Lab 3: Capacitors and Time-Dependent Signals

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1 Time-dependent analysis of RC circuits

We measure the time constant of the RC circuit, first calculating the theoretical value, then comparing it to the experimental value. The resistance is $R = 997\,\Omega$ and the capacitance is $C = 73.5\,\text{nF}$, giving us a theoretical time constant of $\tau = RC = 73.3\,\mu\text{s}$. Our experimental value is found by observing the time it takes for the capacitor to reach $1/e$ of its total charge while discharging, and $1 - (1/e)$ of its total charge while charging. As seen in Figure **??**, the experimental value is $\tau = 62\,\mu\text{s}$.

The discrepancy is likely due to measurement uncertainties and tolerances in the component values. The experimental value is used in all further calculations in this lab.
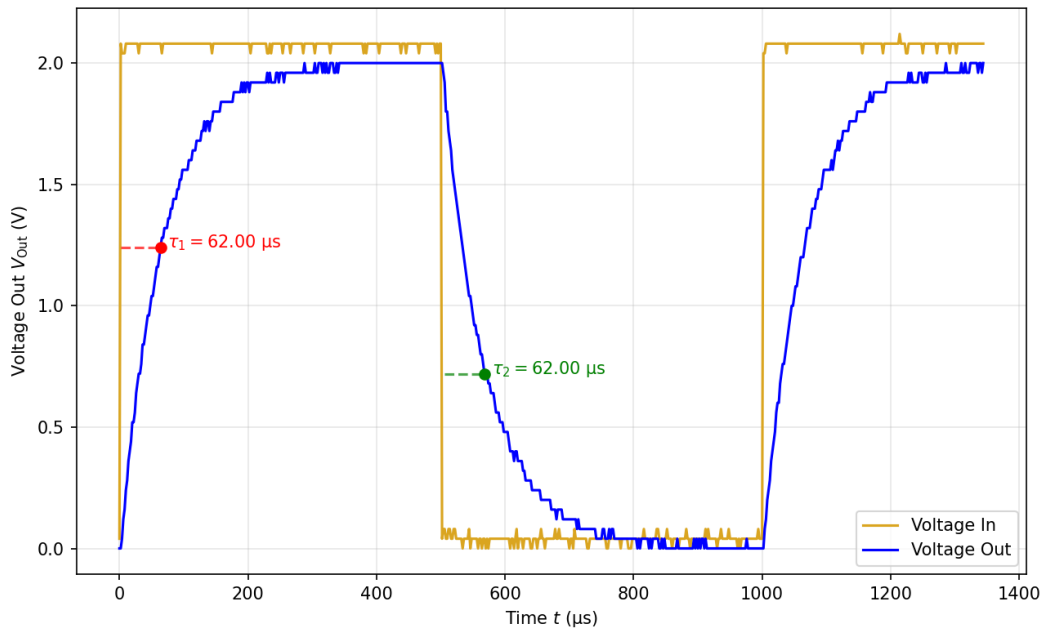

Figure 1: Measurement of time constant $\tau = RC$ by determining the time for the output to drop to $1/e$ of the maximum (in green) and to rise to $1 - (1/e)$ of the maximum (in red). Both values are equal to $\tau = 62\,\mu\text{s}$.

