# The damped driven harmonic oscillator: RLC Circuits

The aim of this lab is to build from the material presented in chapter 2.5 of the course book to demonstrate applications in a lab setting. We will do this by the characterization of a simple RLC resonant circuit, and for that we will use Rhode & Schwarz FPC1500 Spectrum Analyzers equipped with 5 kHz to 3 GHz signal generators.

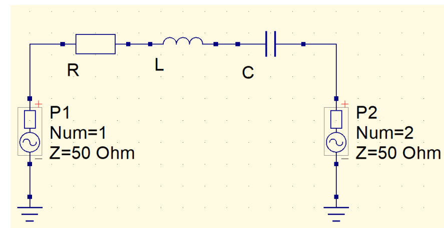



*Figure 1. RLC circuit connected to 50*

### *Accessing the lab setup remotely*

- Note: You will work in pairs, and only one of you will be able to run the analyzer at a time. I recommend switching half way through the lab so that each of you has the chance to run the analyzer.
- Start the Rhode & Schwarz software using the link saved on the desktop. The software searches for any connected equipment (we are using USB). You will need to connect to the analyzer by clicking “Connect”. Once the arrows are green, the analyzer is ready to use. Click “Done”. Switch to the main display by clicking “Instrument” in the menu to the left, and selecting “Remote Display”.
- You should now see the spectrum in the main panel of the screen, and below you will find several function keys, a numeric key pad and a digital dial.

## *Microstrip transmission line measurement*

- Let's start by getting familiar with the spectrum analyzer and simultaneously introduce the platform that our resonator circuit is built on: The microstrip transmission line (Fig. 2). This homemade board consists of fr4 epoxy circuit board which is coated with a copper ground plane on the back side, and a strip of conducting copper tape cut to 3 mm in width acts as the transmission line on the top side. Two SMA connectors allow connection to the *Generator Output* and *RF Input* connections of the spectrum analyzer. The spectrum analyzer's connections, as well as the SMA cables connecting to the board, are 50 Ohm matched. To avoid impedance mismatch in the circuit, which would result in signal losses, the microstrip should also provide a 50 Ohm load match. Therefore, in deciding the required width of the microstrip, both the thickness and permittivity of the insulating fr4 layer as well as the copper tape's thickness were taken into consoderation.

*Figure 2. Microstrip transmission line with SMA*

- Now we'll use the spectrum analyzer to see if the lab responsible did a decent job in designing these. Start with a few default settings:
  - Click the "Meas" function. This opens submenus to the right of the spectrum. Click "Source", and "Off" to be sure that we are not sending any signal.
  - Similarly, do the following: a) "Trace" -> "Trace Mode" -> "Clear/Write"; b) "Span"-> "Full Span"; c) "BW" –> Choose Auto for both RBW and VBW; d) "Ampt" -> "Auto Range".
- The spectrum measured across the microstrip transmission line without and applied signal is shown in the screen, and measured in power loss in dBm (logarithmic measure of power loss in dB per mW) versus frequency along the horizontal axis. Unless the stripline is acting like an antenna and picking up electromagnetic radiation in the lab, there shouldn't be any peaks and the spectrum should show a flat spectrum at very negative dBm values.
- We will now measure S21, or the power transferred from port 1 of the board to port 2. Let's apply a 2 GHz continuous wave (CW) signal and measure the transmitted power. Go to "Meas" -> "Source" -> "CW". At the top right of the spectrum panel you will see an input box for frequency. Use the key pads to enter "2" followed by the unit "GHz".
- Use the "Marker" function to scroll through the measurement and get readings at each data point. Once you have a marker on the screen, you can use the "Mkr->" followed by "Set to peak" to automatically set the marker to the highest signal peak and read out the power transmission/loss.
  - How is the power transmission/loss? (For reference: -1 dBm ≈ 80 % transmission, -3 dBm ≈ 50 %, -10 dBm ≈ 10 % & -20 dBm ≈ 1 %, etc.)

