Physics 160
Lecture 16

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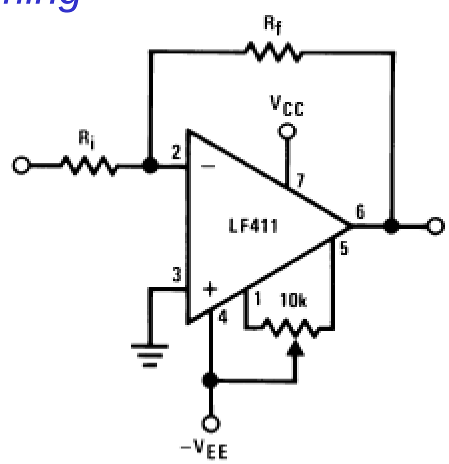
Behavior, Limitations of Real Op-amps

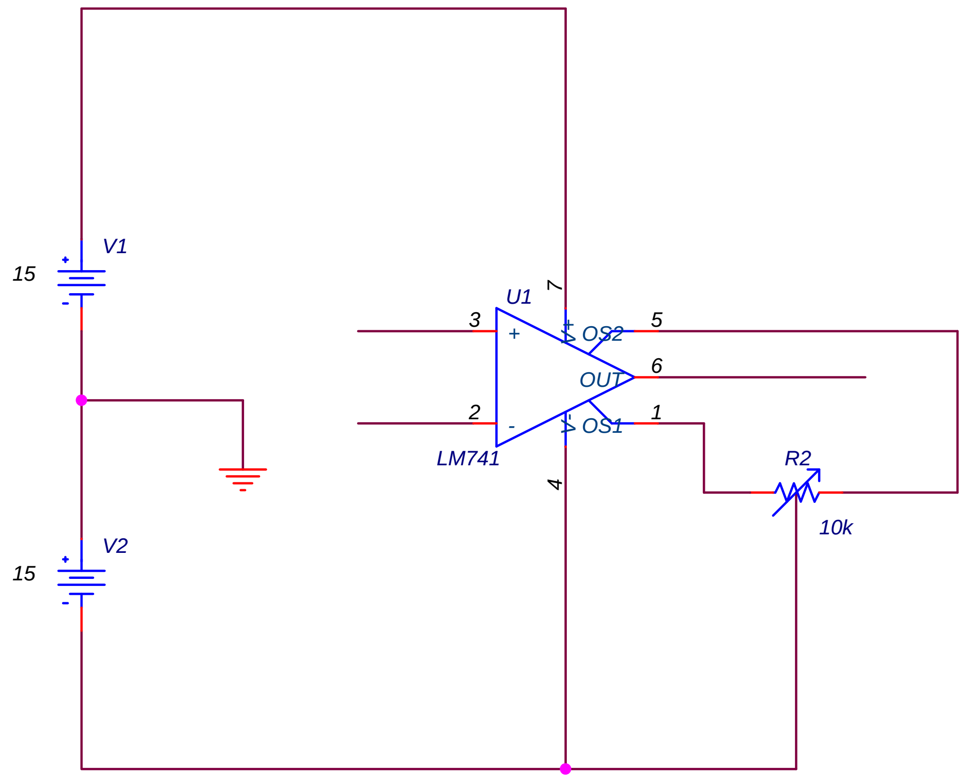
- *Input offset voltage*
- *Input current, and input-current mismatch*
  - *Design to minimize voltage offsets from this current*
  - *Input offset current*
- *Temperature dependences*
- *Slew rate*
  - *e.g. correcting crossover distortion*
- *Frequency range (gen. purpose op amps are not for high frequencies)*
- *Voltage gain and phase shift*
  - *Stability!*
- *CMRR and Common-mode input range*
- *Input impedance with negative feedback is extremely high*
- *Output impedance with negative feedback is very low*
  - *What is really relevant is the limitation on output current drive*
- *Output range (how close can the output get to the supply rails?)*
  - *Single-supply op amps; can the output slew all the way to zero?*

See the data sheet for the LF411 (posted on the course web page).

Offset Voltage and Input Current

- *Offset voltage*
  - *2 mV max. for the 411*
    - *This is the effective mismatch at the input. At the output it gets multiplied by the gain!*
  - *Trimming*



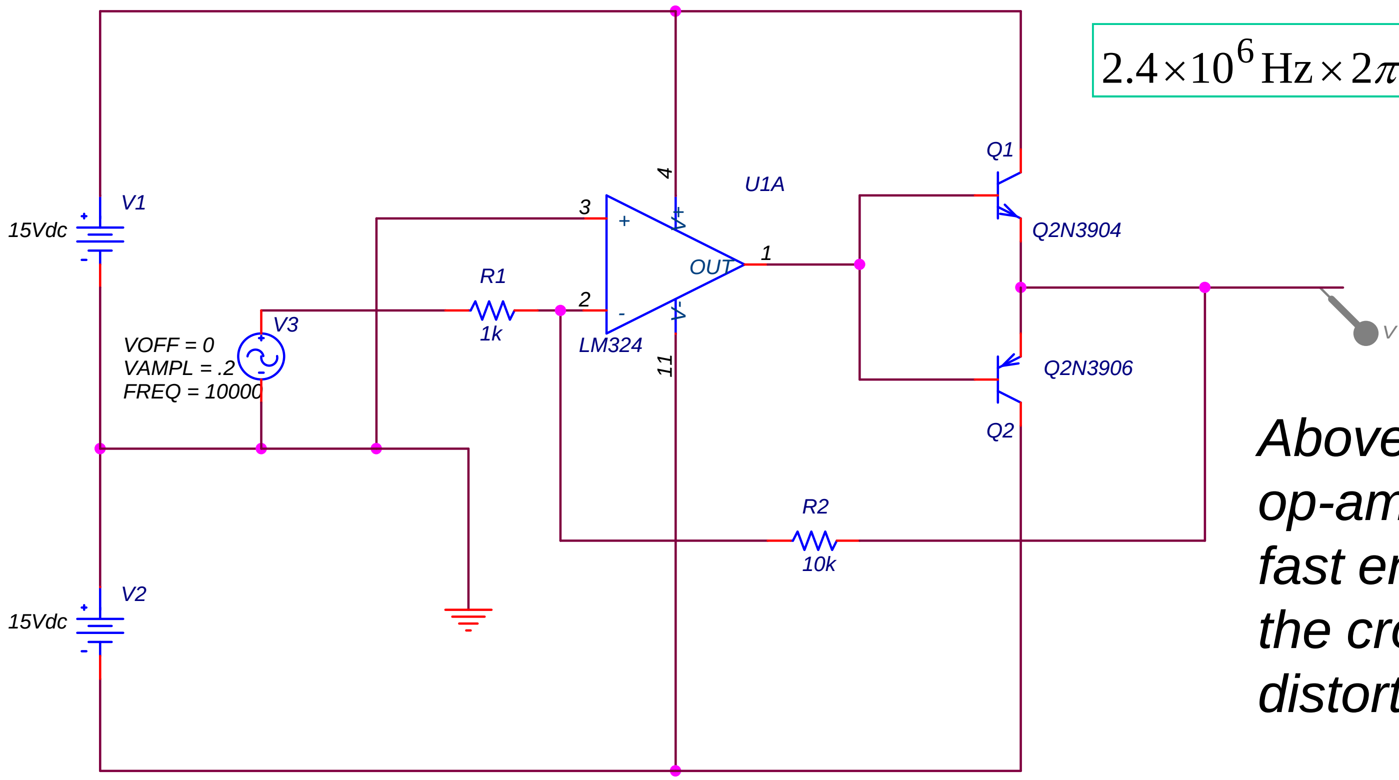


  - *Temperature and time drifts*
- *Input currents (esp. for BJTs)*
  - *Balancing resistors on inputs*
  - *Input offset current*
- *A/C Amp: reduce DC gain to unity to minimize offset effects*

Slew Rate

- *411 can slew outputs up to 15 V/μs with no capacitive load*
  - *For a 1 V sine wave output, for example, this limits the frequency to 2.4 MHz to avoid "harmonic" distortion.*
  - *Recall the limits on using an op-amp to cure crossover distortion*

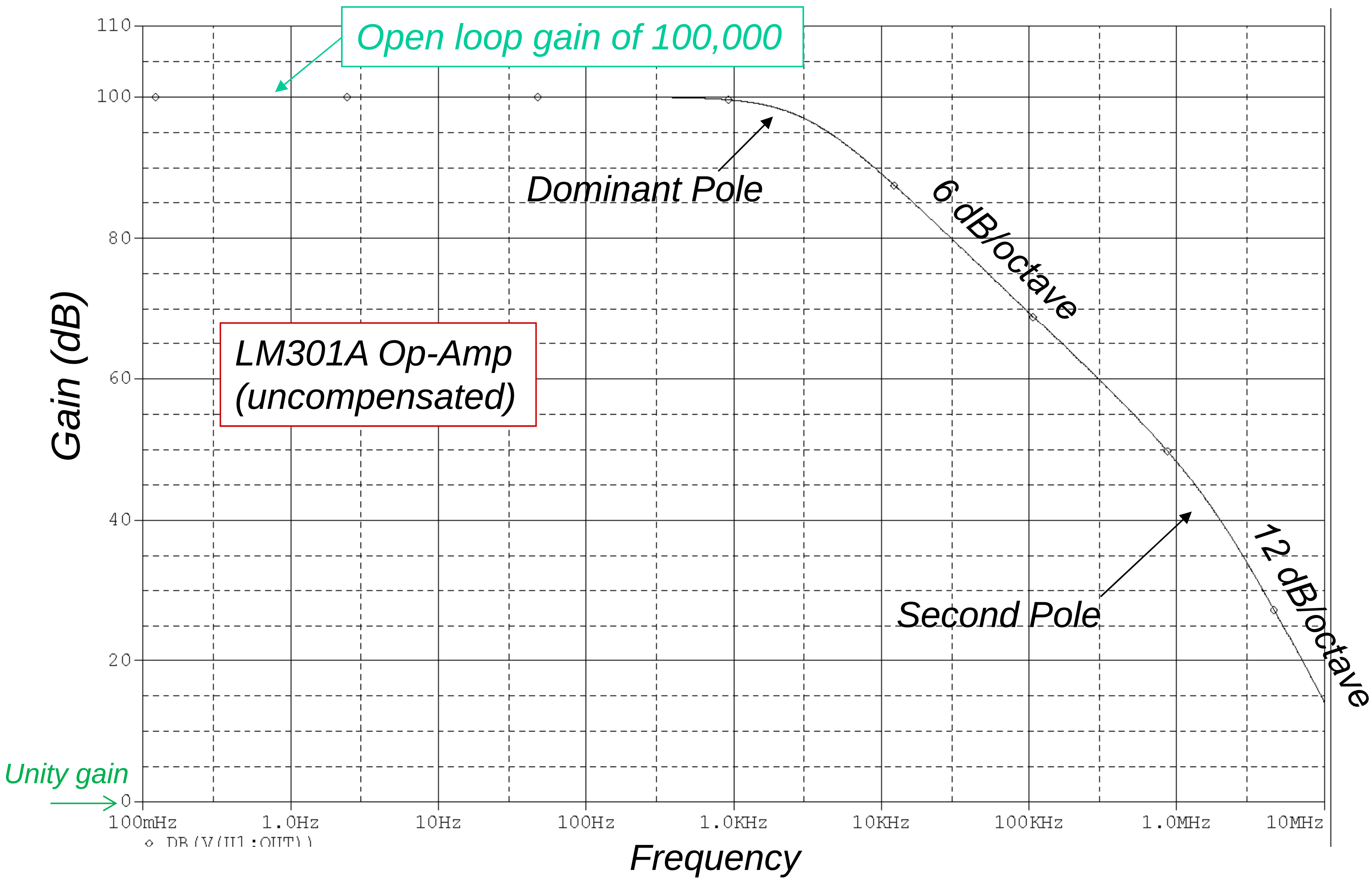
$$2.4\times10^{6}\,\mathrm{Hz}\times2\pi\times1\mathrm{V}=15\times10^{6}\ \mathrm{V/s}$$



Above ~100 Hz the op-amp cannot slew fast enough to cure the cross-over distortion.

