuman Roy

Department of Electrical and Computer Engineering

Background

Electrical engineers are often afraid of inductors. They aren't mentioned too often in their classes. In their labs, most experiments using them don't work out as expected. As a result, electrical engineers tend to avoid inductors due to a lack of both theoretical understanding and practical experience. However, with switching power supplies proliferating everywhere, it is important to understand the basics of an inductor and how to select one for a particular application. Every cell phone charger, LED lightbulb and any electronic product that plugs into the wall has an inductor in it. Inductor design itself, is its own career and there are dedicated engineers who carefully analyze electromagnetics to design inductors and transformers. In this lab we will focus on the basics of inductors and their applications.

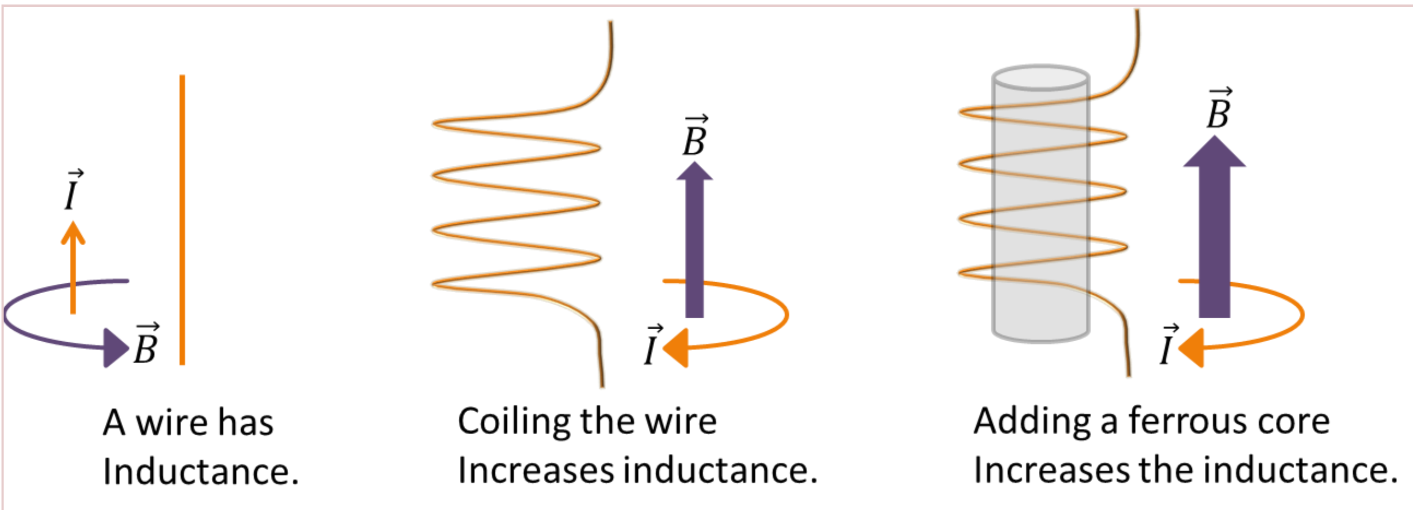


Figure 1. Origins of an inductor.

Consider a simple wire with a current flowing through it. This generates a magnetic field perpendicular to current flow consistent with the "right hand rule". Information on this rule can be found extensively on the internet and will not be covered here nor is it particularly important for this lab. If this wire is coiled, the magnetic field is concentrated and flows through the hollow core of the inductor. This increases the inductance of the inductor. An inductor made in this way is known as an air-core inductor. The inductance can be increased If a ferrous material or any material with some sort of magnetic property is placed in the core of the inductor. The properties of these materials and their interaction with the coiled wire can be extremely complicated and is generally left to dedicated inductor engineers. These basic inductor forms are shown in Fig. 1. The two basic schematic symbols for an inductor are shown in Fig. 2. A solid line is placed next to the air-core inductor to indicate that it has some sort of core. This usage is becoming increasingly archaic and it is common to just use the general symbol and describe the inductor properties in text next to it.

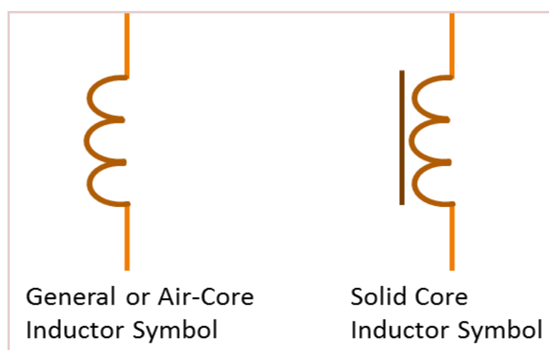


Figure 2. Inductor schematic symbols.

