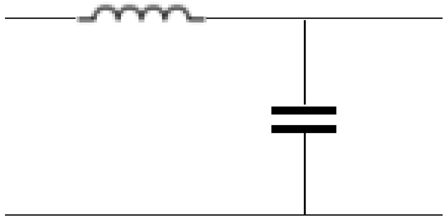
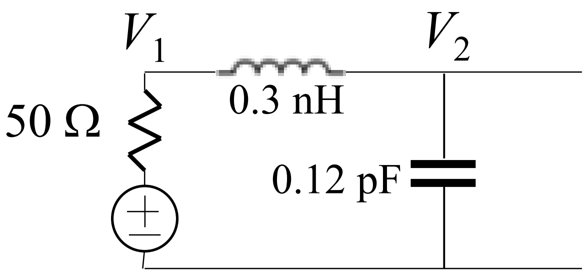
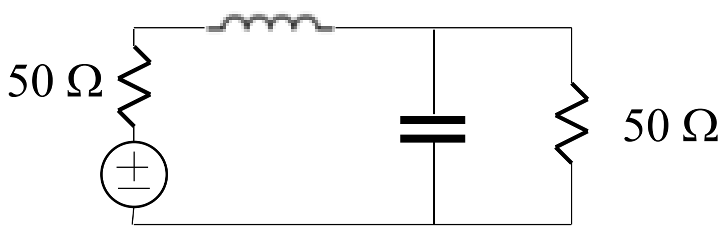
Project

Circuit simulations to transition you from lumped element-based circuit theory



Part 1





Generator: 1 V step, rise time = 0.1 ns. Internal impedance 50 Ω.

Plot the two voltages V_1 and V_2 for the above two cases.

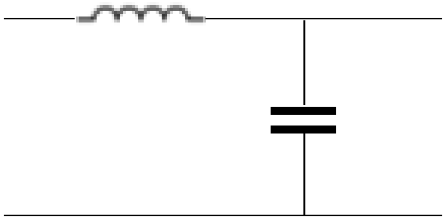
Hint: You may make mistakes. Do a sanity check by a "back of an envelope" analysis.
At the very least, find out the steady state.
Does the simulation give you more or less what you expect?

Ongoing project. Stay tuned for next steps.

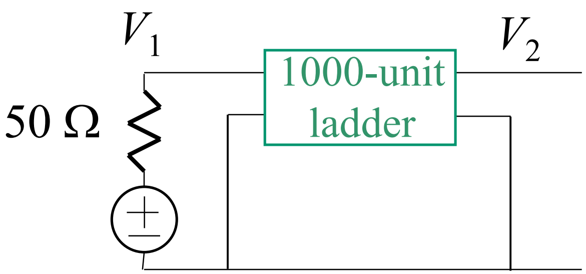
Project

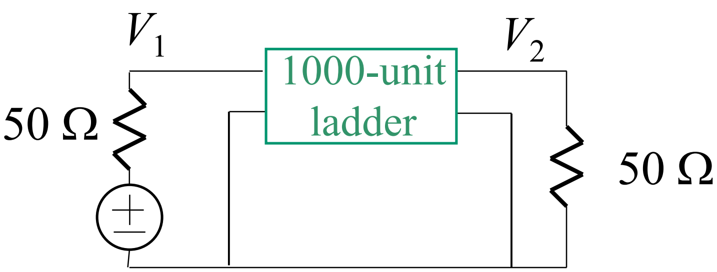
A circuit simulation project to transition you from lumped component-based circuit theory

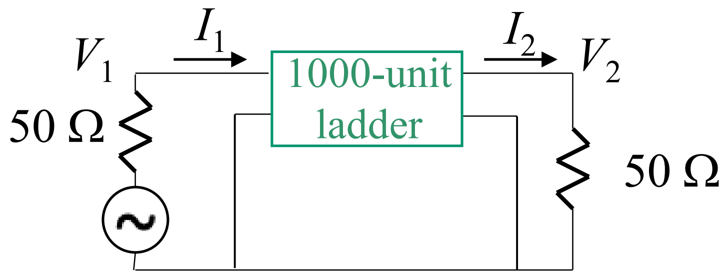
In Part 1, you built an LC network: ☞



Part 2: Now, create a new network that is a cascade of 1000 instances of the above LC network. You may create a symbol for this new network for convenience. Using the same inductance and capacitance values to do the same simulations you have done for the above single LC network. (Same generators with same internal impedance and same rise time. Simulate for both open circuit and 50-ohm loads, as done for the single LC.)