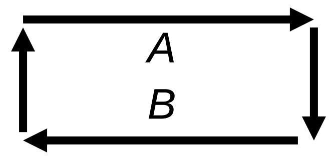
OP-AMP STABILITY

Gain and Phase Shift

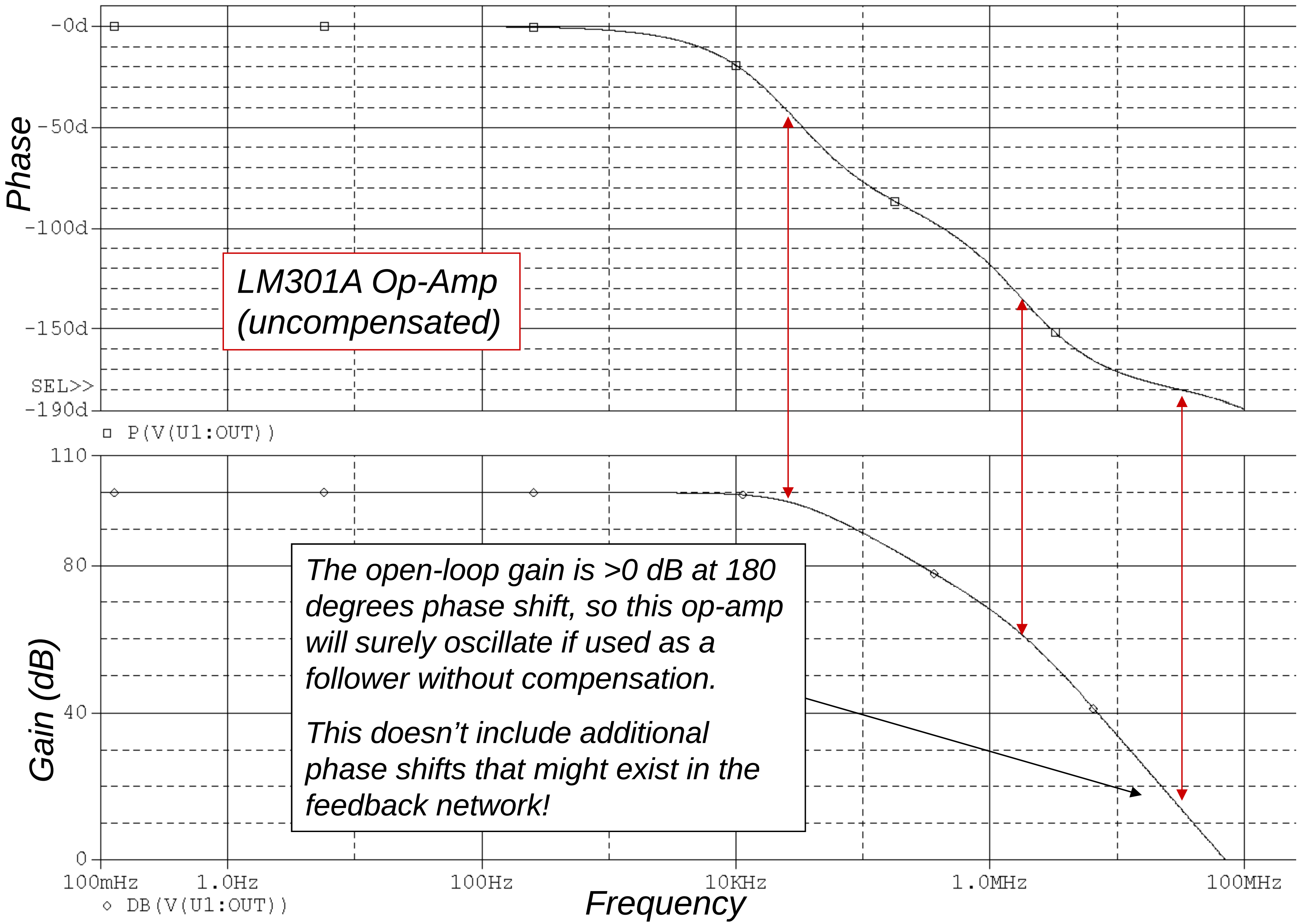


Stability Criterion

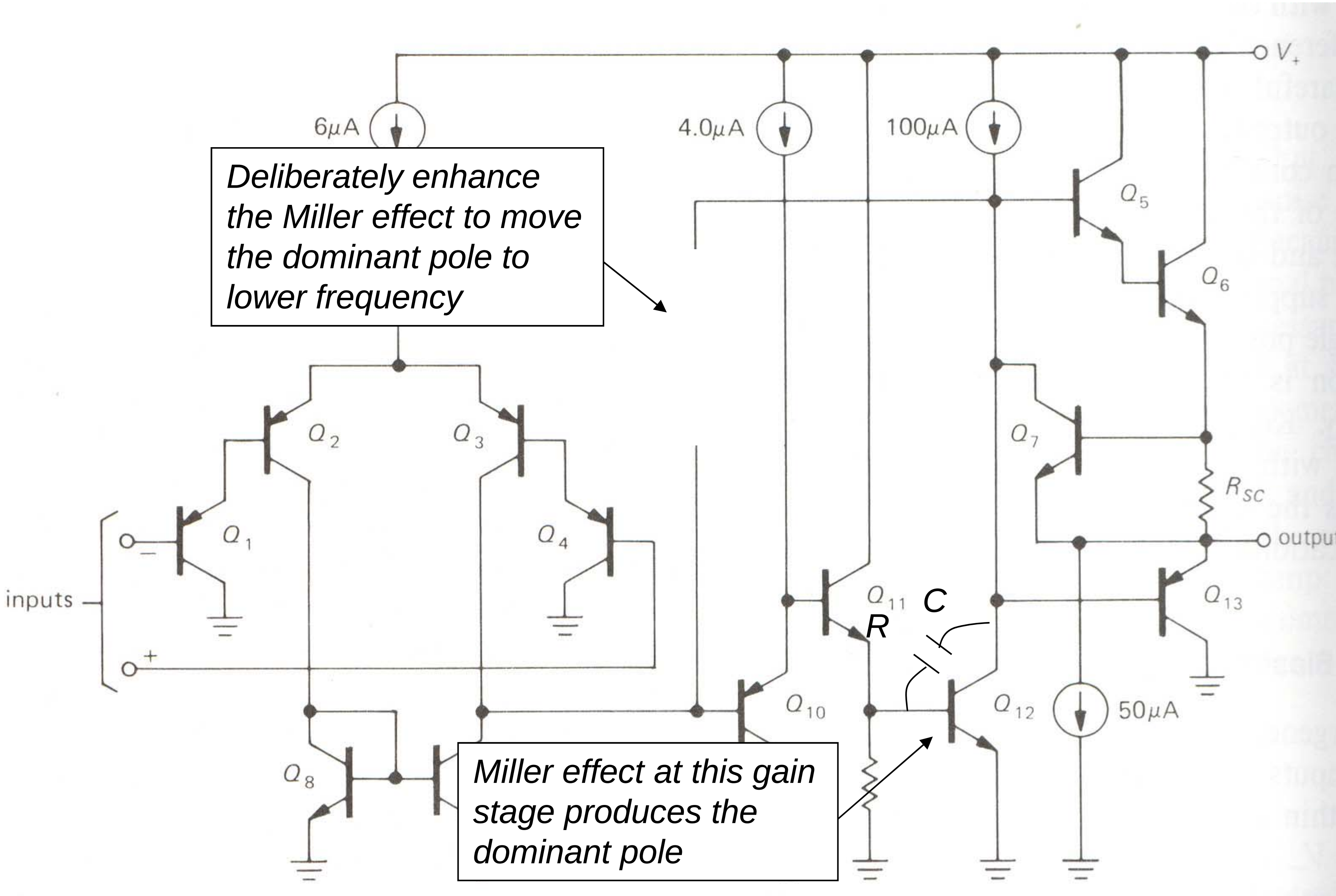
- *If the loop gain is >1 when the phase shift around the negative feedback loop hits 180 degrees, then the circuit will oscillate.*
  - *Your negative feedback becomes positive feedback at high frequency!*
  - *You probably won't see the oscillation in a PSpice transient simulation without doing extra work to introduce real-life effects, plus some stimulus to initiate the oscillation. Don't be fooled by trusting your computer simulation too much!*



- *Remember, the loop gain is AB, where A is the open-loop gain, and B is the gain of the negative feedback.*
  - *The follower has B=1, so that is usually the worst-case scenario for stability (inverting amp usually has B<1)*
    - *(A loop with B>1 is even more dangerous, hence the caution about putting a capacitor across the transistor in the log-amp feedback.)*

