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Lab section: ABH

2 Laboratory exercise

2.1 Objective

- Building a simple RC circuit and explore capacitor characteristics
- Determining RC time constants
- Using the Network analyzer of Scopy to examine frequency response for a RC circuit
- Building a simple envelope detector and understanding the mechanism of the envelope detector

2.2 Capacitor Characteristics

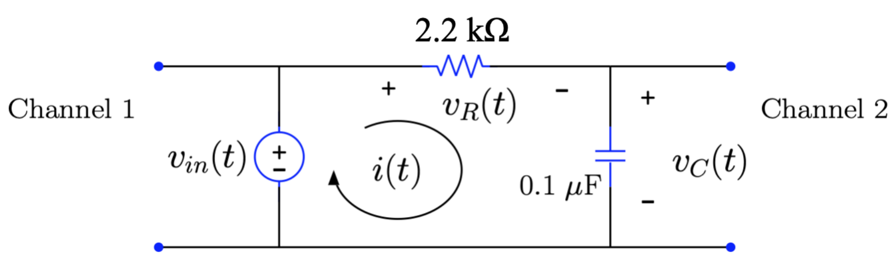


Figure 3: *RC* circuit for laboratory exercises.

In this section, you will study the characteristics of the capacitor in the network of 3. Once you have built the network on the breadboard, connect the circuit with M2K as shown in Figure 4, and complete these steps in Scopy :

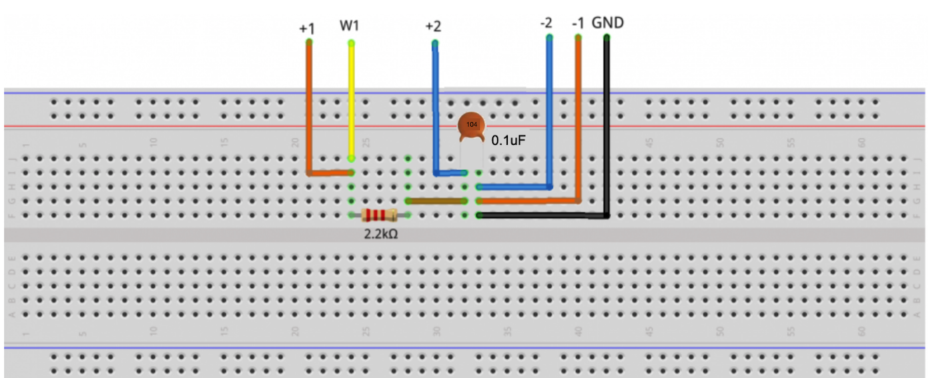
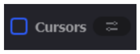


Figure 4: *RC* circuit on breadboard.

1. Apply a 800 Hz sine wave $v_{in}(t)$ measuring 5 V peak to peak amplitude to the RC circuit as shown in Figure 3. (go to Signal Generator module in Scopy and select “Sine” and input 5 V for “Amplitude” and 800 Hz for “Frequency”). Display voltage $v_{in}(t)$ and $v_C(t)$ using Channels 1 and 2 of the oscilloscope, respectively.

    (a) What is the phase difference in degrees between $v_{in}(t)$ and $v_C(t)$? This can be approximated from inspection, but obtain an accurate measurement using Cursor tool in the Oscilloscope module. (In Oscilloscope module, look for 

in the bottom right of the UI. Enable/disable the cursor by clicking the square)

Time difference= 163.918 MicroSec (____/2)

Phase difference (in degrees) $= \frac{\text{Time difference}}{\text{Period}} \times 360^o =$ 47.208384 degrees (____/2)

(b) Repeat step 1a with a 1 kHz sine wave input:

Time difference= .001 Sec (____/2)

Phase difference (in degrees) $= \frac{\text{Time difference}}{\text{Period}} \times 360^o =$ 59.01048 degrees (____/2)

(c) Is $v_C(t)$ leading or lagging $v_{in}(t)$? Hint: If one waveform is leading another, "it happens" earlier in time.