2 The RC Integrator (Low-Pass Filter)

We apply a $20\,\text{kHz}$ square-wave signal to the RC circuit to create a low-pass filter. The waveform, seen in Figure **??**, demonstrates the integrator behavior of this circuit. The graph of voltage out is the integral of the voltage in. We can model the input V_{in} as alternating lines of $y = \pm 1$, so the output integral V_{out} is simply $\pm \int 1\, dx = \pm x + C$, creating the triangle wave pattern of the output voltage.
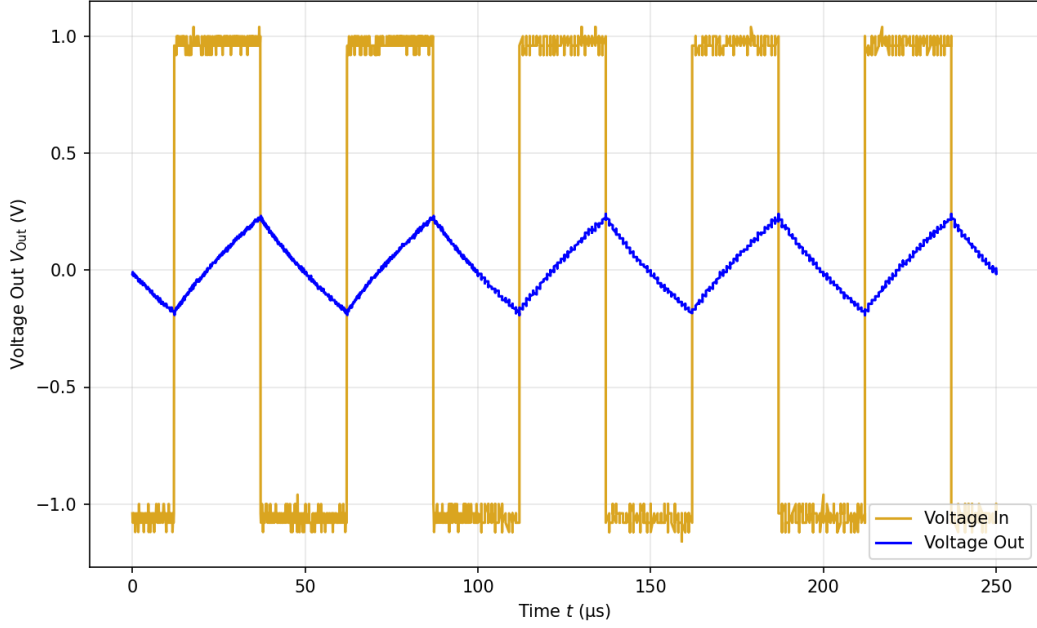
Figure 2: RC integrator (low-pass filter): voltage vs time (20 kHz square input).

In Figure **??**, we see the result of applying a $200\,\mathrm{kHz}$ triangle wave input to the low-pass filter. The triangle wave input V_{in} can be modeled as alternating curves of $y = \pm mx$. The integral of the input voltage is now $\pm \int mx\,dx = \pm \frac{1}{2}mx^2 + C$, with a concave-up parabola when the input is increasing, and a concave-down parabola when the input is decreasing.

This circuit is called a low-pass filter because it allows frequencies below the cutoff frequency to pass relatively unchanged, while applying the integrator behavior to the high frequencies and greatly reducing signal strength. This behavior is most evident in Figure **??**, where we can graph V_{out} at a frequency of $f = 20\,\mathrm{kHz}$ without any scaling. As we approach the $200\,\mathrm{kHz}$ frequency range, the output is so small that we need to scale it $10\times$ to be noticeable at all.
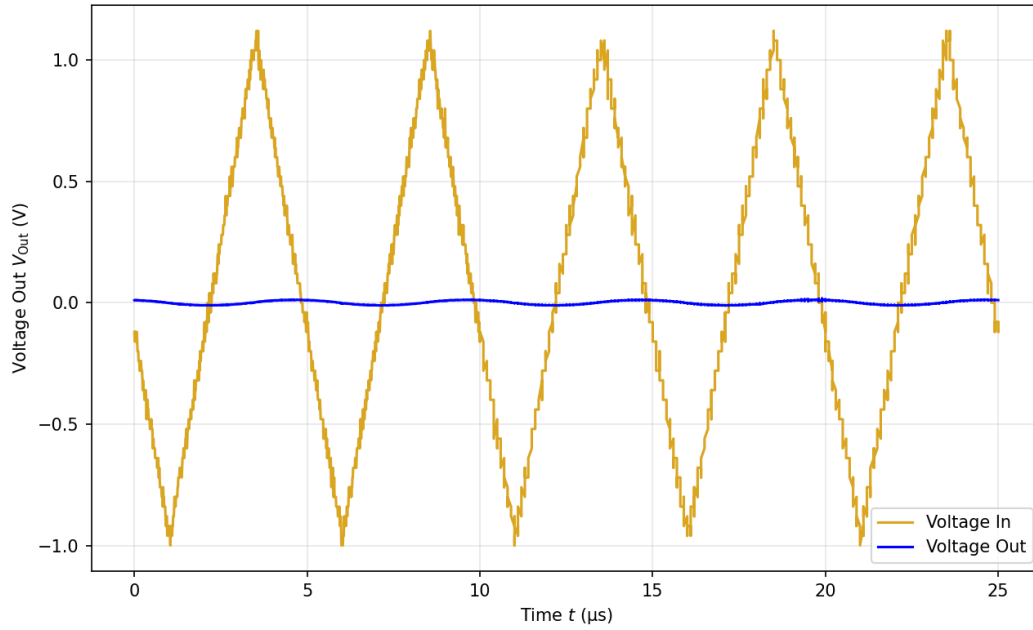
Figure 3: RC integrator (low-pass filter): voltage vs time (200 kHz triangle input). Most of the signal is filtered out due to the high input frequency, so the output voltage is scaled by a factor of 10 to make the integrator behavior more obvious.