Part 3: Consider the circuit above, with a cascade of 1000 LC units, where L = 0.3 nH and C = 0.12 pF). You did a transient simulation of this ladder in **Part 2**. Now, do an AC (frequency-domain) simulation and plot the following: $\left|\frac{\tilde{V}_2}{\tilde{V}_1}\right|$, phase of $\frac{\tilde{V}_2}{\tilde{V}_1}$, $\left|\frac{\tilde{V}_1}{\tilde{I}_1}\right|$, and phase of $\frac{\tilde{V}_1}{\tilde{I}_1}$, against frequency f (or $\omega = 2\pi f$, if you want to convert). Use linear scales. For the magnitude ratios, do not use dB (which put the ratios on the log scale). For the phases, make it clear whether you use degree or radian as the unit. **Hint**: Since you are plotting on linear scales, you should choose frequencies with equal intervals (i.e., on a linear scale). Simulate up to f = 100 GHz is sufficient.

Let $\Delta\varphi$ be the phase of $\frac{\tilde{V}_2}{\tilde{V}_1}$. Plot $\frac{\mathrm{d}}{\mathrm{d}f}\Delta\varphi$ or $\frac{\mathrm{d}}{\mathrm{d}\omega}\Delta\varphi$ against frequency f (or $\omega = 2\pi f$).

Hint: The simulation results will not be as "neat" as you might be used to or expected from simple circuits. You may want to generate more than one plot for each quantity to show details (i.e. to "zoom in").

Explain the physical meaning of the quantities plotted above.

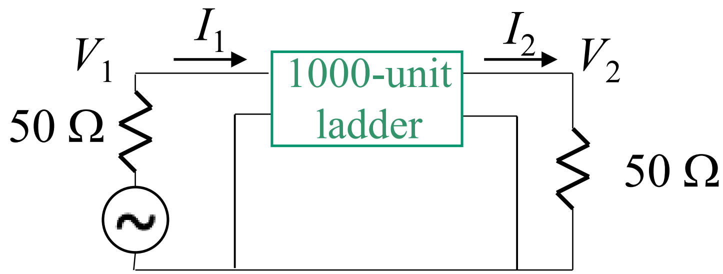
Additional Hint: If $\Delta\varphi$ as a function of f is oscillatory, so is $\frac{\mathrm{d}}{\mathrm{d}f}\Delta\varphi$. In this case, you may want to graphically get the trend of $\frac{\mathrm{d}}{\mathrm{d}f}\Delta\varphi$ vs f.

Part 3 cont'd

Up to this point, you may submit your simulation results as an optional preliminary report. The TAs will check it to make sure you have done the simulations correctly thus far.

For your interest: Such a cascade is often called an "artificial transmission line" or simply an "artificial line", which is used to delay a signal. To better understand it, you may search for information using these key words. T. H. Lee's book, *The Design of CMOS Radio-Frequency Integrated Circuits* has a good discussion. UT Library has it; you may also borrow it from me.

Ongoing project. Stay tuned for next steps.