$v_C(t)$ is lagging $v_{in}(t)$. (____/2)

2. Set the input frequency to 4 kHz for this part. Determine the peak to peak amplitude of current $i(t)$ in the circuit by first measuring the voltage $v_R(t)$ across the 2.2kΩ resistor. You can measure $v_R(t)$ without moving your M2K connection—instead, subtract Channel 2 from Channel 1. By KVL, $v_{in} = v_R + v_C$, so $v_R = v_{in} - v_C$. This subtraction can be displayed on the Oscilloscope using the math panel

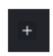
- Go to Oscilloscope module in Scopy, look for  next to the Channel 2 setting in the bottom of the UI and click it.
- In the math setting panel, input "t0-t1" for f(t) as shown in Figure 5 ("t0" and "t1" represent the time series for channel 1 and channel 2)

Figure 5: math panel in Scopy

- Click "Add channel" .You may see the full usage of the math function in `https://wiki.analog.com/university/tools/m2k/scopy/oscilloscope#working_with_math_channels`

Voltage peak to peak amplitude across the resistor : $v_R =$ 4.875 V (____/2)

Current peak to peak amplitude: $i =$ 0.00221590909091 Amps (____/2)

What is the phase shift of the current relative to $v_C(t)$? (Hint: find the time difference first) Phase shift :

$\phi =$ 96.40944 Degrees (____/2)

Is $i(t)$ leading or lagging $v_C(t)$? $i(t)$ is leads $v_C(t)$. (____/2)

2.3 RC Time Constants

To investigate the transient response of your RC circuit, change the signal generator output to a 100 Hz **square wave** measuring 1 V peak to peak amplitude with a 0.5 V DC offset. As in the previous section, Channel 1 should display $v_{in}(t)$, and Channel 2 should display $v_C(t)$.

Across its positive half-period, the square wave approximates a unit step and the capacitor is charged. During the negative half-period, input voltage is zero and the capacitor discharges through the resistor starting from a peak voltage value v_{max} and with a time constant RC. Thus, the voltage across the capacitor over the negative one-half period is w

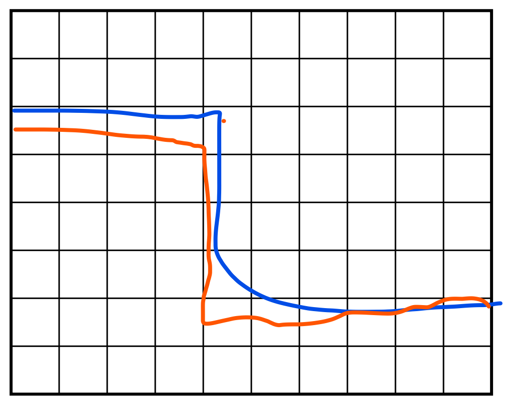
$$v_C(t) = v_{max}e^{-\frac{t}{RC}},$$

and, when $t = RC$,

$$v_C = v_{max}e^{-1} \approx 0.368v_{max}.$$

Measure the time constant by determining the amount of time required for the capacitor voltage to decay to 37% of v_{max} on the scope.

- Set the Time Base to 500µs and the Volts/Div of channels 1 and 2 to 200 mV.
- The Trigger should be set to the "falling edge". (In Oscilloscope module, look for trigger in the bottom right of the UI and click icon , under "condition" tap select "falling edge"). Disable the Channel 1 to focus on the output and move Channel 2 vertically to center it in the scope display.
- Use the cursors to measure the time constant, i.e. the time it takes for $v_C(t)$ to decay to 37% of v_{max}. If you place one 'y-axis' cursor in the bottom of the signal it should measure 0V, moving it to the top of the signal should indicate 1V. So place it in the 37% of that. Use 'x-axis' cursor to measure the time.
- Sketch what you see on the oscilloscope including the vertical and horizontal lines of the cursors.