3   The CR Differentiator (High-Pass Filter)

We apply a 510 Hz square-wave signal to the CR circuit to create a high-pass filter. This circuit is called a high-pass filter because it allows frequencies above the cutoff frequency to pass relatively unchanged, while applying the differentiator behavior to the low frequencies.
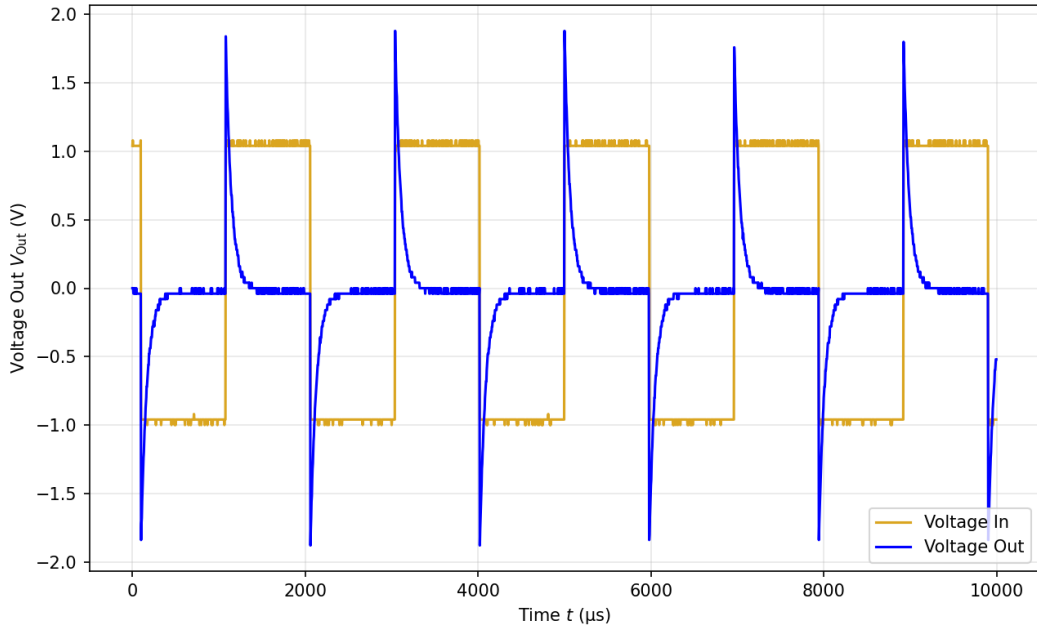
Figure 4: High-pass filter: voltage vs time (510 Hz square input).