Part 4: Refine your results obtained in **Part 3**. Plot $\left|\frac{\tilde{V}_2}{\tilde{V}_1}\right|$, phase of $\frac{\tilde{V}_2}{\tilde{V}_1}$, $\left|\frac{\tilde{V}_1}{\tilde{I}_1}\right|$, and phase of $\frac{\tilde{V}_1}{\tilde{I}_1}$, against frequency f in the following range (on the linear scale):

- 0 to 100 MHz (step size 5 MHz or finer)
- 0 to 1 GHz (set your step size accordingly)
- 0 to 10 GHz
- 0 to 100 GHz

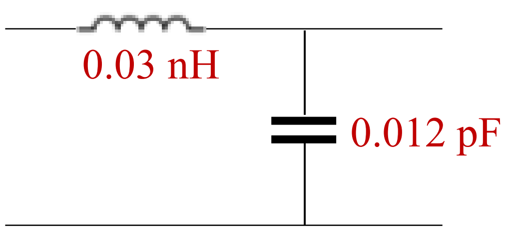
Let $\Delta\varphi$ be the phase of $\frac{\tilde{V}_2}{\tilde{V}_1}$. Plot $\frac{\mathrm{d}}{\mathrm{d}f}\Delta\varphi$ or $\frac{\mathrm{d}}{\mathrm{d}\omega}\Delta\varphi$ against frequency f (or $\omega = 2\pi f$) in the above range.

Hint: If $\Delta\varphi$ as a function of f is oscillatory, so is $\frac{\mathrm{d}}{\mathrm{d}f}\Delta\varphi$. In this case, you may want to graphically get the trend of $\frac{\mathrm{d}}{\mathrm{d}f}\Delta\varphi$ vs f.

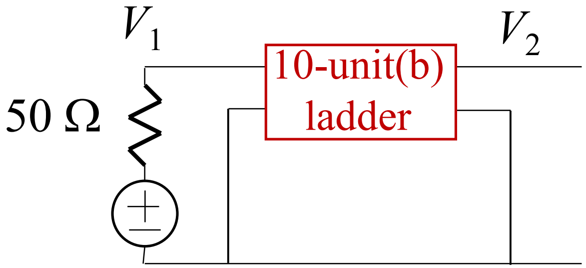
Explain the physical meaning of the quantities plotted above.

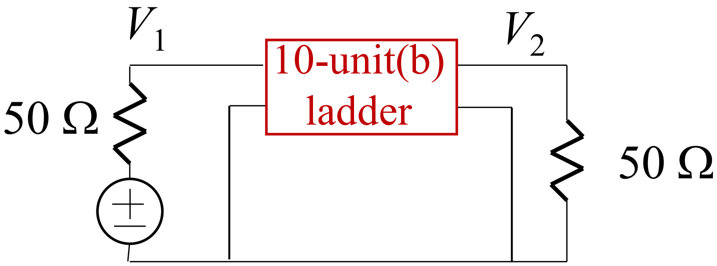
Additional Hint: Pay attention to the low frequency ranges, where the plots look "neater" thus better hint at the physical meanings.

Part 5: Build a new unit LC network but with $L = 0.03$ nH and $C = 0.012$ pF. Notice that these values are a tenth those in **Part 1**. To avoid confusion with the original unit network, I will refer to the new one as unit(b) hereafter.

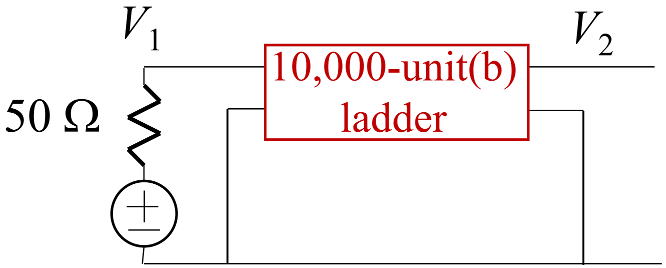


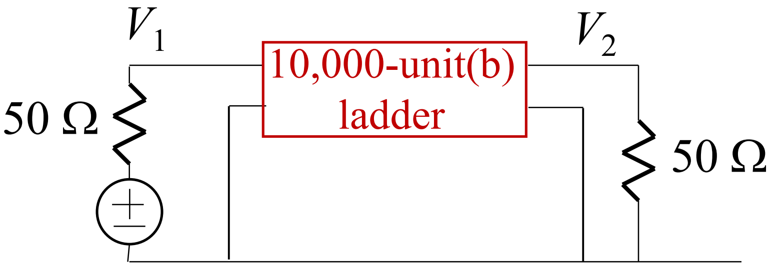
Build a cascade of 10 instances of unit(b), and run the same simulations as you did in **Part 1** for the original single unit.