- We are limited to a set number of data points across the full frequency range. For better resolution we should probably reduce this range. Let's set a 40 MHz window around our 2 GHz peak. Go to "Freq" -> "Center Frequency" and type in 2 GHz followed by "Span" -> "Manual Span" and type in 40 MHz.
- Now re-center the marker using "Mkr->" -> "Set to Peak" as before (or try "Marker Tracking").
  - Is the power transmission/loss reading different now that we have better resolution?
- Notice that the signal seems very wide when using a 40 MHz span. The width is set by the resolution bandwidth (RBW), and we can reduce that by going "BW" -> "RBW: Manual" and changing it to 10 kHz. This gives a much sharper signal.
  - Has the power transmission/loss reading changed this time?
- The trade-off for increasing the resolution bandwidth is that it measurement time increases quite a bit. For example, change the span of your measurement to 400 MHz, and you can quickly imagine that this RBW setting would not be ideal for scanning over the entire 3 GHz range of the analyzer.
- Set RBW back to auto by "BW" -> "RBW: Auto". Note that I haven't talked about the video bandwidth (VBW), but we'll leave that on auto for the lab as well. Finally, let's go back to the full 3 GHz range by "Span" -> "Full Span".
- If you want to turn off the marker, go "Marker" and deselect any markers in the menu that are on by clicking on them.
- So far we have investigated the loss in the microstrip transmission line at a single frequency, but we want to characterize it over the whole 3 GHz range. Begin by typing in new continuous input wave frequencies in "Meas" -> "Source" -> "CW".
  - Can you step across the full range and characterize the microstrip's S21?
  - Do you notice multiple peaks occurring for frequencies at or below 1.5 GHz? What causes these?
- Cleaning up the signal: Instead of constantly refreshing the measured signal, we can take an average over multiple readings by going to "Trace" -> "Trace Mode" -> "Average" and setting the number of traces to average using the number keys. Average over 3 traces and see how the signal-to-noise level on the analyzer improves.
  - Set Trace Mode back to "Clear/Write" before continuing.
- Manually sweeping through the frequency range gave a feel of the microstrip's response to various frequencies, but has obvious drawbacks. For a detailed analysis we will now use the Tracking Generator feature: "Meas" -> "Source" -> "Tracking Generator". The signal output of the spectrum analyzer is now sweeping frequency over its full range (5 kHz to 3 GHz), and recording the (microstrip) circuit's S21 response in dBm vs frequency.
  - Set a marker to 2 GHz to measure the loss. How does this measurement compare with the sampling you did earlier?

    - More importantly, is the microstrip 50 Ohm load matched?
    - Do you observe a frequency dependence?

- Save a copy of this trace: On the menu to the left in the InstrumentView software, click “Get Trace”. This opens a new tab in the software with a screen grab of the data. Click “Save” (to the left), name the file, choose a path to where you want it saved and choose to save it as a CSV file so you can open it later. You can repeat to save a PNG Image version if you want as well, but this is not necessary.
- Now that a copy of the measurement data is saved on the lab computer, it is your responsibility to transfer any needed data files to your computer. This can be done either by emailing a copy from the lab computer to yourself, or using the S: drive. Whichever method you choose, be sure that you have the files before the lab ends. (I recommend sending it now, because we are almost at a good place to swap control with your lab partner.)
- We are almost ready to switch to the RLC board. First, return to the Remote Display tab, and stop applying signal from the analyzer’s source: “Meas” -> “Source” -> “Off”
- Now ask you lab teacher (Ekin) to switch from the transmission line board to the resonator board for the next part of this lab.
- *This would be a good time to switch with your lab partner so that both of you have the chance to control the analyzer*:

### *Plucked harmonic oscillator (description only)*

When the RLC circuit, a lightly damped harmonic oscillator, is “plucked” (e.g. pulled away from equilibrium and then allowed to freely respond) the amplitude of its response oscillates as it decays. The oscillation is a function of its natural resonant frequency.

Unfortunately, I was not able to incorporate this into a remote function for the VT21 lab, so we will focus on the system when driven by a sinusoidal signal.

### *Driven harmonic oscillator*

- The RLC circuit board for the lab is similar to the microstrip transmission line, but sections of the line have been cut out and a surface mount inductor and capacitor have been soldered into the circuit, Fig. 3. Note that no resistor component has been included, but an effective resistance from the internal resistance of the inductor and the circuit itself will become evident when you fit the data later.

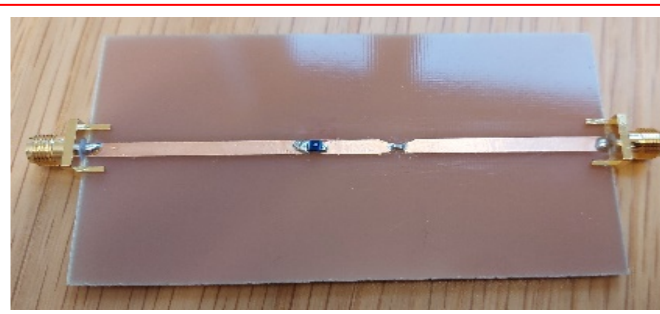


*Figure 3. (R)LC circuit board with microstrip transmission lines and SMA connectors.*

- Instead of walking through, I will leave it to you to use what you learned previously to optimize your measurement of the circuit’s response. I do suggest reducing the frequency range to 5 kHz – 750 MHz. Apply a continuous wave “Meas” -> “Source” -> “CW” and start around 10 MHz. If you have a mouse with a scroll wheel function, you should be able to scroll through frequencies. Otherwise, clicking the right half of the dial (just beside the number keys) on the virtual instrument also works.

- At the resonant frequency of the RLC circuit, S21 will peak. Can you estimate the resonant frequency of your circuit?
- Given the inductance, L = 100 nH, what do you estimate the circuit's capacitance to be?

○ Use the tracking generator function to measure the response of the RLC circuit. Save at least one data set to fit, and maybe even a second over a different frequency range. *Fitting this data will be the main focus of your lab report*.