The waveform, seen in Figure **??**, demonstrates the differentiator behavior of this circuit. The graph of voltage out is the derivative of the voltage in. We can model the input V_{in} as the alternating step function $y = \pm\Theta(x)$, so the output derivative is $\pm\frac{d}{dx}\Theta(x) = \pm\delta(x)$, the Dirac delta function, creating the spiking pattern of the output voltage.
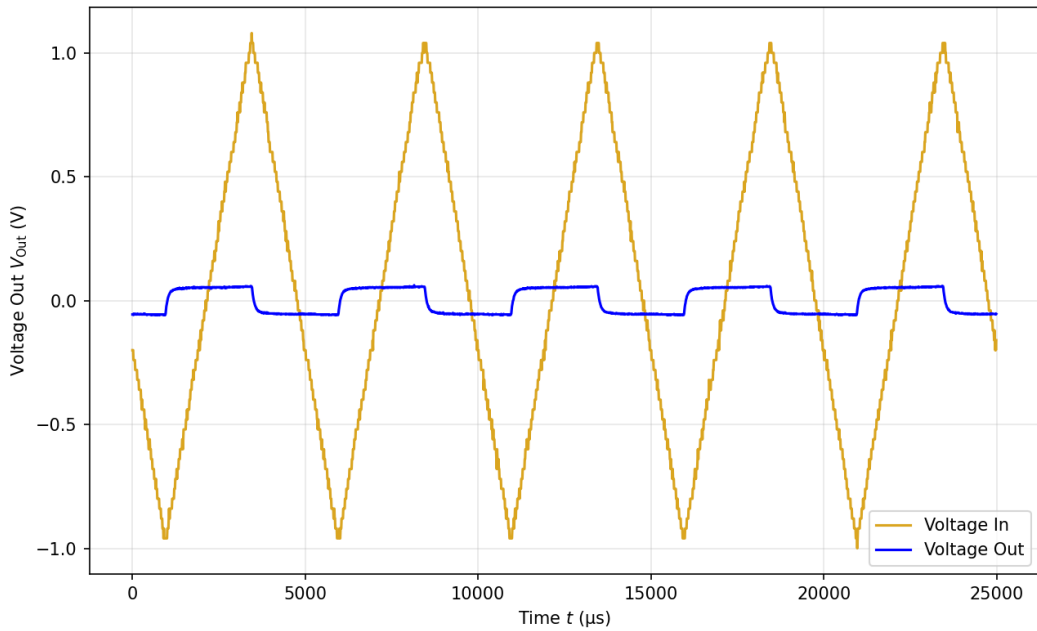

Figure 5: CR differentiator (high-pass filter): voltage vs time (200 Hz triangle input).

Likewise, in Figure **??**, we can model the triangle wave input V_{in} as alternating curves of $y = \pm mx$. The output derivative is $\pm\frac{d}{dx}mx = \pm m$, approaching a square wave pattern. As we approach lower frequencies, we lose signal

strength, so the data becomes increasingly noisy. For higher frequencies in the $100\,\mathrm{kHz}$–$1\,\mathrm{MHz}$ range, the output and input would closely resemble one another, and the differentiator behavior would be absent.