V/div : 0.2 t/div : 0.0005 (____/2)

Measured time constant : tau = R * 0.1

$\tau =$ (206.242 * 10^-6) sec (____/2)

Theoretical value for RC:

$RC =$ (220 * 10^-6) sec (____/2)

Give the percent error:

$\delta_{\%} = \left| \frac{\text{measured value} - \text{theoretical value}}{\text{theoretical value}} \right| \times 100\%$

% error = 6.25363636364 %

(____/2)

1.002 * .37 = 0.37074

2.4 Frequency Response

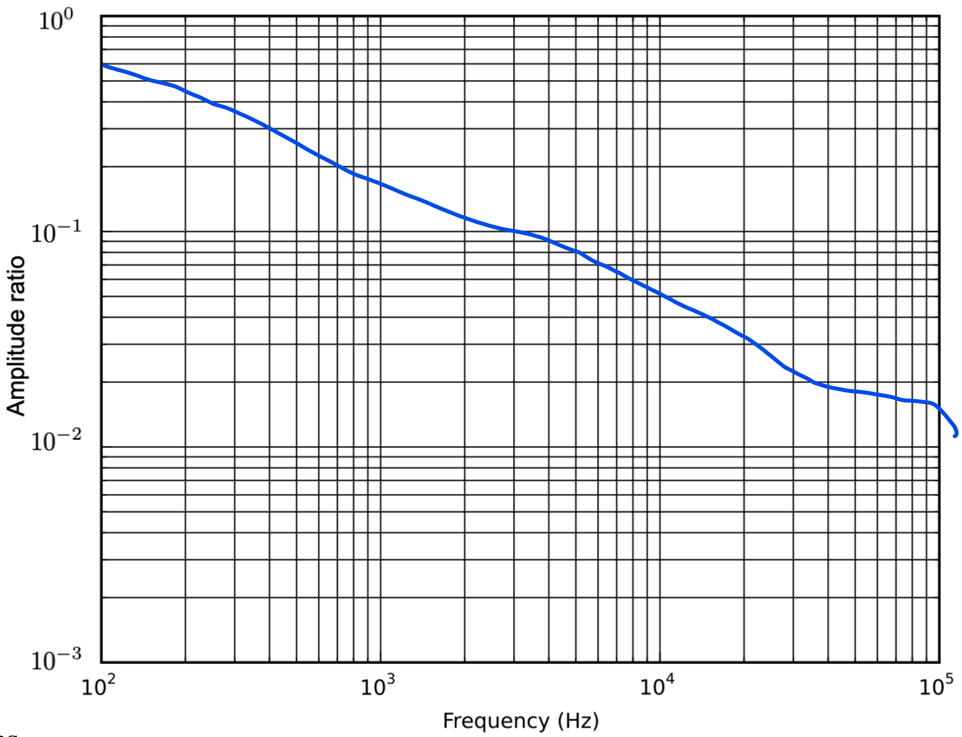
RC circuits have the very useful property that co-sinusoidal voltage measured across the capacitor or resistor changes in response to a change in the frequency of the input co-sinusoid. This property provides the basis of the filters (and envelope detectors) commonly found in AM radio receivers. You will investigate and graphically display the frequency dependence of capacitor voltage $v_C(t)$ in this section.

This can be done using the "Network Analyzer" module in Scopy. In "Network Analyzer" module, click "Run" and the frequency response of the network will be displayed slowly as frequency increasing. You may stop it at 100 kHz. In the log-log plot, you should expect to see a linear relationship.

*graph not drawn perfectly
should be linear relationship

-1.04dB = 0.887
-5.1dB = 0.55
-22dB = 0.08
-42dB = 0.008
n -> m
m=10^{n/20}

Plot the amplitude ratio versus frequency data from the table in the box below — note that the axes are labeled using a logarithmic scale. To help finding the coordinates in a Log-Log graph, there are arrows showing the location of some numbers as an example.