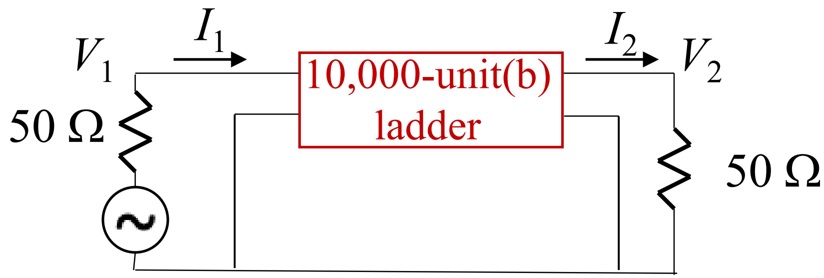


Build a 10,000-unit(b) ladder by cascading 1000 instances of the 10-unit(b) ladder. To make sure that you have built the long ladder correctly, you may run the simulations you did in **Part 2** for the original 1000-unit ladder. Examine the results and see if they make sense to you. If you do so, keep your results; we will revisit these simulations in a later part.



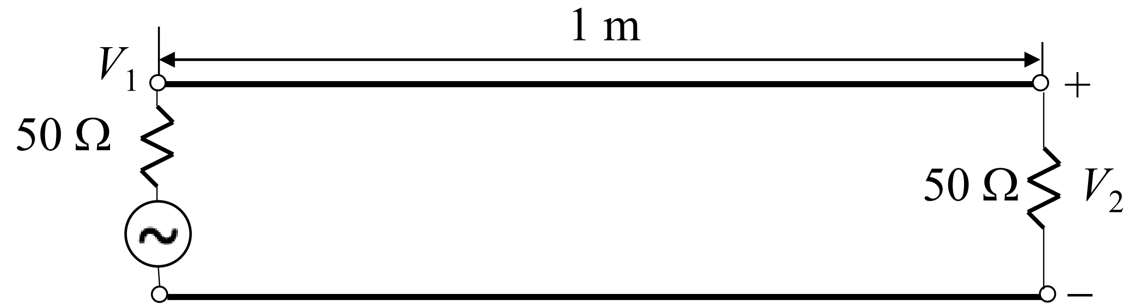


Part 5 cont'd



With the new 10,000-unit(b) ladder, run the same AC (frequency-domain) simulation as you did in **Parts 3 & 4** for the original 1000-unit ladder: The simulation is defined in **Part 3**. You are expected to refine your presentation of the results as you did in **Part 4**.

Note: This part is **not** to be done by simulation. **You** do the analysis.



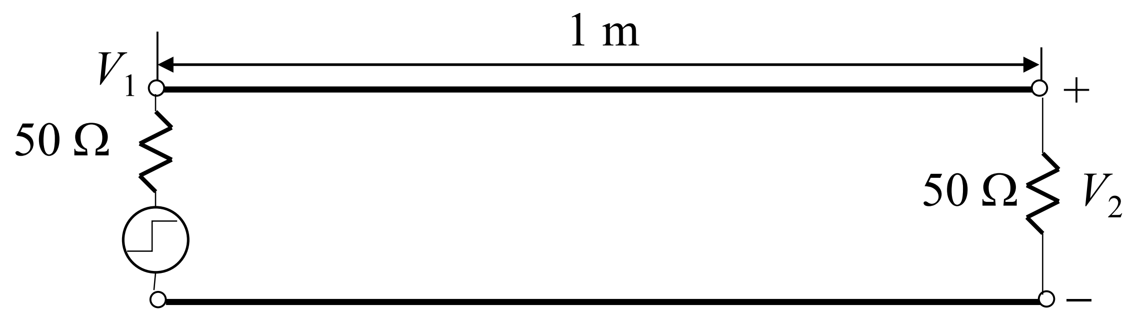
Part 6: A lossless transmission line system is shown as above. The transmission line parameters are as follows: Unit length inductance $L' = 0.3$ nH/mm, unit length capacitance $C' = 0.12$ pF/mm.

