RADIO-FREQUENCY CHARACTERISTICS OF COMPONENTS

Lab #1

The purpose of this lab is to become familiar with the real-world high frequency performance of capacitors, inductors, and resistors. You will also become familiar with impedance measurements using a multi-frequency LCR meter.

You should read the supplemental notes at the end of this handout before coming to lab–they explain the basic operation of the measurement equipment to be used as well as the common equivalent circuits for the components to be measured in the lab.

Before starting with measurement of actual circuit components, it is first necessary to characterize the LCR meter fixture. This fixture has parasitic resistance, inductance, and capacitance as described in the supplemental notes section of this write up. In order to determine the values of these parasitic elements and find an "equivalent circuit" for the measurement fixture, it is necessary to make some measurements of the fixture itself, and extract the values of the parasitic resistance, capacitance, and inductance from these measurements. The firmware in the LCR meter provides a convenient means for accomplishing this and removing the effects of the fixture from subsequent measurements by way of the calibration procedure.

Calibration:

In order to accurately determine the parasitics associated with the test fixture, measurements of at least two known impedance standards must be made. Although any standard impedances could be used, the built-in firmware assumes that the standards to be used are an open circuit and a short circuit. To calibrate the instrument, first remove any component from the fixture and press the “open” calibration button on the front panel. The LCR meter then measures the impedance it sees at its terminals at 10 kHz, 20 kHz, 40 kHz, 100 kHz, 200 kHz, 400 kHz, 1 MHz, 2 MHz, 4 MHz, and 10 MHz, and stores the results in internal memory. When this is complete, short the input terminals with a short piece of heavy wire, and press the “short” calibration button; the instrument again measures the impedance it sees at its terminals, and uses the expressions in the supplemental notes section of this handout to correct for the parasitics of the test fixture.

Component Characterization:

1. Capacitors

Capacitors have series lead inductance as well as internal lead inductance and resistive losses caused by the finite (i.e. non-zero) conductivity of the dielectric material. The losses in capacitors are often very small, so that they can be modeled as a series LC circuit. As a consequence, a capacitor will have a *series resonant frequency* above which the impedance will be inductive – at resonance, the impedance of a series LC circuit is zero (it is common to refer to impedances with negative phase angles as capacitive, and those with positive phases as inductive – this can be rationalized by noting that the sign of the angle for $Z=1/j\omega C$ is negative, and that for $Z=j\omega L$ is positive).

a.) Measure and plot the reactance vs. frequency of two capacitors with values in the 0.01 µF to 0.001 µF range. From the plot, estimate the series resonant frequency of each. Note that you may have to extrapolate or interpolate (using the series LC model as a basis) to find an accurate estimate of the resonance frequency. The Z, θ display mode is probably the simplest to use for this purpose.

b.) Using a series LC circuit as the equivalent circuit for the capacitor (i.e. neglecting dielectric loss) find approximate values for L and C from very high and very low frequency measurements. Are the values you found for L reasonable? (compare them, for example, to the inductance of a wire above a ground plane given in class).

2. Inductors

Inductors have capacitance between turns of the coil and resistance due to the finite conductivity of the wire. The loss is usually small, but is significant in determining the "Q" of the inductor. To keep things simple in this lab, we will neglect the resistance of the windings and the inductor will be modeled as a parallel LC circuit.

a.) Measure the and plot the reactance as a function of frequency for two inductors between 10 µH and 300 µH. For each inductor, estimate the parallel resonance frequency of each inductor (at resonance, a parallel LC circuit has infinite impedance, and the phase of the impedance goes from inductive below resonance to capacitive above).