We will only concern ourselves with the lumped properties of an inductor, which are the inductance, series resistance and parallel capacitance. The reactance of an ideal inductor is given by

$$Z_L = j\omega L$$

The equivalent model of a real inductor with associated parasitics is shown in Fig. 3. Since inductors are generally wound from wire, the series resistance can be quite large, especially if hundreds of turns are needed. There is also a parasitic parallel capacitance due to turns of wire being next to each other. The resulting parallel LC network can be characterized by its self-resonant frequency which is often given in datasheets. This lets engineers decide at a glance whether an inductor is appropriate for their application. The rule of thumb is to use an inductor with a self-resonant frequency that is 10 times higher than the operating frequency range. For example, if an inductor was to be used in a switching power supply with a 100 KHz operating frequency it should have a self-resonant frequency greater than 1 MHz. A graph of impedance as a function of frequency for a real inductor is shown in Fig. 5.

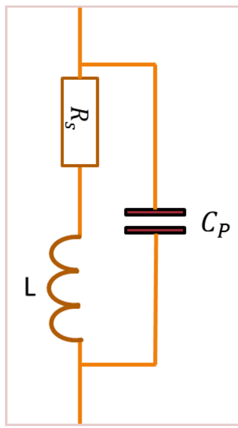


Figure 3. Model of a real inductor.

Various types of inductors are shown in Fig. 4. The 6.8 uH inductor on the left is physically small and fits in the same area as a typical ¼ watt resistor. These inductors are common in the lab but they often have high series resistance due to the packaging constraints. The inductor in the middle is a 100 uH inductor formed by a coil of magnet wire around a ferrite core. This inductor has series resistance and is suitable for use in switching power supplies and as power line filters. The 1 mH inductor on the right is of the same type of construction but has a much higher series resistance due to the large number of turns.

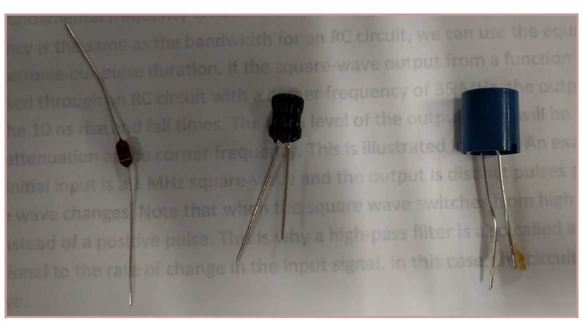


Figure 4. Real inductors.