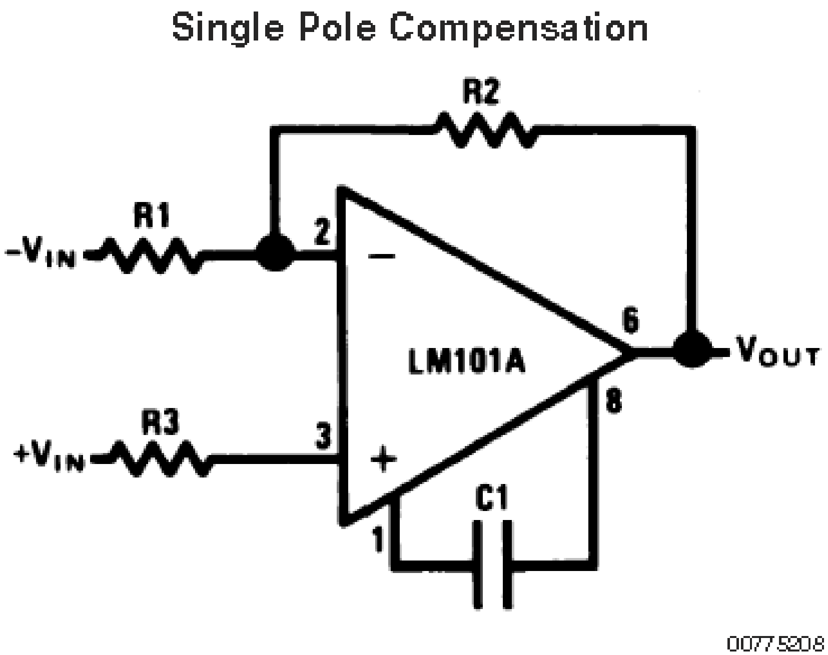

Phase
-0d
-50d
-100d
-150d
SEL>>
-190d
P(V(U1:OUT))
110
80
40
0
Gain (dB)
100mHz
1.0Hz
100Hz
10KHz
1.0MHz
100MHz
DB(V(U1:OUT))
Frequency
LM301A Op-Amp (uncompensated)
The open-loop gain is >0 dB at 180 degrees phase shift, so this op-amp will surely oscillate if used as a follower without compensation.
This doesn't include additional phase shifts that might exist in the feedback network!

Compensated Op-Amp



External Compensation

Advantage of external compensation: you don't need to compensate as much if B<1, so you can have higher frequency performance.

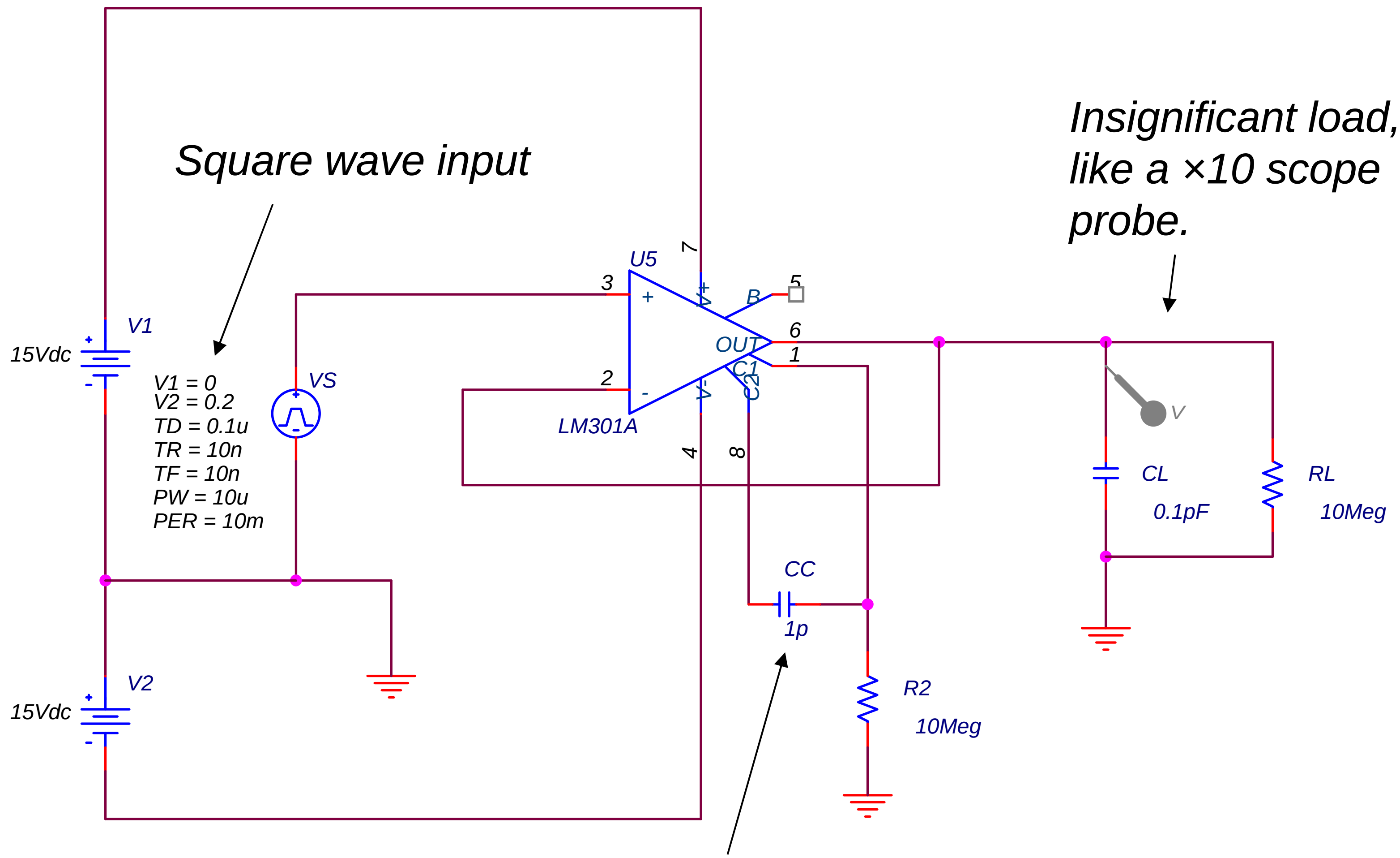


$$C1 \geq \frac{R1\, C_S}{R1 + R2}$$

Cs=30 pF

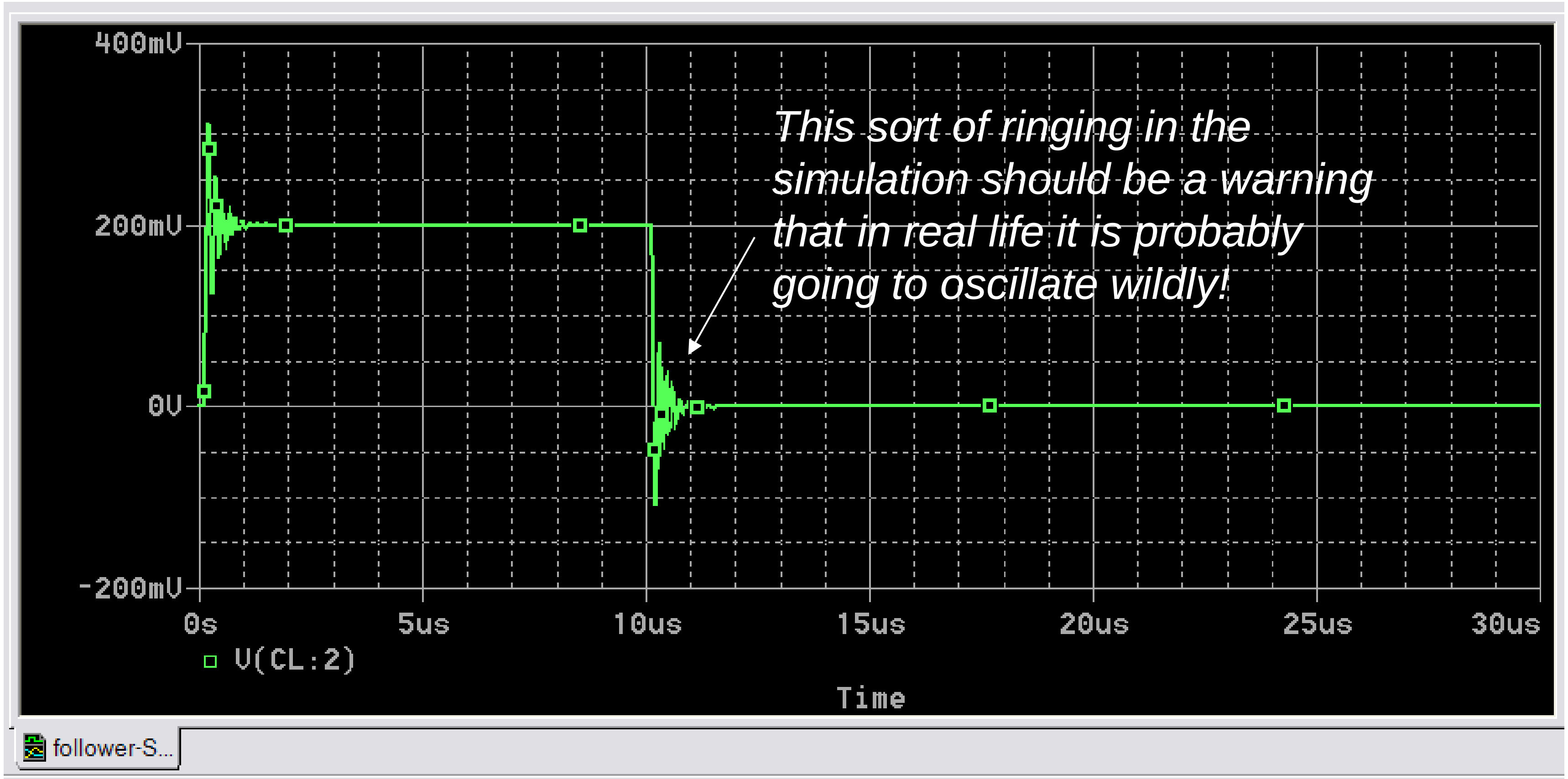
*According to this formula from the data sheet, to make a **follower**, with R1>>R2, C1 needs to be at least equal to Cs.*