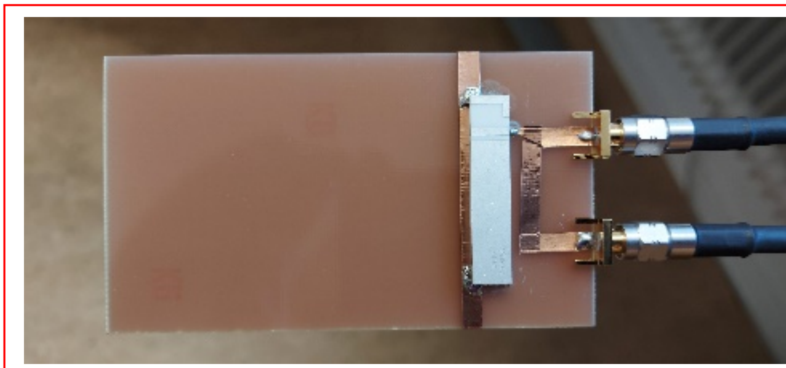
- How close were you previously at estimating the resonant frequency, and what is the resonant frequency using the tracking generator?
- How much has your capacitance estimate changed as a result?
- Refer to Chapter 2.5 in the course book for analysis after the lab. The data measured here is equivalent to the "resonance curve" of Fig. 2.11. Using the description in the book, fit your data to extract R and C in the circuit (L = 100 nH).
- What is the Q-factor of the RLC circuit?

○ Turn off the source before continuing.

### *Antenna measurement*

○ Kindly ask the lab teacher to now connect the antenna circuit board as in Figure 3.

○ As our last exercise, let's use the spectrum analyzer to characterize an antenna, and see if we can also pick up frequencies in the lab. Figure 3 shows a test board with a Molex 206760 Cellular Antenna[1] mounted to it. Two SMA connections crudely enable a return loss measurement.



○ Use the track function to effectively measure S11 (the power returned to port 1 from port 1).

- Within the 1.71 GHz to 2.7 GHz window, does the test board antenna's performance qualitatively resemble the spec sheet data given in Fig. 4?
- Over the full span of the analyzer, what other regimes do you think this antenna is effective at picking up? What ranges of frequency can it not pick up?

- Now turn off the source to measure any frequencies the antenna is picking up in the lab. You may need to experiment in "Trace" -> "Trace Mode" to improve your signal either by averaging or by trying "Max Hold".
    - What frequencies are detected?
    - Using a quick Google search, what technologies can you ties these signals to? (e.g. Bluetooth, cell signal, …)
- After experimenting with the antenna a little, you have reached the end of the lab! On the final page of this manual there are a few details about what is expected in the lab report.

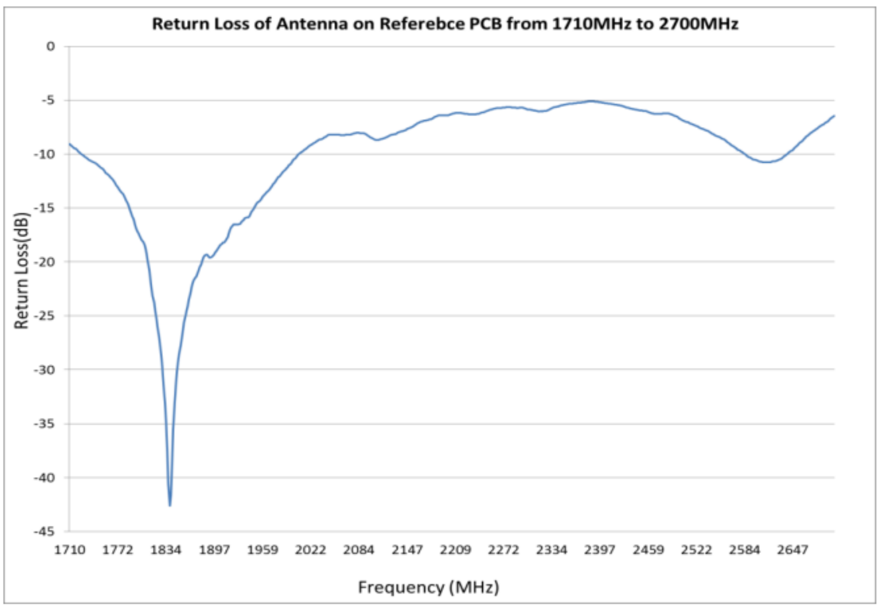



**FIGURE 4.3.2 RETURN LOSS OF ANTENNA FROM 1710MHZ TO 2700MHZ IN FREE SPACE**

## *Lab Report*

- The lab report is due 28th of November and is written in pairs. A length of 3-5 pages including plots and any references seems appropriate.
- Focus for the lab report is on the analysis and fit of the RLC circuit's "resonance curve", and should address the circuit's Q-factor as well.
- Any other aspects of the lab can be included in the lab report as wanted, or to support the RLC analysis, but are not required.

## *References*

[1]https://www.molex.com/molex/products/part-detail/antennas/2067600001