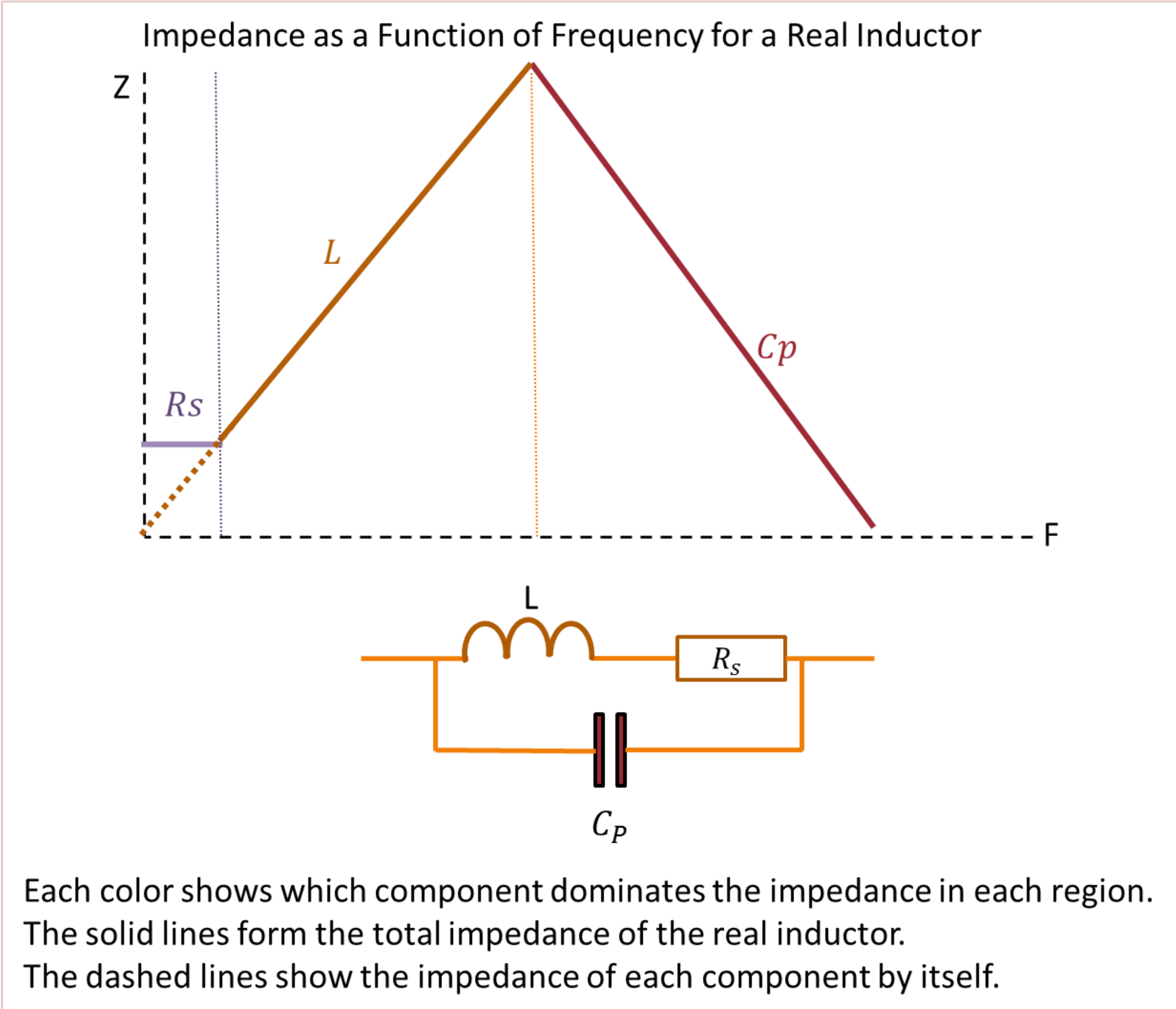


Figure 5. Impedance of a real inductor as a function of frequency.

Prelab Summary

You will simulate basic inductor circuits in this prelab using .ac commands. You will also do simple PCB layouts.

Prelab Tasks

Prelab #1: PCB and Netlist Required
Prelab #2: PCB and Netlist Required

Prelab

This prelab will extensively use LTSpice. It is assumed that the student has some familiarity with LTSpice and we will not go over basic functions. More complex functions will be detailed however. There are many LTSpice tutorial resources available on the web.

Prelab #1

Follow the steps below. Deliverables are in bold.

1. Simulate the schematic shown below in Fig. 6. Plot the current through the inductor. Next, in the expression editor, divide the input voltage by the current through the inductor. This will give the impedance of the inductor as a function of frequency. The Y axis defaults to dB, right click on the Y axis, select manual limits and change to "linear". This will show the units in Ohms. **(Schematic, Plot)**

2. Add the parasitic components as shown in Fig. 7. Note that the AC sweep values have changed to make it easier to see the parasitic effects. Make a plot of impedance vs. frequency as described in the previous step. However due to the parallel capacitance, you need to divide "Vin" by the current through the voltage source V1. If you use the inductor current you won't get the correct result. What is the self-resonant frequency? **(Schematic, Plot)**

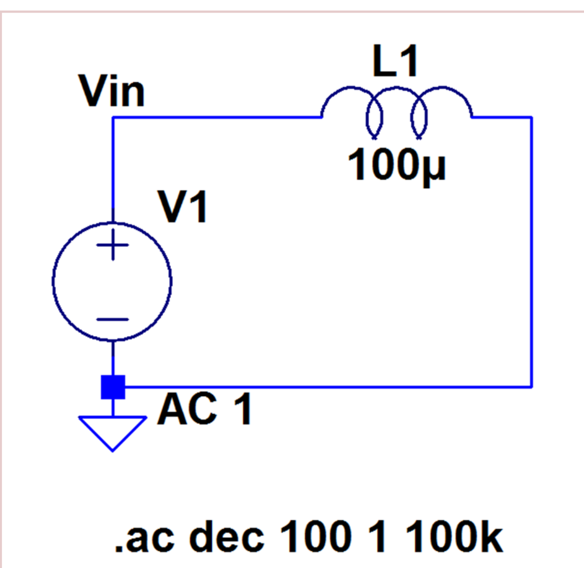


Figure 6. Schematic for Prelab #1, step 1.