Simulation of Follower Instability

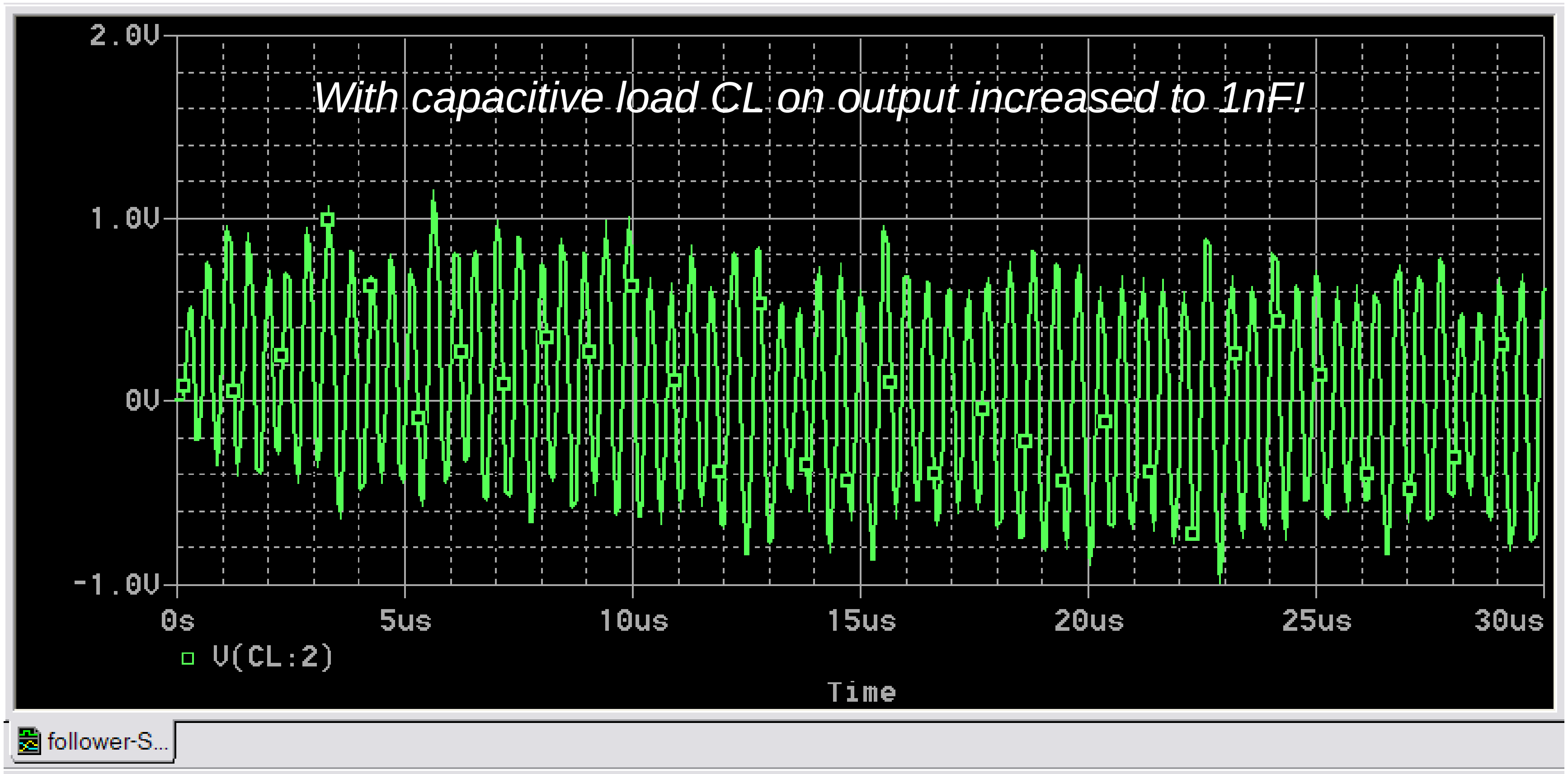


Should be 30pF for compensation at unity gain (B=1).

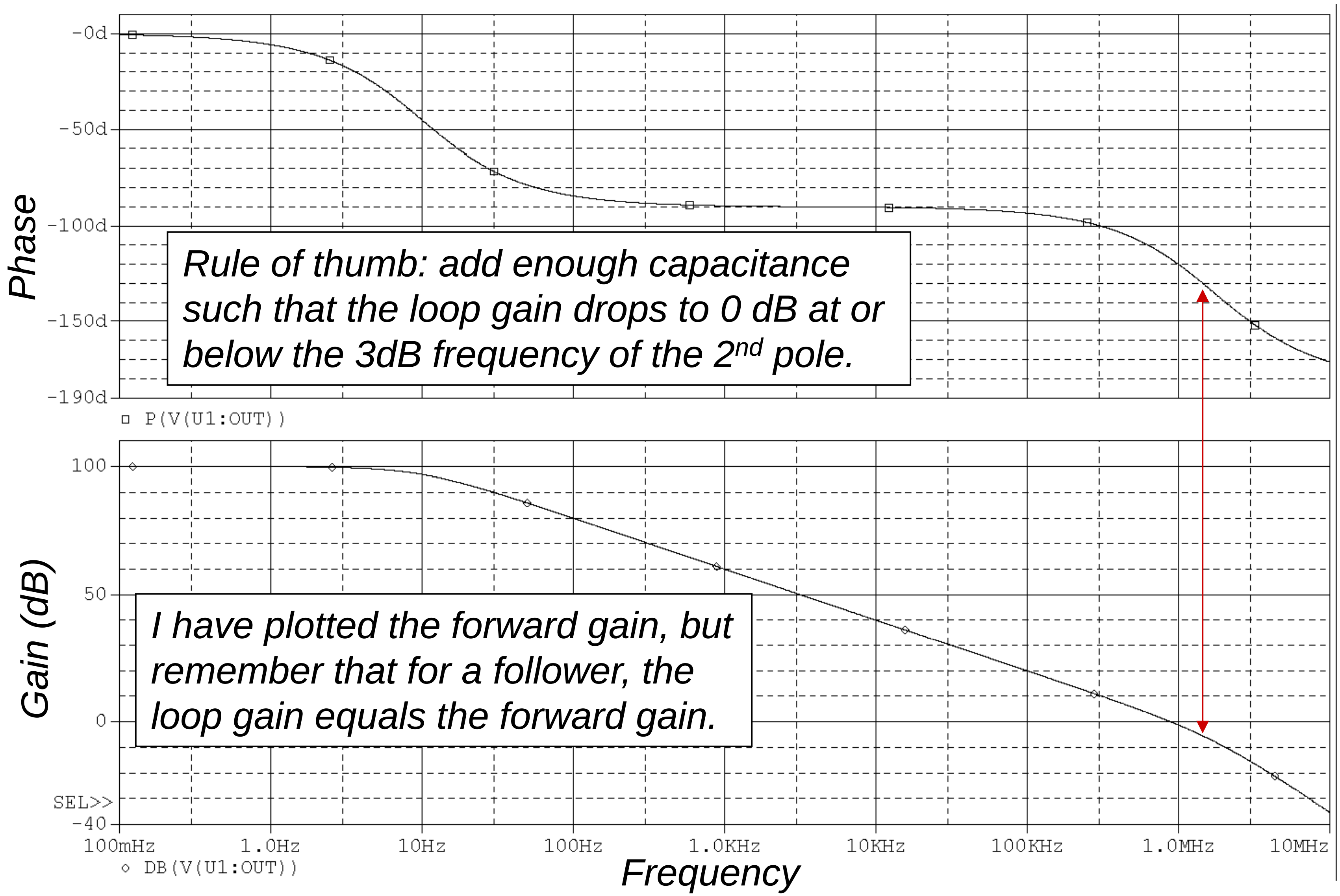
Simulation of Follower Instability



Simulation of Follower Instability



LM301a with 30pF Single-Pole Compensation



Finite Gain Effects and Bandwidth

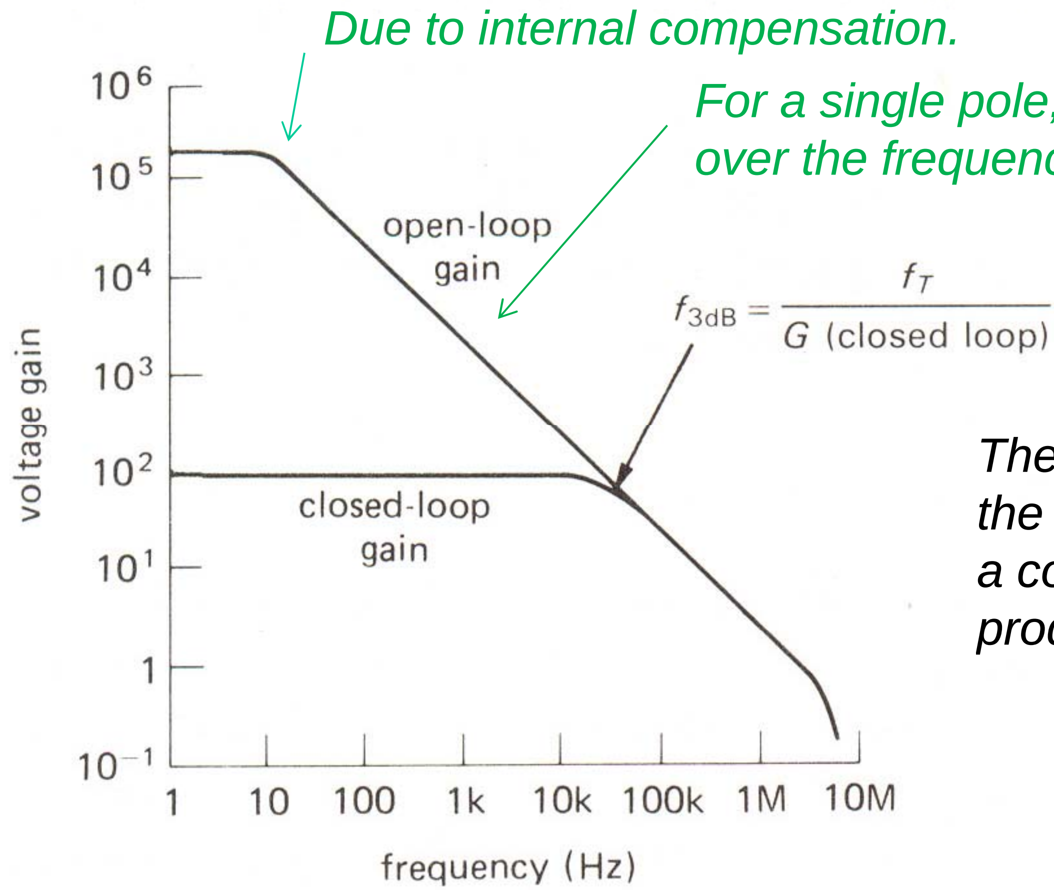
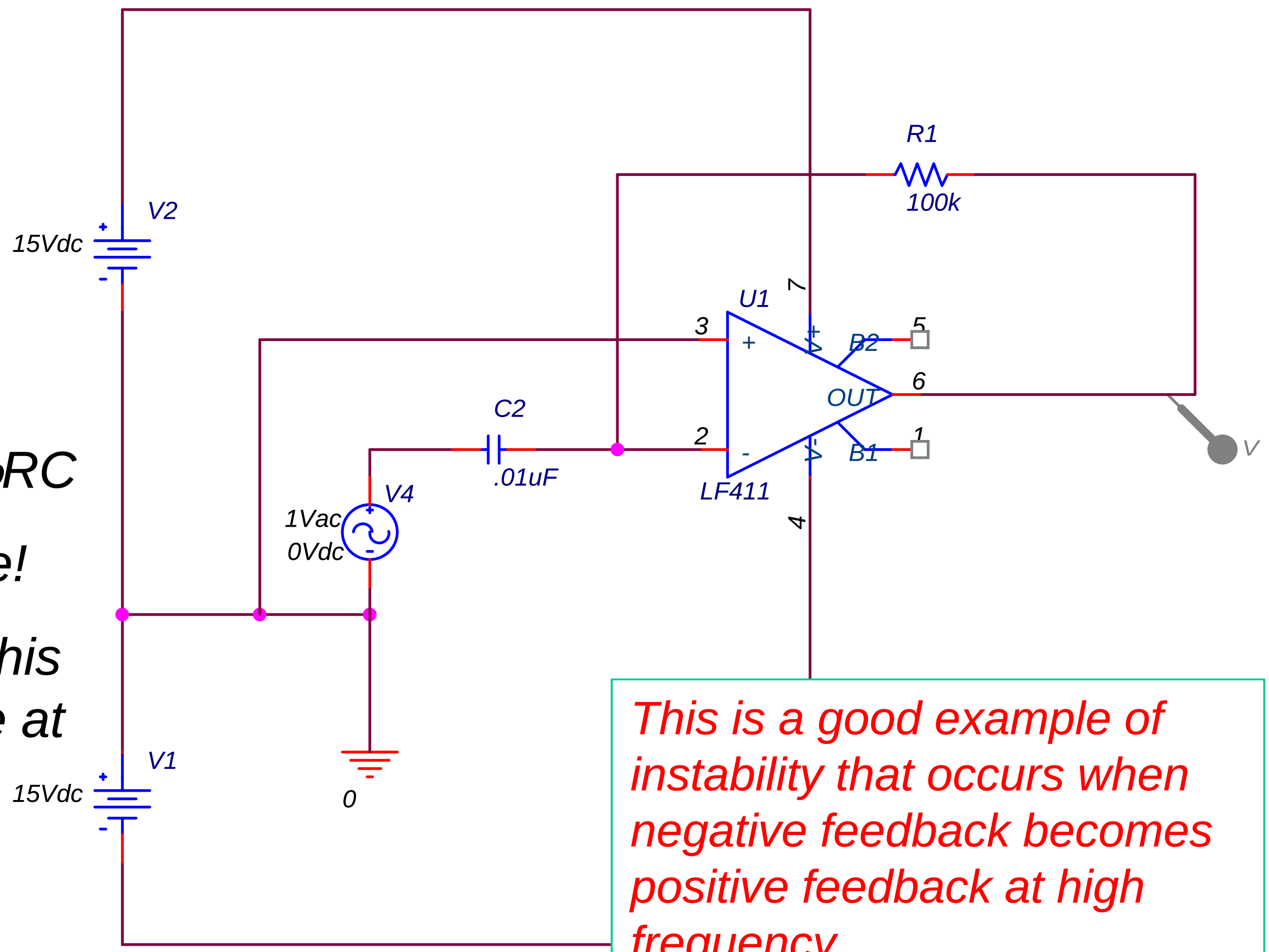