About Log-Log graphs

When plotting a function in a Log-Log graph, if the dependent variable is proportional to a power of the independent variable then the graph will be a straight line and the slope of the line will be the power. In our graph, for $f \gg 1\,\text{kHz}$, the amplitude should be proportional to f^{-1}, i.e. $A(f) \propto f^{-1}$. Then, you can verify that for $f \gg 1\,\text{kHz}$, the slope is -1 decade/decade, where one "decade" is a factor of 10 difference between two numbers(an order of magnitude difference) measured on a logarithmic scale.

2.5 AM Signal and Signal Envelope

An AM radio signal consists of a high-frequency sinusoid whose amplitude is **modulated**, or scaled, by a message signal. The message signal is the speech or music recorded at the radio station, and the objective of the AM radio receiver is to recover this message signal to present through loudspeakers to the listener. Figure 6 illustrates an AM signal with a co-sinusoidal amplitude modulation. The horizontal axis represents time, and the vertical axis is signal voltage. You can see the amplitude of the high-frequency sinusoid changes over time. In this case, the message signal is a low-frequency sinusoid. You can imagine the message signal as a low-frequency sinusoid connecting the peaks of the high-frequency sinusoid. Because the message signal connects the peaks of the high-frequency sinusoid, it is also called the AM signal's **envelope**, and a circuit that detects this envelope, producing the message signal, is called an **envelope detector**. The Signal Generator module can create an AM signal for you:

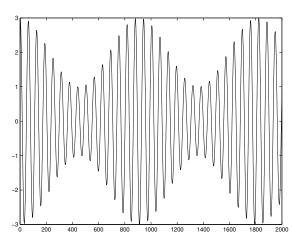


Figure 6: Illustration of AM radio signal.

Below there is a set of instructions to set the function generator to create an AM signal with $f_c = 13$ kHz and 1 V peak to peak amplitude modulated by 880 Hz sine-wave :

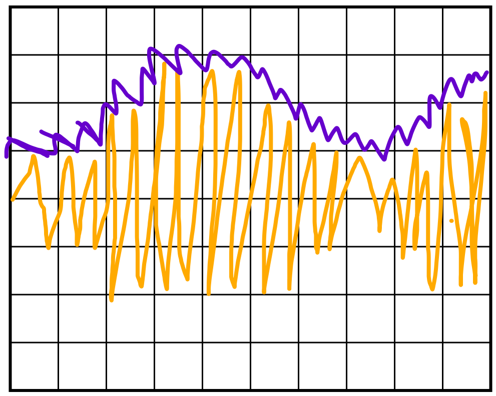
- In "Signal Generator" module, select "math"
  - Set Record Length to be 25 ms and SampleRate to be 5 Msps
  - Set $f(t) = \cos(13000 * 2 * pi * t) * (\cos(880 * 2 * pi * t) + 2)$
  - Click "Run"
  - Go to Oscilloscope module, click "Single" (rather than "Run" as you used to do)

– Adjust the oscilloscope until the display resembles Figure Figure 6. You might have to click multiple times of "Single" to update the setting.

2.6 Envelope Detector Circuit (Demo Required)

With a simple modification to your *RC* circuit, you can create an envelope detector that will recover the message signal in the signal generator's AM signal. Change your circuit to match Figure 7b. Make sure you reconnect the function generator to the circuit, as indicated.

1. • Go to the Oscilloscope Module (____/2)
   • Set the Time Base to 100 μs
   • Click "Single"
   • Sketch the output



V/div : 1 Volt t/div : 1.5 Volts

2. Now, select the Time Base in the oscilloscope to 500 μs, and view the voltage across the capacitor on the oscilloscope. Describe the output of the Envelope Detector:

Describe the output. (____/2)

The output of the Envelope Detector shows a graph of the voltage over the capacitor that is almost sinusoidal, with a period of ~1.21 ms. The lowest voltage is 200 mV and the highest voltage is 2100 mV.