Calculate the characteristic impedance Z_0 of the line and the phase velocity v_p.

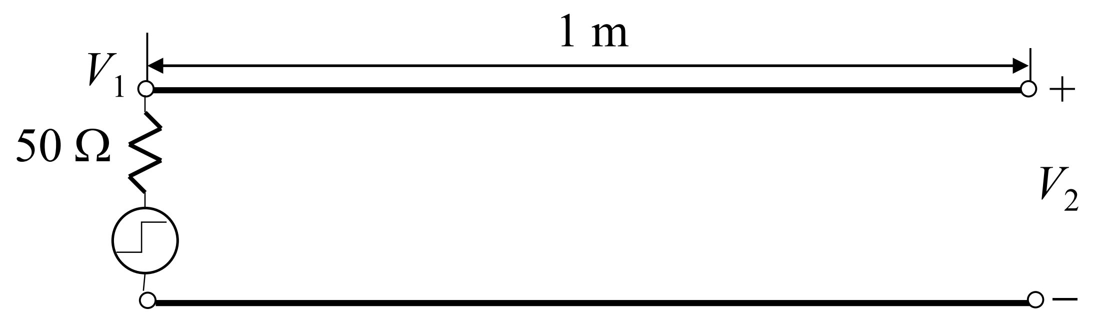
Schematically plot the following: $\left|\frac{\tilde{V}_2}{\tilde{V}_1}\right|$, phase of $\frac{\tilde{V}_2}{\tilde{V}_1}$, $\left|\frac{\tilde{V}_1}{\tilde{I}_1}\right|$, and phase of $\frac{\tilde{V}_1}{\tilde{I}_1}$, against frequency f (or $\omega = 2\pi f$, if you want to convert).

Think: How do you relate these plots to the simulations you have done? (Not a task in this part, but will be helpful to future parts.)

Note: This part is not to be done by simulation. You do the analysis.



Part 7: Transient analysis of the transmission line system in Part 6, with the generator signal replaced with an ideal step 1 V high.
Plot the waveforms of V_1 and V_2.



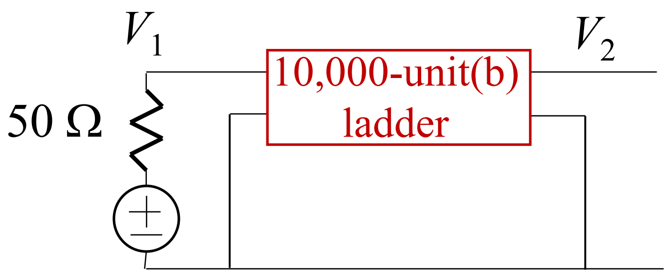
Now, the 50 Ω load is replaced with an open circuit.
Plot the waveforms of V_1 and V_2.
(You may construct a bounce diagram if needed.)

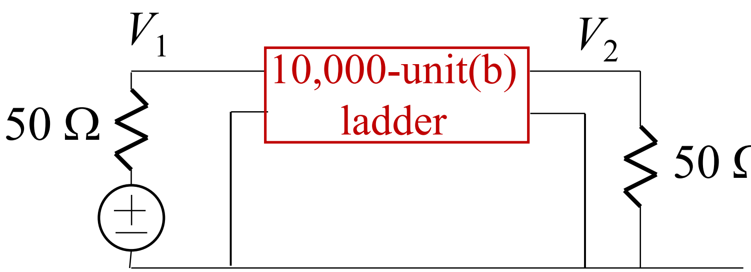
Think: How do you relate these waveforms to the simulations you have done? (Not a task in this part, but will be helpful to future parts.)