Figure 4.31. LF411 gain versus frequency ("Bode plot").

The bandwidth (f_{3dB}) times the gain (G) will always equal a constant gain-bandwidth-product (f_T).

Pure Differentiator



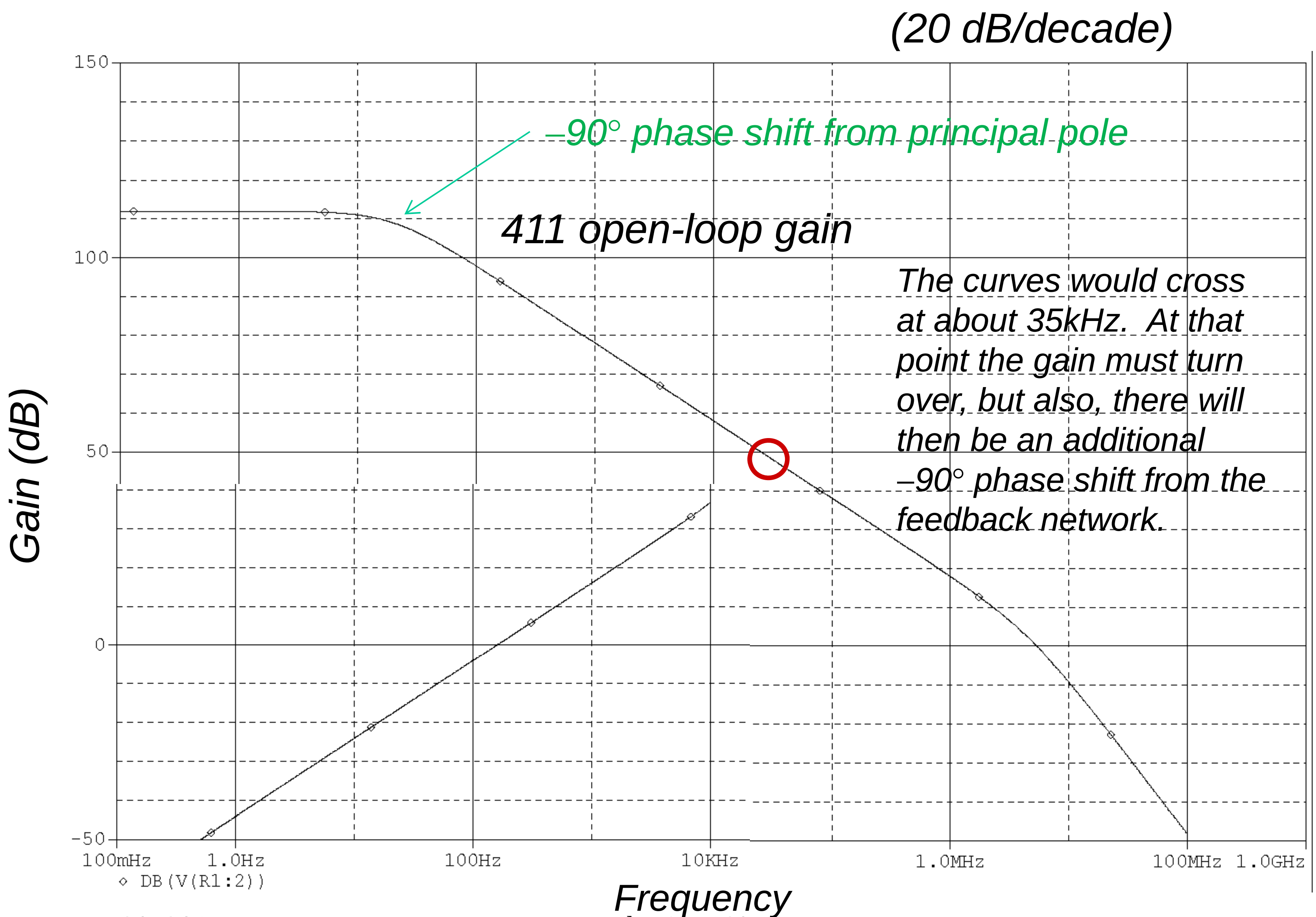
Voltage gain = $j\omega RC$

Rises 6dB/octave!

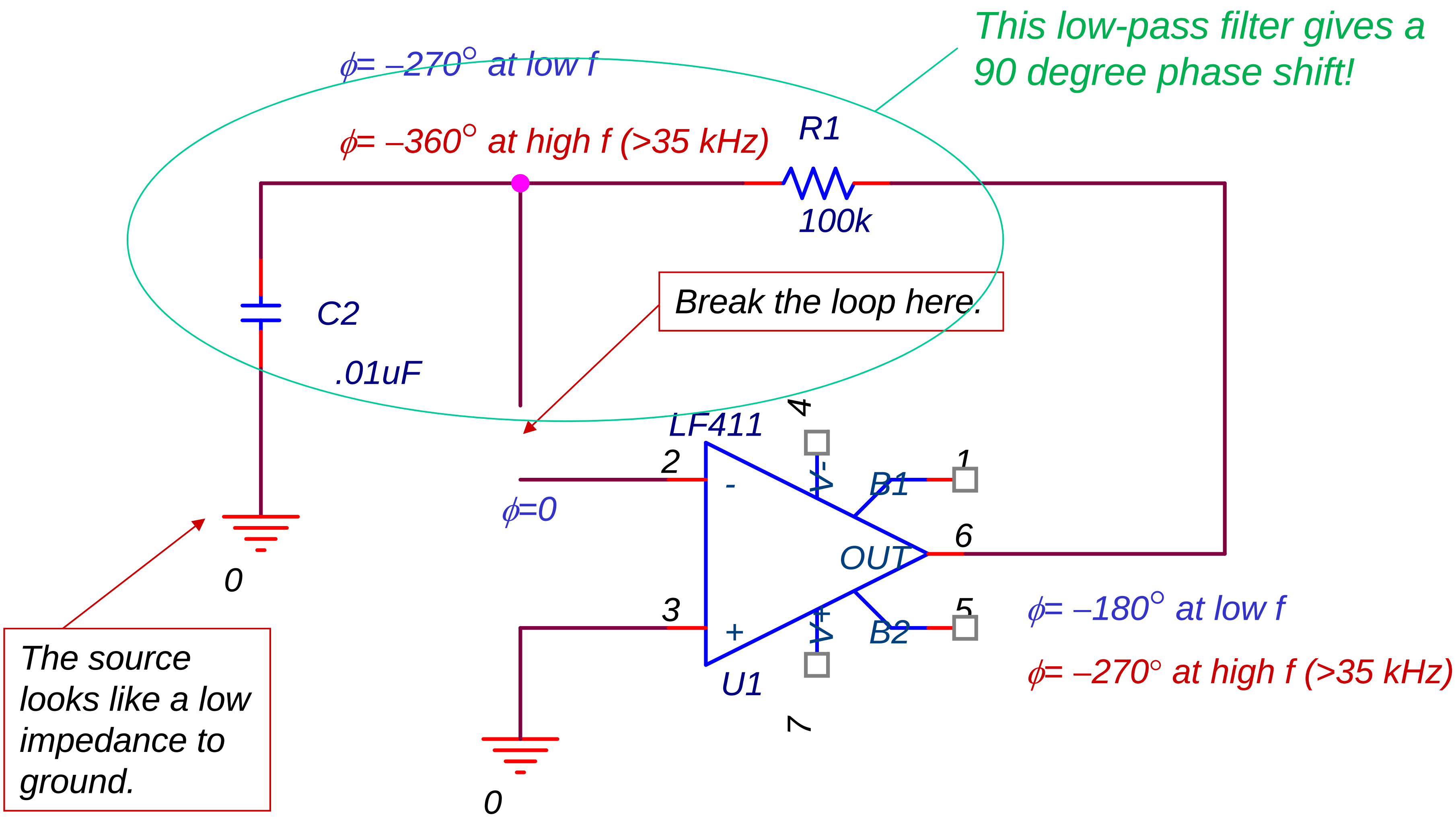
Remember that this circuit is unstable at high frequency.