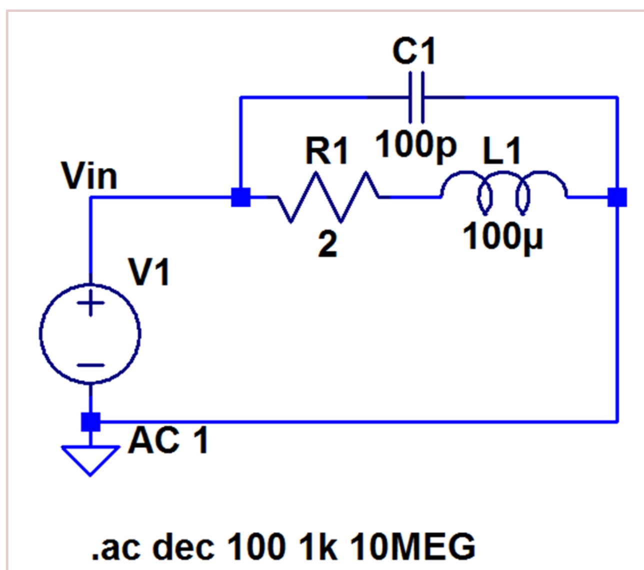


Figure 7. Schematic for Prelab #1, step 2.

Prelab #2

Follow the steps below. Deliverables are in bold.

1. The function generators in the lab have a 50 ohm output impedance. This means that if a 50 ohm load is connected, the output voltage will drop to half. Please note that on most function generators, the level entered on the front panel accounts for this and assumes that it will be connected to a 50 ohm load. To compensate for the drop, it actually outputs double the voltage entered on the panel unless it is set to "high-Z" mode. Calculate the inductor values that result in a 50 ohm reactance at frequencies of 1 KHz, 10 KHz and 100 KHz. **(Hand calcs)**
2. Simulate the schematic shown in Fig. 8. Replace the "?" with the inductor values you have calculated. Make sure to also change the input frequency. Verify your hand calculations with your transient analysis plots. **(Schematic, Plots)**

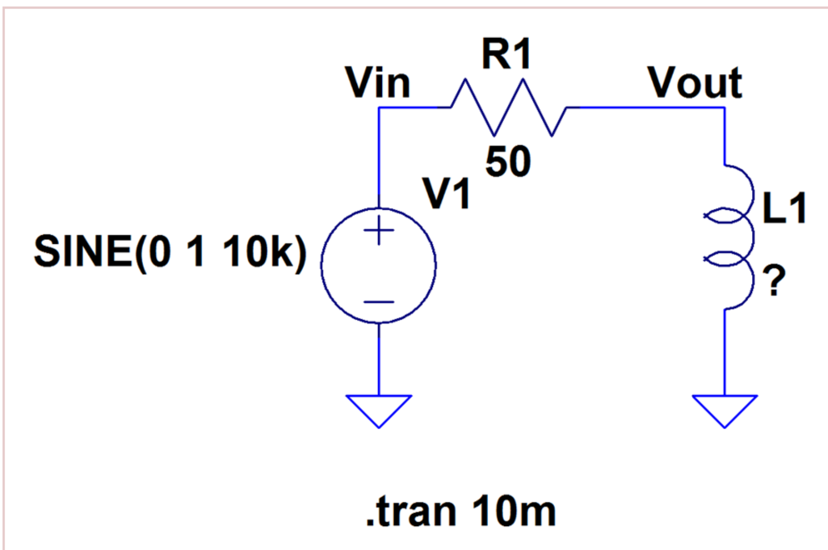
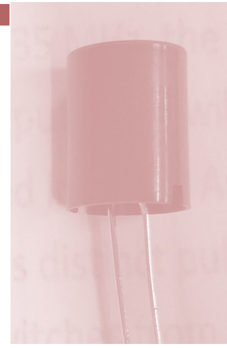


Figure 7. Schematic for Prelab #2, step 1.

Required Materials and Equipment

1. Function Generator
2. Oscilloscope
3. Inductors and Resistors
4. Breadboard
5. BNC to BNC Cable
6. Scope Probe
7. BNC to Alligator Cable
8. T Coupler
9. 50-ohm Terminator



Postlab Tasks

Task 1: Inductive Reactance

Task 2: Impedance vs. Frequency

Task 3: Ferrite Beads

Postlab #1: Inductive Reactance

Follow the steps below. Deliverables are in bold. All work must be typed.