4 Frequency response of both low-pass and high-pass filters

We explored the frequency dependence of each filter's response to a sine wave input by varying frequency from $1\,\mathrm{Hz}$ to $1\,\mathrm{MHz}$ and measuring the amplitude and phase of the output V_{out} relative to the input V_{in}.
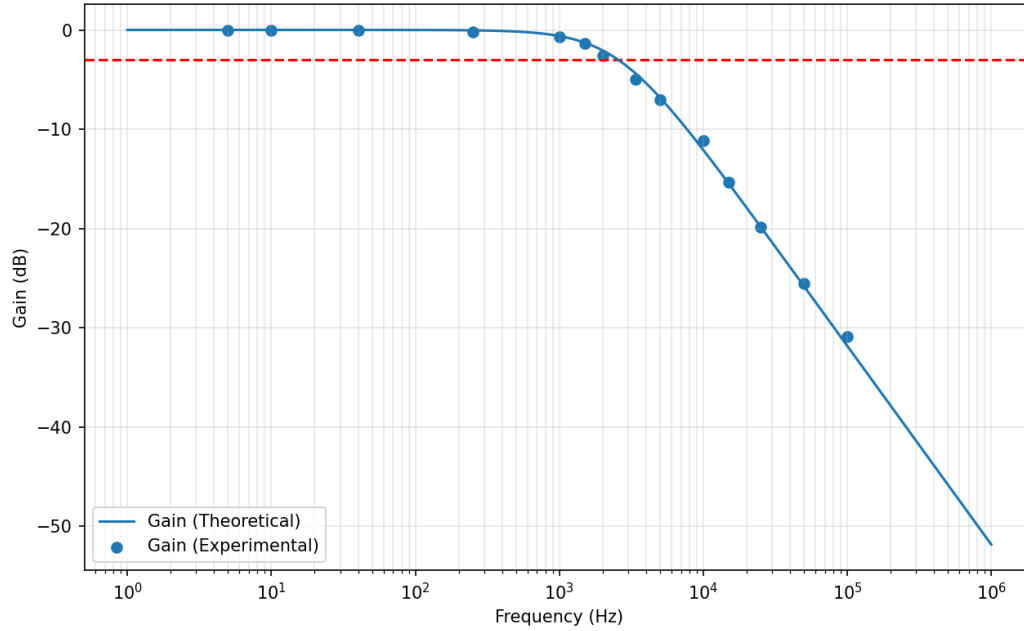

Figure 6: Low-pass filter: Bode plot. The blue vertical line marks the experimental cutoff $f_{c,\mathrm{exp}}$.
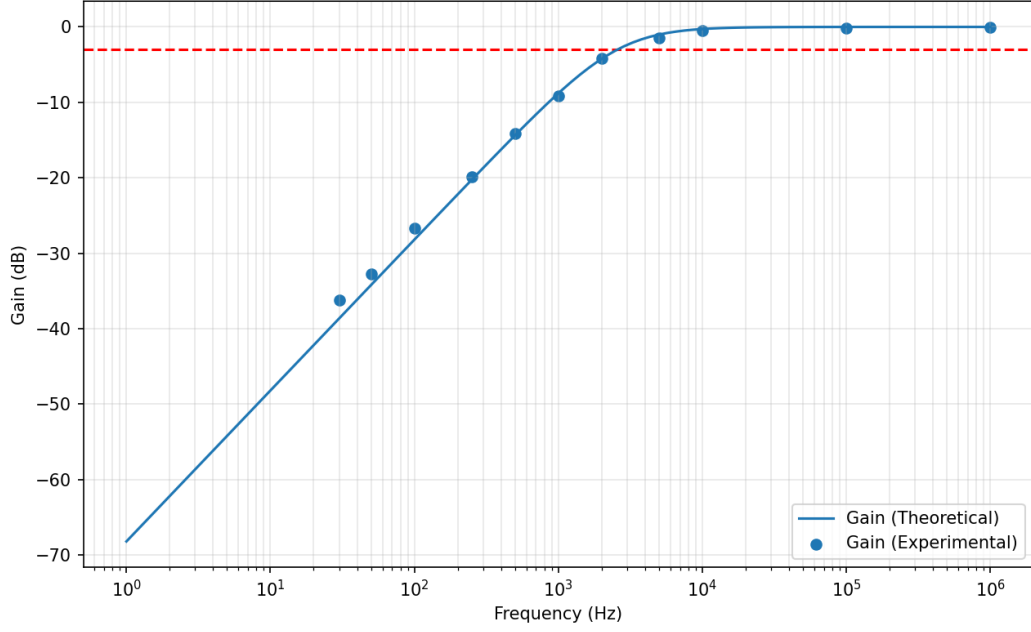
Figure 7: High-pass filter: Bode plot. The blue vertical line marks the experimental cutoff $f_{c,\mathrm{exp}}$.