This is a good example of instability that occurs when negative feedback becomes positive feedback at high frequency.

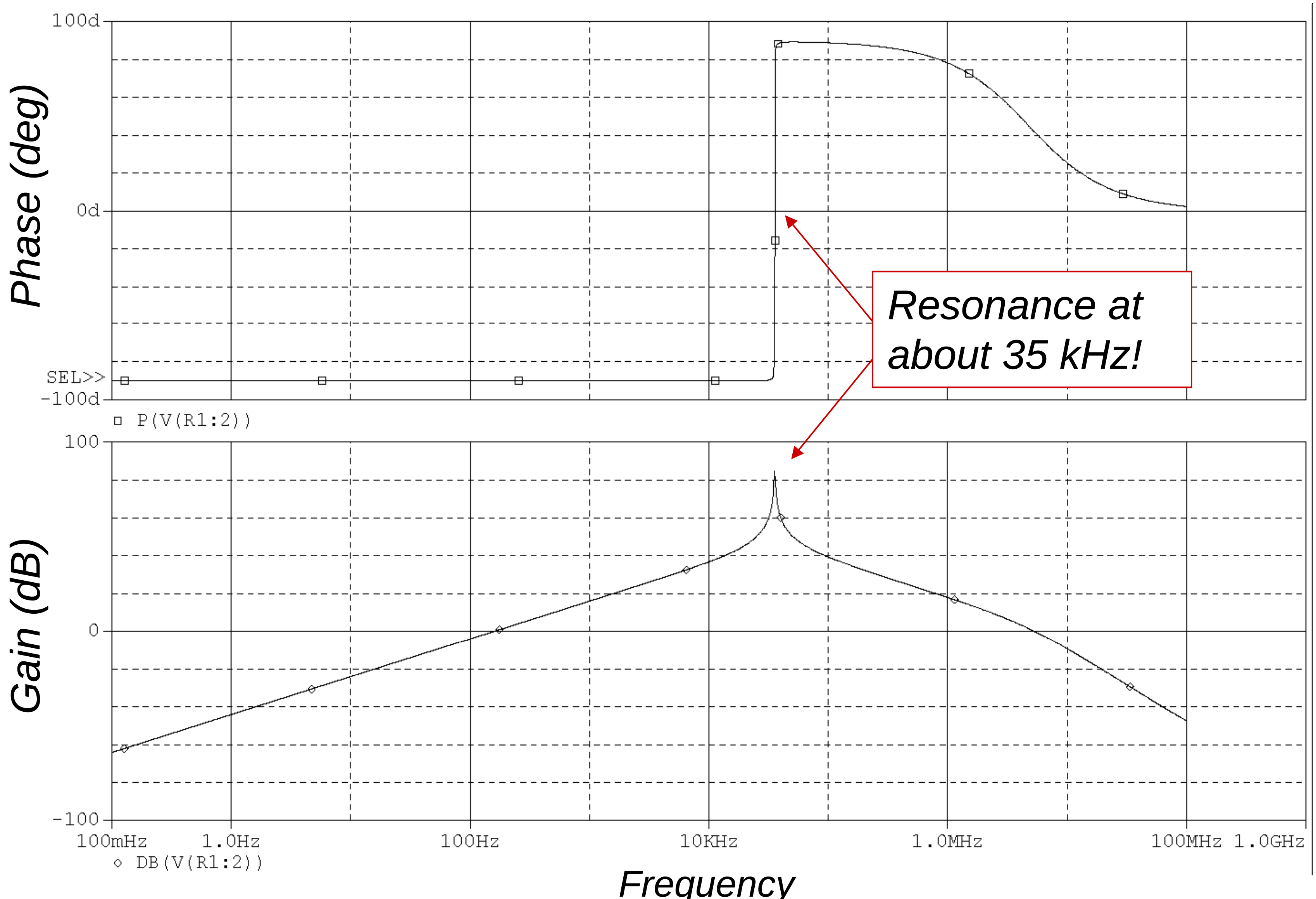
Spice AC-sim: gain rising at 6dB/octave



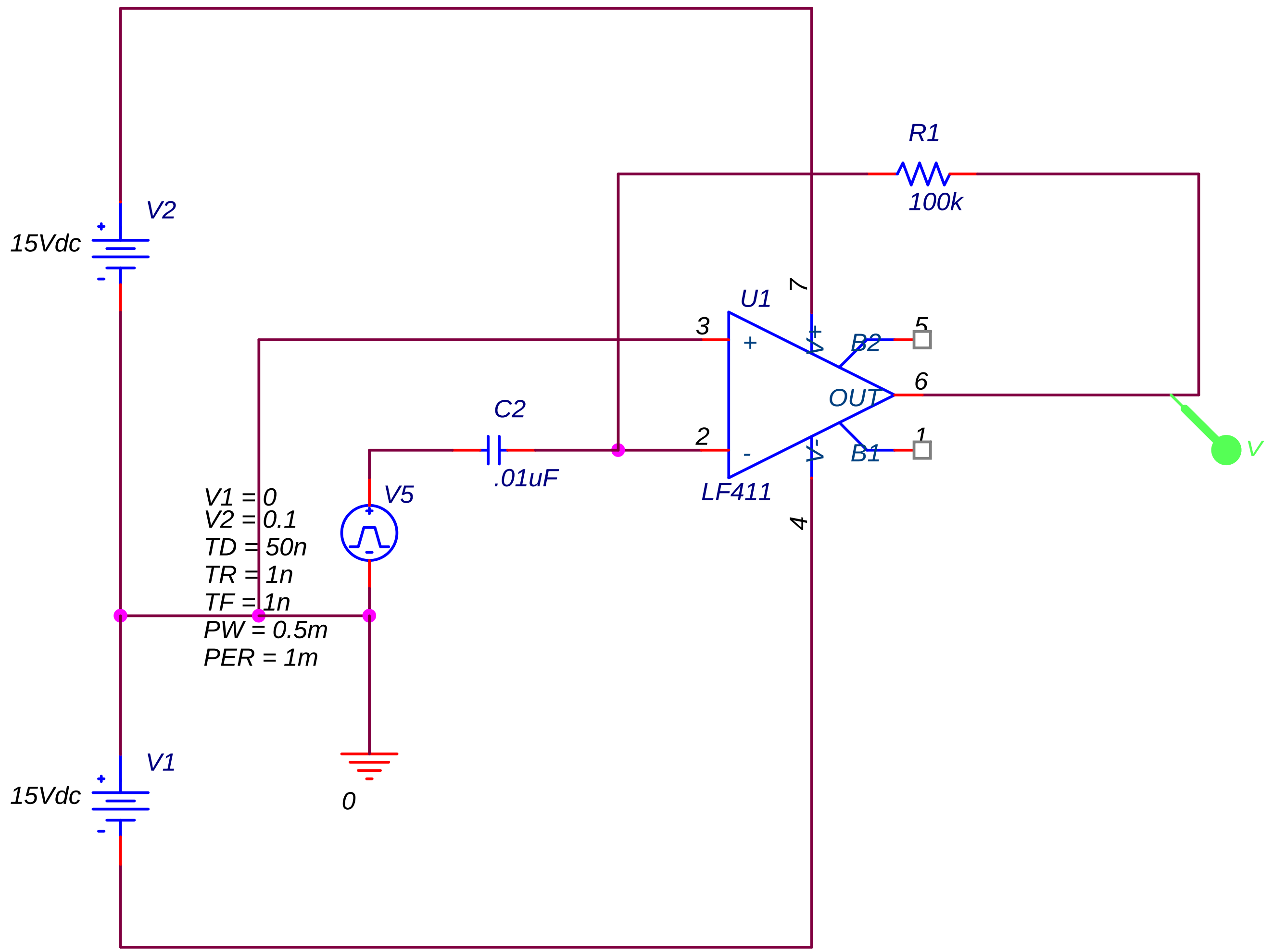
Phase Shifts Around the Loop



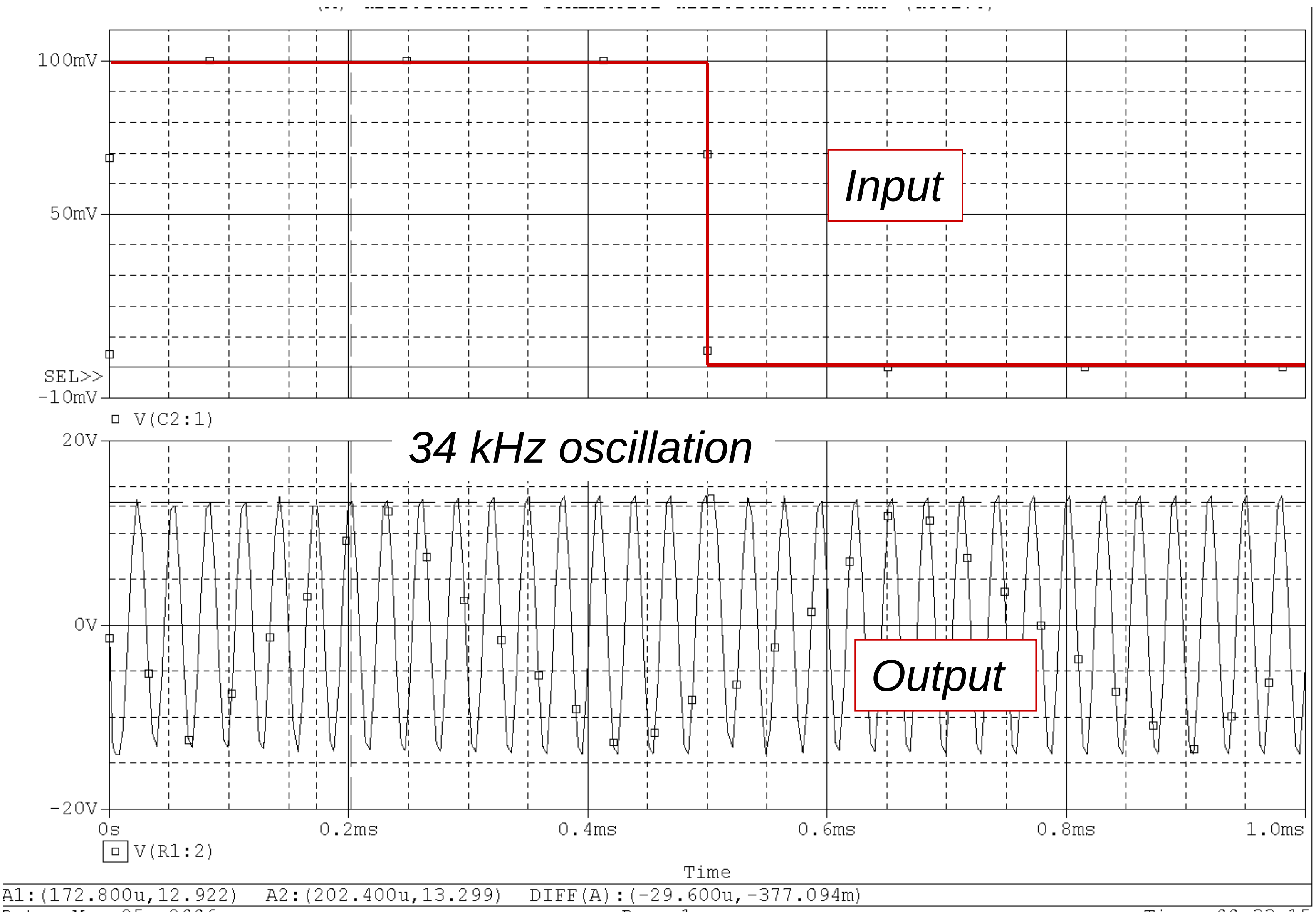
Spice AC-sim up to high frequency:



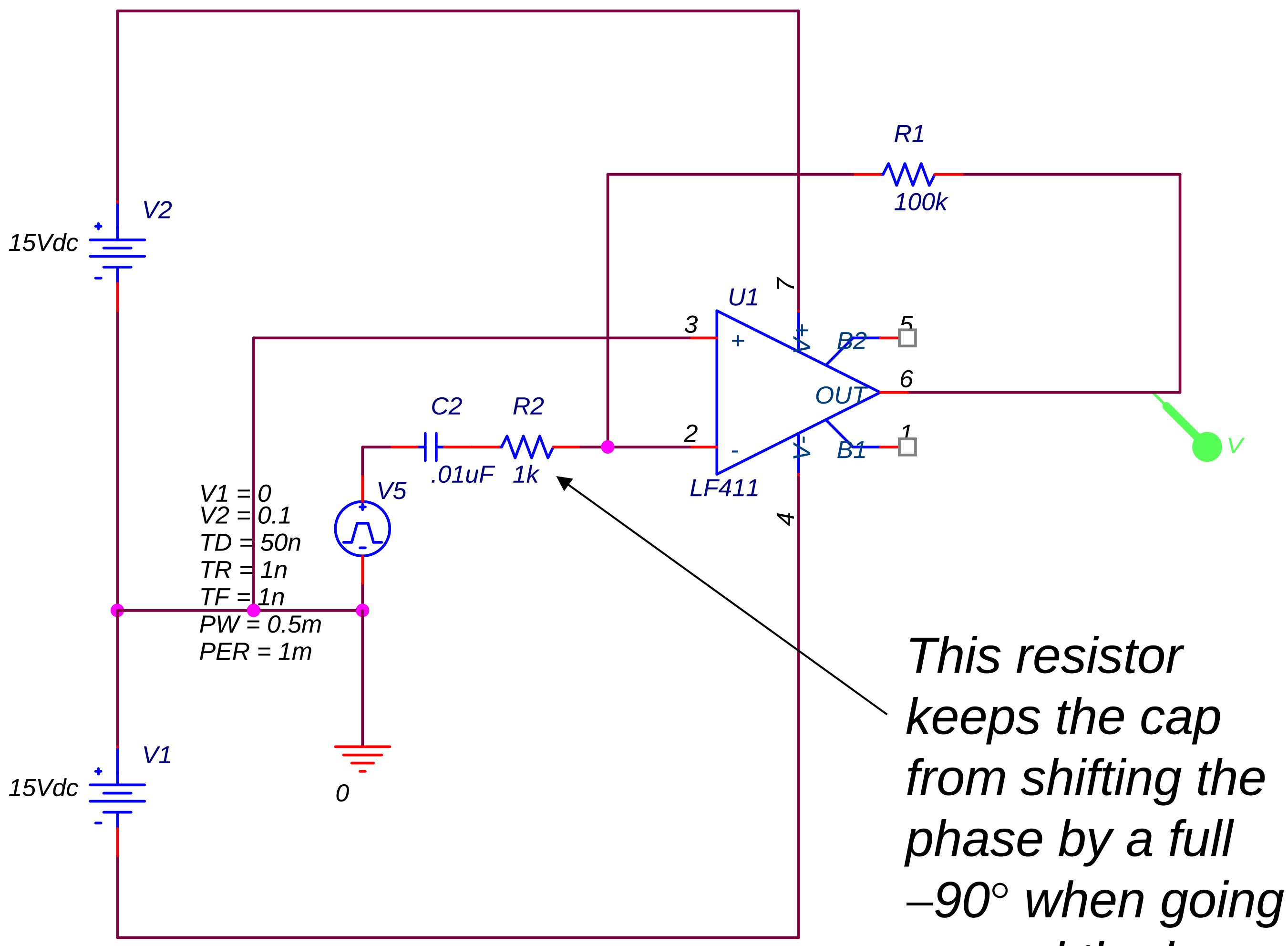
Transient Simulation with Square-Wave Input