1. Set up the function generator with 1V p-p amplitude, 0V offset and sine output.
2. Find three inductors in the lab that most closely match your calculated values from prelab #2 for 50 ohm reactance at 1 KHz, 100 KHz and 1 MHz. Or you will be provided three inductors since there is a limited number of inductor values available. If you are given inductors, find the frequency at which they have a 50 ohm reactance.
3. Set up the oscilloscope with AC coupling; appropriate probe settings; and vertical divisions and horizontal divisions to best fit a few cycles of the waveform.
4. Add a peak-to-peak measurement to the main display screen. The previous lab #3 has more detail on making peak-to-peak measurements. If you need additional assistance consult the manual. The waveform should be quite small in amplitude at low frequencies because of the low reactance of the inductor. As you increase the frequency the amplitude should rise.
5. Use a 50-ohm BNC to alligator clip cable and connect the output of the function generator to the inductor you are testing. Connect the oscilloscope probe to the inductor as well. Adjust the frequency until the peak-to-peak measurement on the screen is equal to the output amplitude setting on the function generator (1 volt peak-to-peak). Disconnect the inductor and verify that the output voltage doubles. This indicates that the inductor does indeed have a 50 ohm reactance at that frequency. The test set-up is shown in Fig. 8.
6. Repeat for the other values. (**Measured Results with Photos)**

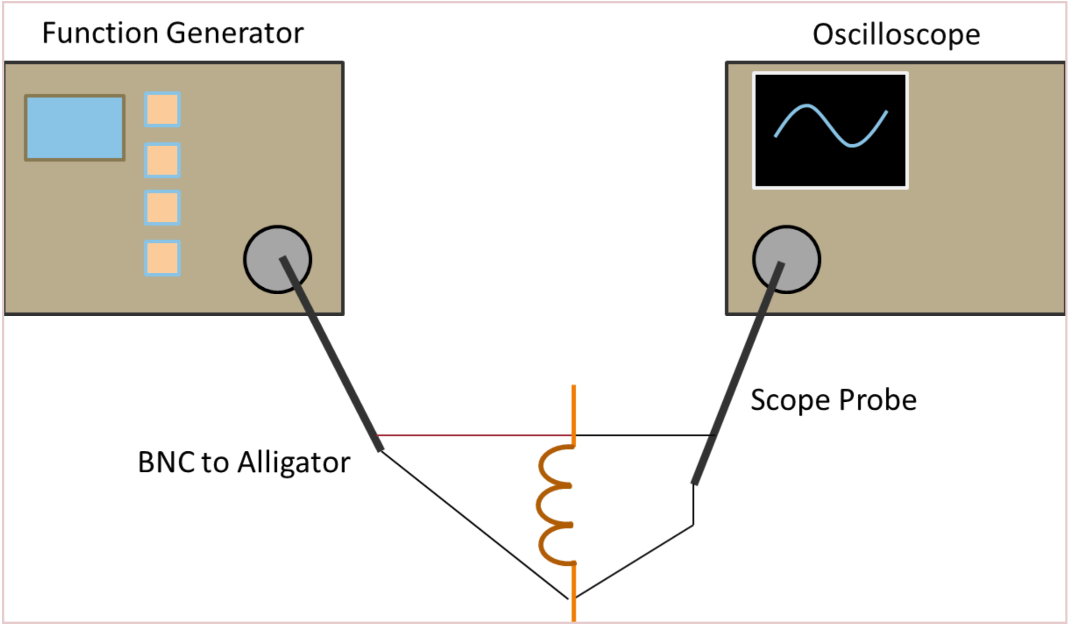


Figure 8. Test set-up for Postlab #1

Postlab #2: Impedance Vs. Frequency

Follow the steps below. Deliverables are in bold. All work must be typed.