Part 8: Do the transient simulation of the 10,000-unit(b) ladder (L = 0.03 nH and C = 0.012 pF) as suggested **Part 5**, if you have not done that.

To think and to observe: Compare with the results of **Part 2**, keeping in mind that the new L and C values here are a factor of 10 smaller while there are 10 times more units. Look for similarities and differences.

Hint: To view details of your results for a good comparison, you may need to adjust the time scale of your plots (zoom in/out). You may display the same result in multiple plots on different scales if needed. You may want to re-plot your **Part 2** results.





In **Part 2** and **Part 3** (as well as **Part 4**), you simulated the 1000-unit ladder, with $L = 0.3$ nH and $C = 0.12$ pF in each unit.

In **Part 6** and **Part 7**, you analyzed a 1 m long ideal transmission line with $L' = 0.3$ nH/mm and $C' = 0.12$ pF/mm.

In **Part 5** and **Part 8**, you simulated the 10,000-unit(b) ladder, with $L = 0.03$ nH and $C = 0.012$ pF in each unit.

Part 9: Now, quantitatively compare the above 3 sets of results. What similarities do you observe? What differences do you observe?

How do you relate the similarities in transient results to the similarities in AC results?

How do you relate the differences in transient results to the differences in AC results?

How do you explain the observed differences? How do you relate your observations to the circuit model of the transmission line?

Conclude with **what you have learned in this project**.

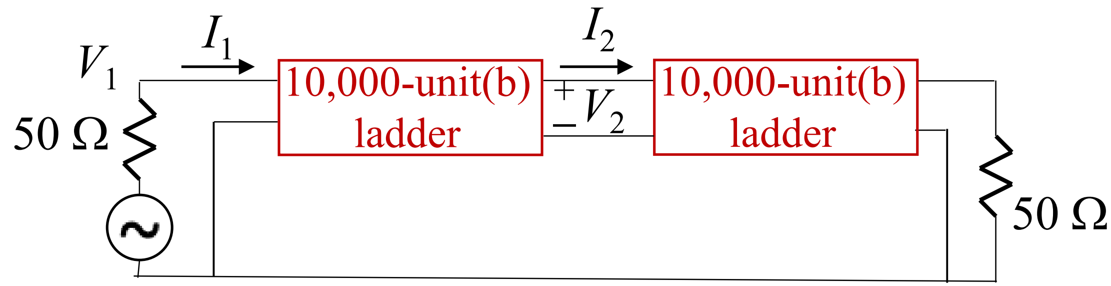
Hint: Extra simulations might be helpful in answering the above questions. For example, you may do the transient simulations with much longer and shorter rise time, say, 1 ns and 10 ps. Knowing the general trend in the the spectra of the step functions (with different rise times) may also be helpful. You may also want to plot the transient voltage waveforms and/or ac simulation results of the internal nodes of ladders (e.g. some nodes between adjacent 10-unit(b) ladder in the 10,000-unit(b) ladder).

Part 9 cont'd

Optional questions for bonus points

Do the following simulation with the circuit shown to the right:

1. AC simulation as you did in **Part 5** and,
2. Transient simulation as you did in **Part 8** for the circuit with the 50 Ω load.



Notice that this circuit just uses a second 10,000-unit(b) ladder as the load for the first one.

Compare the results with those you got in **Part 5** and **Part 8**. What similarities and differences do you observe? Discuss what you have learned from the observations.

What practical application can you come up with of the kind of long LC ladders as simulated in this project? For the practical application, you may use very different L and C values than in these simulations (maybe by orders of magnitude), and you may use as few as 10 to 100s of units.

What are the advantages of using such LC ladders compared with using a transmission line for the same purpose?

What are the limitations?

The End