We determined the transmission function $A(\nu)$ by dividing the output amplitude by the input amplitude at each frequency. The input amplitude was measured peak-to-peak from the function generator at each frequency to account for changes due to the circuit and generator limitations. For each filter we plotted the data together with the theoretical curves. The amplitude is presented on a Bode plot with the decibel scale $20 \log_{10} A(\nu)$ on the vertical axis and $\log \nu$ on the horizontal axis, as shown in Figures ?? and ??.
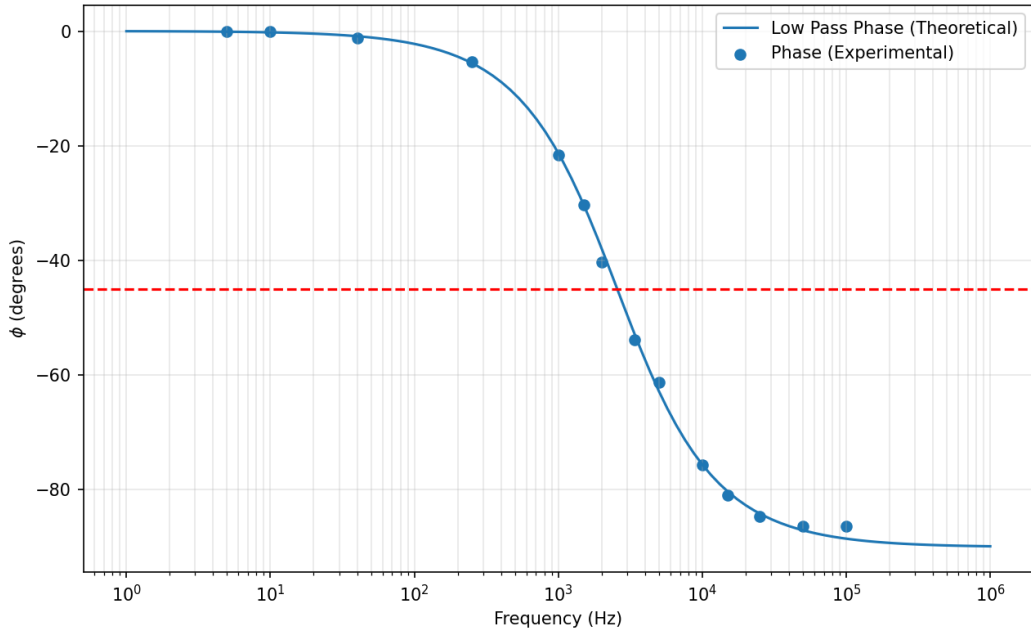

Figure 8: Low-pass filter: phase plot. The blue vertical line marks $f_{c,\mathrm{exp}}$.

The phase difference $\phi(\nu)$ between output and input was measured using the cursor function on the oscilloscope

to measure the time difference between the peaks of the input and output waveforms. A phase lag (output peak after the input peak) corresponds to a negative phase. The experimental phase is calculated with the formula $\phi_{\text{exp}} = 2\pi t/T = 2\pi t f$. The theoretical phase curve is given by $\phi_{\text{theoretical}} = \pm\arctan(2\pi f/\omega_c)$.

The experimental characteristic frequency $f_{c,\text{exp}}$ is obtained by linear extrapolation in $\log f$ from the data point closest to the $-3\,\text{dB}$ point on the Bode plot or the $45°$ point on the phase plot; the blue vertical line on each figure marks this extrapolated value. Slight discrepancies between $f_{c,\text{exp}}$ and the theoretical f_c are expected due to the sensitive nature of the log scale; despite that, the measured phase and amplitude data fit the theoretical curves well.