1. Use the test set-up of Fig. 9.
2. Place the inductor in the test set-up from Fig. 9. Set up the function generator as shown in Fig. 10.
3. Set the function generator to a very low frequency such as 10 Hz. At this frequency, the inductor should appear to be a short. However you will see some small voltage appear on the oscilloscope. Use the peak-to-peak measurement on the oscilloscope and use the value to calculate the series resistance of the inductor. Use the schematic in Fig. 11 to calculate the series resistance. Assume that the capacitor is open and that the inductor is a short leaving the series resistance. Next find the Thevenin equivalent and use that to calculate what value of load resistance would result in the measured output voltage. Fig. 12 shows the voltage developed across an inductor at 10 Hz. With a 2 V p-p input the output is 600 mV which is quite high. This indicates a high series resistance. Your inductors may have significantly lower series resistance and you may need to use the lowest oscilloscope vertical setting to see the waveform. **(Photos and Hand Calc)**
4. Increase the frequency and the output voltage should rise. Select two points as you increase the frequency and use that to calculate the inductance. This corresponds to the rising portion of the impedance vs. frequency graph shown in Fig. 5. You can neglect the parasitics to make the calculation easier. **(Photos and Hand Calc)**
5. Eventually, the reactance of the inductor will rise to the point that the output voltage will reach 2V p-p. Continue increasing the frequency until the output voltage begins to fall. This point is close to the resonant frequency shown in Fig. 5. Select two points on the falling slope and use that to calculate the parallel capacitance. You may have to go as far out to 20 MHz as shown in Fig. 15 to get a good data point. If these points are beyond the frequency range of the function generator in the lab, simply note this and you don't have to do the calculation. **(Photos and Hand Calcs)**

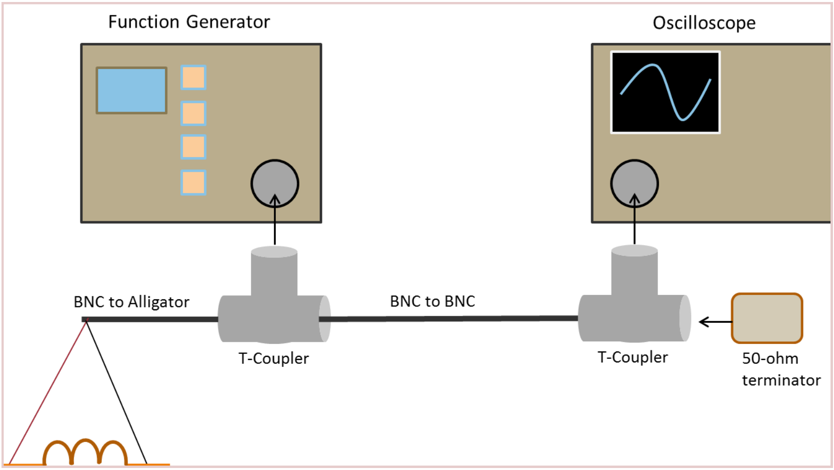


Figure 9. Test set-up for Postlab #1

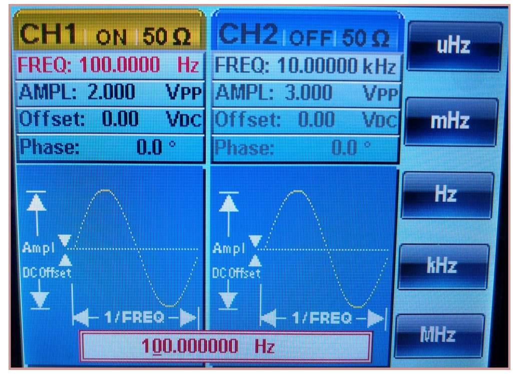


Figure 10. Function generator set-up.

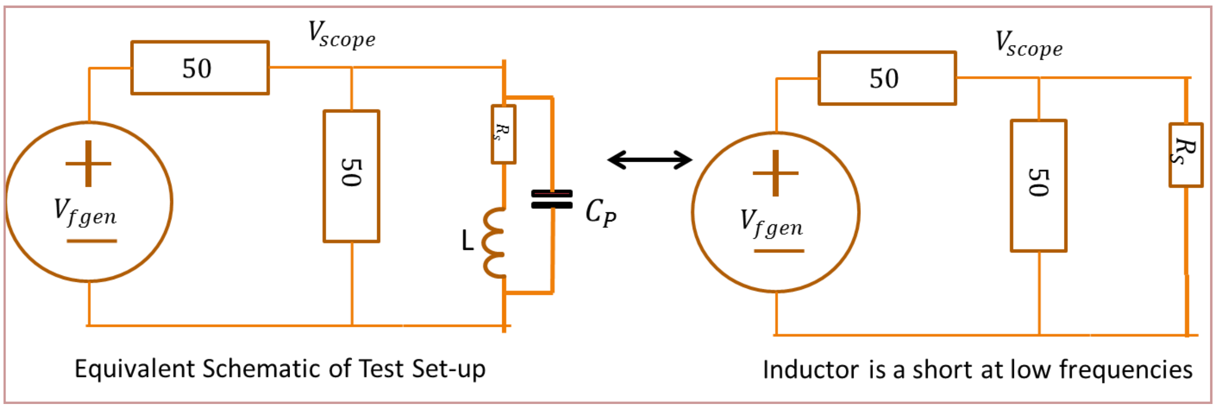


Figure 11. Equivalent schematic of test set-up.