Use the Cursor tool to determine the frequency of the output : $f =$ 826 Hz . (____/2)

Is this the message signal (yes/no) ? f = (1/T) = 1/(1.21*10^-3) 826.446 Hz

Explain your reasoning (____/2)

This is a message signal because this graph approximates the lower frequency signal that is formed by the peaks of the sinusoid with a high frequency.

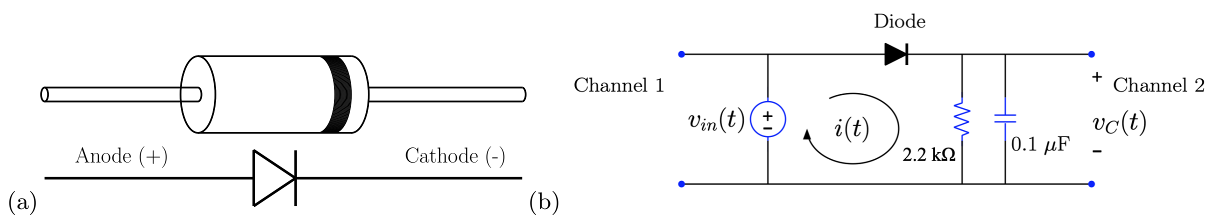


Figure 7: (a) Circuit symbol and physical diagram for a diode, and (b) an "envelope detector" circuit using a diode. For the Envelope detector we will use a **Germanium(Ge) diode** to take advantage of the low forward voltage drop (approximately 0.2 V) compared with that of silicon diodes (approximately 0.7 V).

3. The diode in the circuit will be conducting part of each cycle and non-conducting in the remainder — figure out how the capacitor voltage will vary when the diode is conducting and non-conducting.
When is the RC time constant in the circuit relevant — when the diode is conducting or not? (R is the $2\,\mathrm{k}\Omega$ resistor and C is the $0.1\,\mu\mathrm{F}$ capacitor.)

When is the RC time constant relevant?. Explain your reasoning.

The RC time constant is relevant when the diode is non-conducting, because when the diode is conducting, the resistor is not in series with the capacitor. Therefore, the time constant is only valid when the resistor has the same current as the capacitor.

(____/3)

Can you explain how the circuit works?

Explain how the circuit works:

The circuit works because the diode prevents the capacitor from experiencing a negative voltage. When the diode does allow current through the resistor, the resistance which "charges" the capacitor is negligible, so the voltage across the capacitor spikes almost to the magnitude of the voltage of the message signal, lasting only a short amount of time before the diode prevents current flow. When this happens, the capacitor resorts to discharging through the resistor, causing jagged edges in the voltage graph after being sent from the capacitor.

(____/3)

Also consider these questions:

(a) Is the envelope detector circuit linear or non-linear? (*Hint*: when inverting the input, does the output invert?)

Explain your reasoning

The envelope detector circuit is non-linear, as not being composed of solely linear elements causes non-linear behavior. When the input voltage is reversed, the signal over the capacitor does not follow suit, rather is remains positive.

(____/3)

(b) Recall that a capacitor is a charge-storage device. When you turn on your radio, the capacitor will store an unknown charge (i.e. the initial condition is $v_c(0^-) > 0$). Will it be necessary to account for this in the design of your AM receiver circuit? Explain your reasoning:

Why or why not?

Within reasonable charge and power considerations, it is not necessary to take into account this unknown charge as it will be continuously dissipated through the resistor. Therefore, the input voltage does not affect the steady state voltage.

(____/3)

The Next Step

Already you have come far: Your circuit can detect the message-containing envelope of an AM signal. In the next lab session, you will explore amplifier circuits. You will build an audio amplifier and connect your envelope detector to it so you can listen to the message signal you recovered in this session.