3. Resistors

The general model for RF performance of resistors consists of an inductor in series with a parallel RC circuit. For low resistance value resistors, the effect of the parallel capacitance is most often negligible and the resistor can be modeled as a series RL circuit.

a.) Measure and plot R_s and X_s vs. frequency for a 50 Ω resistor. Estimate the series inductance, L_s from the data. You should examine the effects of using the series and parallel circuit display options on the LCR meter as well as the polar display to see the effects of this choice as the frequency is changed. Is either the parallel or series circuit interpretation valid? For resistors with larger resistance values, the equivalent circuit model can often be simplified to a parallel RC circuit. In your lab book, discuss why this is true.

b.) Measure and plot R_p and C_p vs. frequency for a 10 kΩ resistor. Discuss and explain your results. Again, examine the effects of using the series and parallel circuit display options on the LCR meter as well as the polar display to see the effects of this choice as the frequency is changed for a large resistance value. Is either the parallel or series circuit interpretation valid in this case?

Supplemental Notes – Lab #1

Multi-Frequency LCR Meter

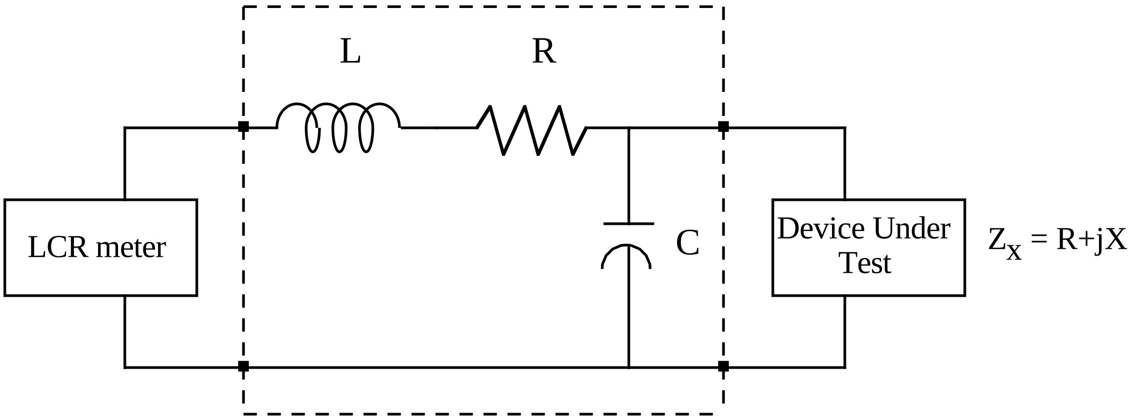
Impedance is measured by the LCR meter by indicating on the display the quotient (complex) of voltage across the fixture divided by the current injected from the fixture into the circuit. The internal oscillator of the LCR meter allows impedance measurements at 10, 20, 40, and 100 kHz, and 1, 2, 4, and 10 MHz. The display has several modes; it can be set to display impedance in polar format (magnitude and phase) as well as resistance and capacitance for parallel RC circuits and resistance and inductance for series RL circuits. Interpretation of the polar format is perhaps the most straightforward, but the other formats are convenient in particular situations as well.

Calibration Background Material:

An important feature to keep in mind about RF instrumentation in general, and the LCR meter in particular, is that the measurement fixture can have a significant effect on the measurement results. For example, the parasitic capacitance and inductance of the measurement fixture itself imposes limits on the values displayed by the LCR meter, and these parasitics "mix" with the circuit being measured and can corrupt the measurement if not properly accounted for. Fortunately, if we can measure the fixture parasitics, we can remove their effect on the measurement and significantly improve the measurement accuracy.

A simple model for the measurement fixture includes a series resistance, series inductance, and parallel capacitance. The equivalent circuit for the fixture is shown below:

Measurement Fixture Equivalent Circuit



As a result, the impedance that is actually measured by the LCR meter is that of the measurement fixture cascaded with the circuit to be measured. The circuit being measured is often called the "device under test," or DUT. The fixture's resistance, inductance, and capacitance can be computed by noting the impedances measured when the fixture is open- and short-circuited. If these impedances (at a particular frequency) are denoted Z_o and Z_s, respectively, and the impedance displayed on the meter is Z_m, then the actual impedance of the DUT (Z_{DUT} = R+jX) can be computed using the following formulae from elementary (but messy) circuit analysis:

$$R = \frac{\left(|Z_o|\cos(\theta_m) - |Z_m|\cos(\theta_o)\right)\cdot|Z_m||Z_o|}{\left(|Z_o|\cos(\theta_m) - |Z_m|\cos(\theta_o)\right)^2 + \left(|Z_m|\sin(\theta_o) - |Z_o|\sin(\theta_m)\right)^2} - |Z_s|\cos(\theta_s)$$

$$X = \frac{\left(|Z_o|\sin(\theta_m) - |Z_m|\sin(\theta_o)\right)\cdot|Z_m||Z_o|}{\left(|Z_o|\cos(\theta_m) - |Z_m|\cos(\theta_o)\right)^2 + \left(|Z_m|\sin(\theta_o) - |Z_o|\sin(\theta_m)\right)^2} - |Z_s|\sin(\theta_s)$$

where $|Z_o|$ and θ_o are the magnitude and phase displayed with the fixture open-circuited, $|Z_s|$ and θ_s are the magnitude and phase displayed with the fixture short-circuited, and $|Z_m|$ and θ_m are the magnitude and phase of the displayed impedance with the DUT connected to the fixture. Note that the derivation of these formulae assume that $|Z_o| >> |Z_s|$, and the correction implemented by these expressions is only significant when the magnitude of the measured impedance is of the same order (i.e. within a factor of ten) of either Z_o or Z_s.

Operational Hints for the LCR Meter – Data Display Formats

After calibration of the LCR meter, the instrument attempts to display the impedance of the device connected to the test fixture, internally correcting for the fixture parasitics using the expressions shown in the Calibration section above. The LCR meter actually measures the real and imaginary parts of the impedance, and is able to display the results in several formats. The selection of which format is most appropriate requires some attention on behalf of the operator in order to ensure correct interpretation of the results.

The most straightforward display mode is the polar display ($|Z|$, θ); this mode displays the magnitude on display A, and the phase angle on display B, and makes no assumptions about the circuit or device connected to the test fixture terminals.

The other main display mode (R, L/C) displays the resistance and capacitance or inductance of the device on the A and B displays, respectively. Its action is further modified by the circuit mode switches (auto, parallel, and series), which it uses to determine how to display the results. In parallel mode (the default), the impedance is assumed to be of the form $Z=1/(G+jS)$, and $R=1/G$ is displayed in display A, and S is converted to a capacitance using the known frequency (since $S=\omega C$ for a capacitor). In series mode, the impedance is assumed to be of the form $Z=R+jX$; R is displayed in A, and B displays a value of inductance obtained from $X=\omega L$ for an inductor. This works well and is very convenient if the circuit is well modeled by either a parallel RC or series RL circuit, but produces “interesting” results for other circuits. These “interesting” results are not really incorrect but they do require care to be interpreted properly. One point that this brings up is the question of when the R, L/C interpretation is valid, and when another interpretation is more appropriate. To determine the validity of the R, L/C model, note that as we change the frequency for either a parallel or series circuit the impedance seen by the LCR meter changes, but *if the model is correct, the R and C or L values should not change with frequency*. Thus a quick check on the validity of a series or parallel interpretation is to examine the values as a function of frequency, and determine if they are (mostly) constant, or if they vary with frequency or if non-physical results (e.g. negative capacitances or inductances) are obtained at some frequencies.

For the case where the series or parallel models break down, a more complicated circuit model (e.g. an inductor in series with an RC parallel circuit) might be more appropriate, but since the LCR meter does not have this model built in, the user must supply the interpretation of the results. This can be done either by recording the $|Z|$, θ of the measured impedance, or finding the R, X or G, S values from the series or parallel measurements by reversing the computations done internally by the LCR meter. The data can then be analyzed by the user graphically or numerically to find the appropriate component values for the equivalent circuit model.