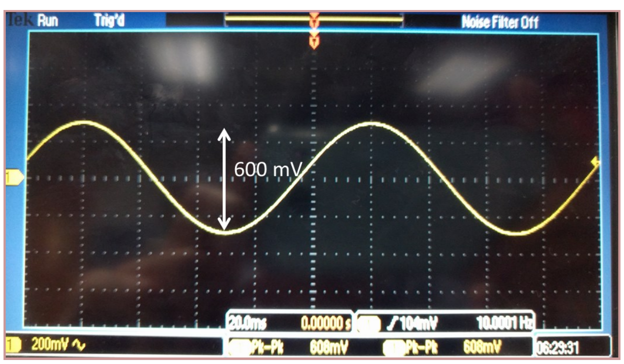


Figure 12. Voltage across inductor at 10 Hz with a 2V p-p input. 600 mV indicates a very high series resistance.

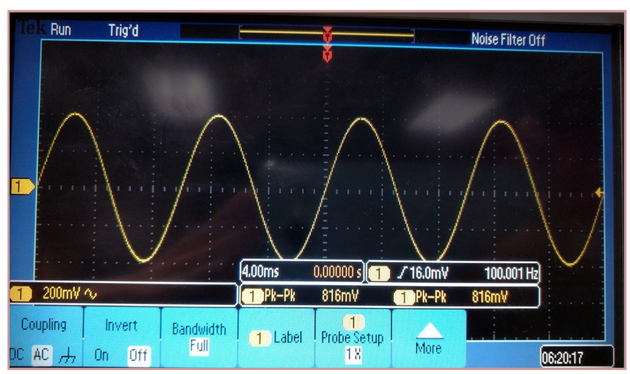


Figure 13. Output voltage rising with frequency.

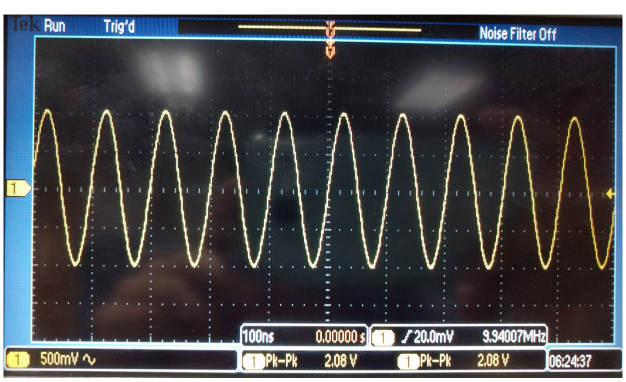


Figure 14. Resonant frequency around 10 MHz.

Figure 15. Impedance is mainly capacitive at 20 MHz

Postlab #3: Ferrite Beads

Follow the steps below. Deliverables are in bold. All work must be typed.

1. Ferrite beads are called such because they are similar in size and shape to a bead. A wire passes through the middle of the bead. The ferrite material increases the inductance of the wire. At low frequencies a ferrite bead behaves as a wire and lets the signal pass. The inductance makes it more difficult for high frequencies to pass. For a circuit that is intended for operation at a particular low frequency band, a ferrite bead reduces high frequency noise and interference. You will be given a ferrite bead. Generally ferrite beads have an impedance specified at a particular frequency for example, 100 ohms at 100 MHz. Of course, our function generator can not go that high and we'll have to test at a lower frequency. The same inductor should have an impedance of around 10 ohms at 10 MHz.
2. Place the inductor in the test set-up from Fig. 8. Follow the procedures in Postlab #1 to calculate the reactance of the ferrite bead. For example, at 10 MHz, you could measure the voltage drop and use that to calculate its reactance at that frequency. Convert this reactance to an inductance value. **(Hand calcs)**
3. Set the function generator to output a 2 V p-p white noise waveform. Set the oscilloscope to a 1 ms time base; an appropriate vertical division to show as much of the waveform as possible without exceeding the screen; and select an "RMS" measurement. This is done with the same set of menu options you used to display a peak to peak measurement. The RMS value is important because white noise is a completely random signal that has an equal power at each frequency up to the limit of the function generator. We want to look at the total power of the noise and see how the noise power goes down with the addition of the ferrite bead.
4. Use the test set-up of Fig. 16. Omit the ferrite bead and connect the alligator clip directly to the 51 ohm resistor on a breadboard. Measure the RMS noise value on the scope. Adjust the screen to get the most accurate measurement. **(Photo and measured value).**
5. Add the ferrite bead as shown in Fig. 16 and measure the RMS noise power. It should go down but depending on your ferrite bead it may not be resolvable by the oscilloscope. Be sure to note this if it is the case. **(Photo and measured value).**

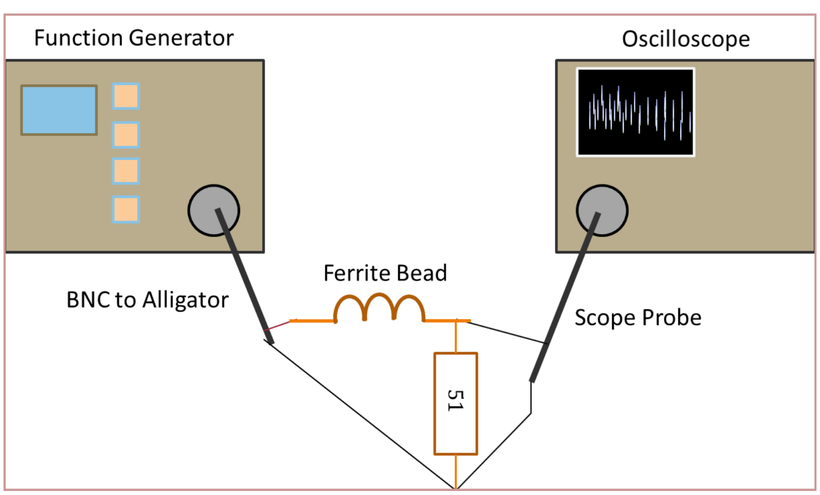


Figure 16. Ferrite bead test set-up.

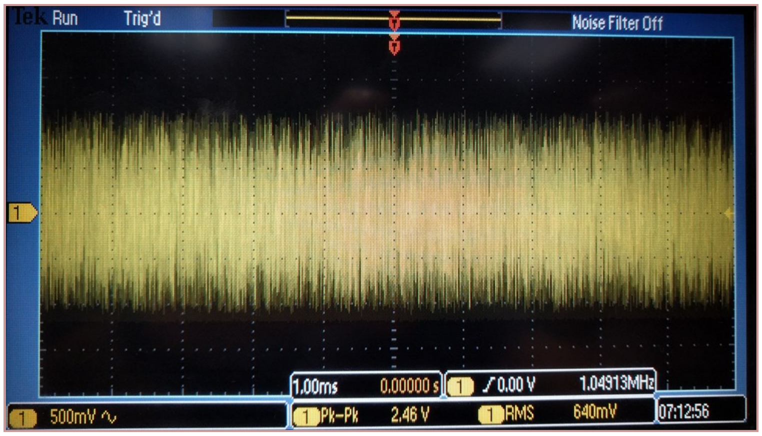


Figure 17. Noise power of 640 mV RMS without ferrite bead.

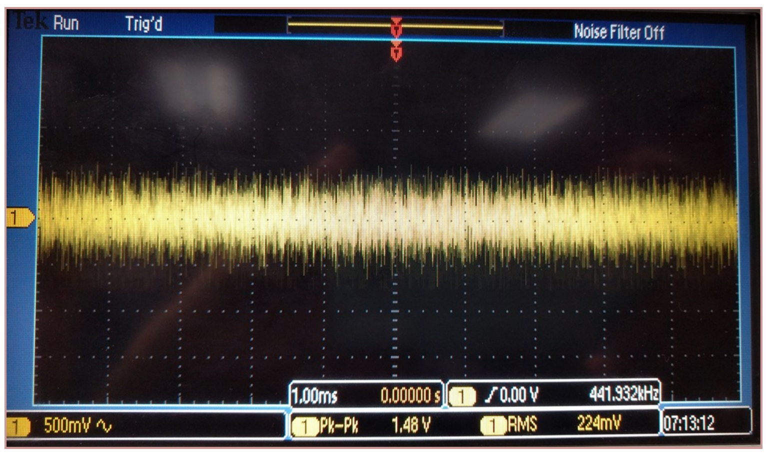


Figure 18. Noise power reduction to 224 mV RMS with addition of ferrite bead. Your results may vary.