Transient Simulation with Square-Wave Input

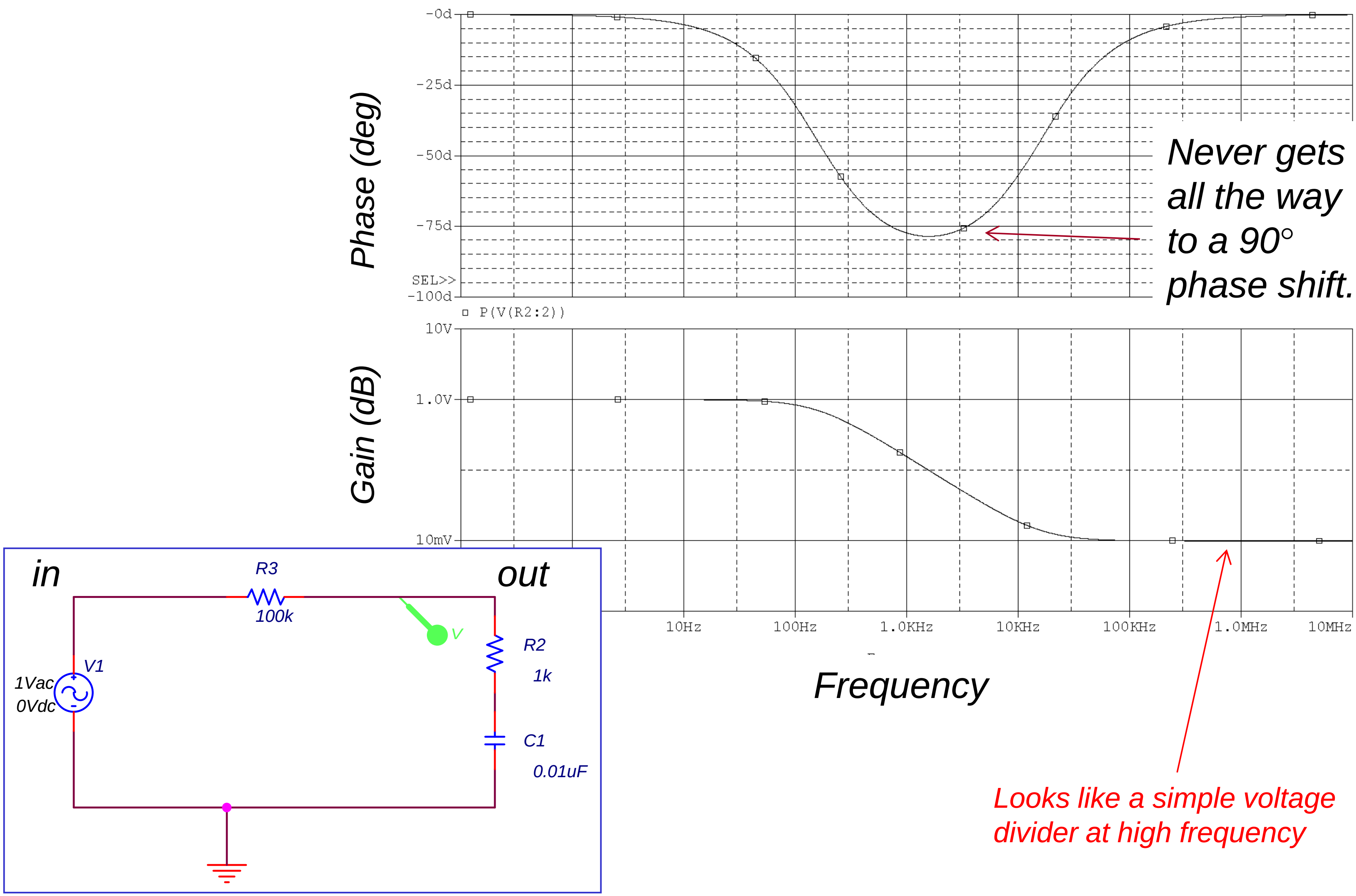


Add a 1k Resistor in Series with the Cap

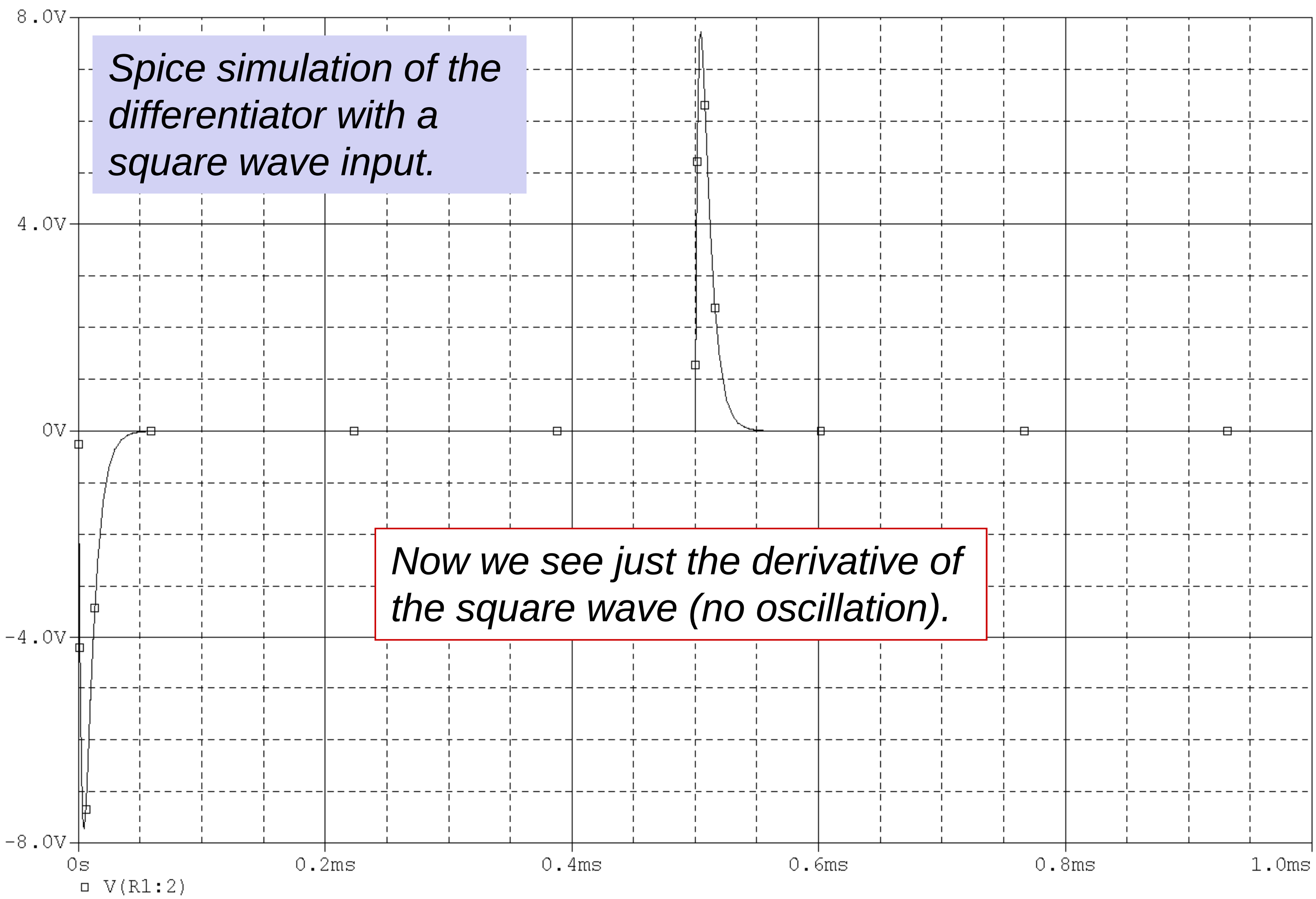


This resistor keeps the cap from shifting the phase by a full –90° when going around the loop.

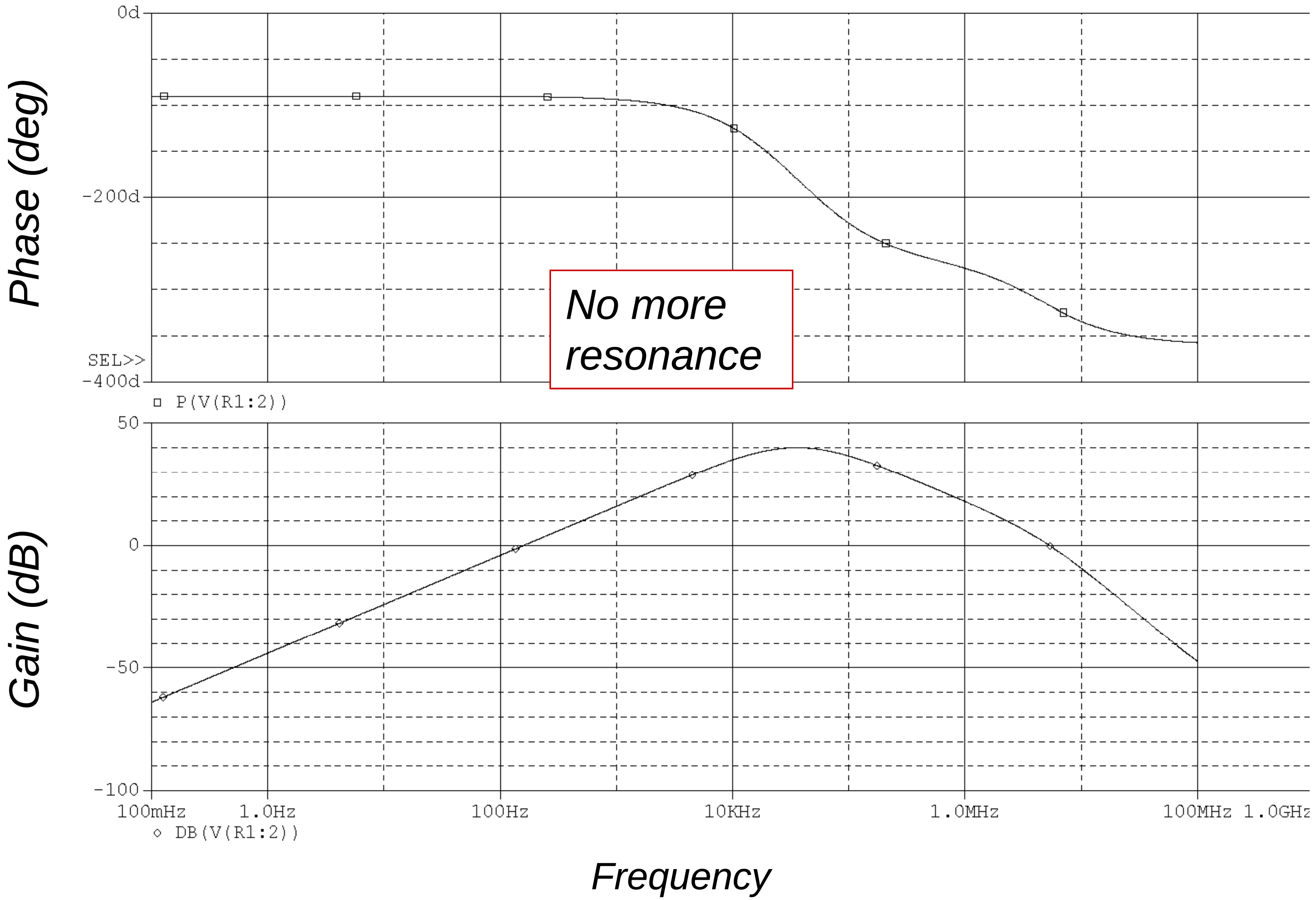
Low-Pass Filter with Extra Resistor



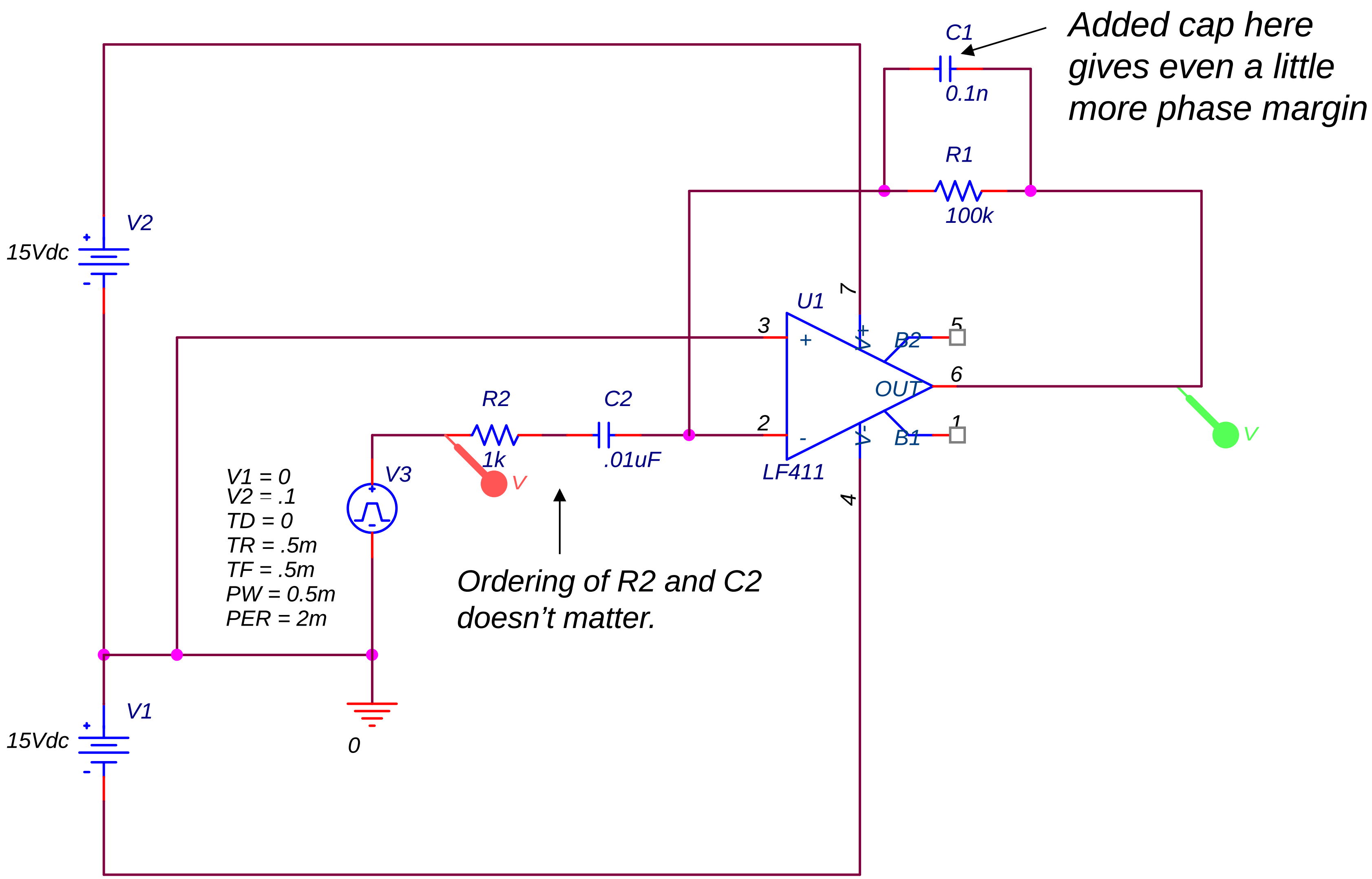
With 1k Resistor in Series with Cap



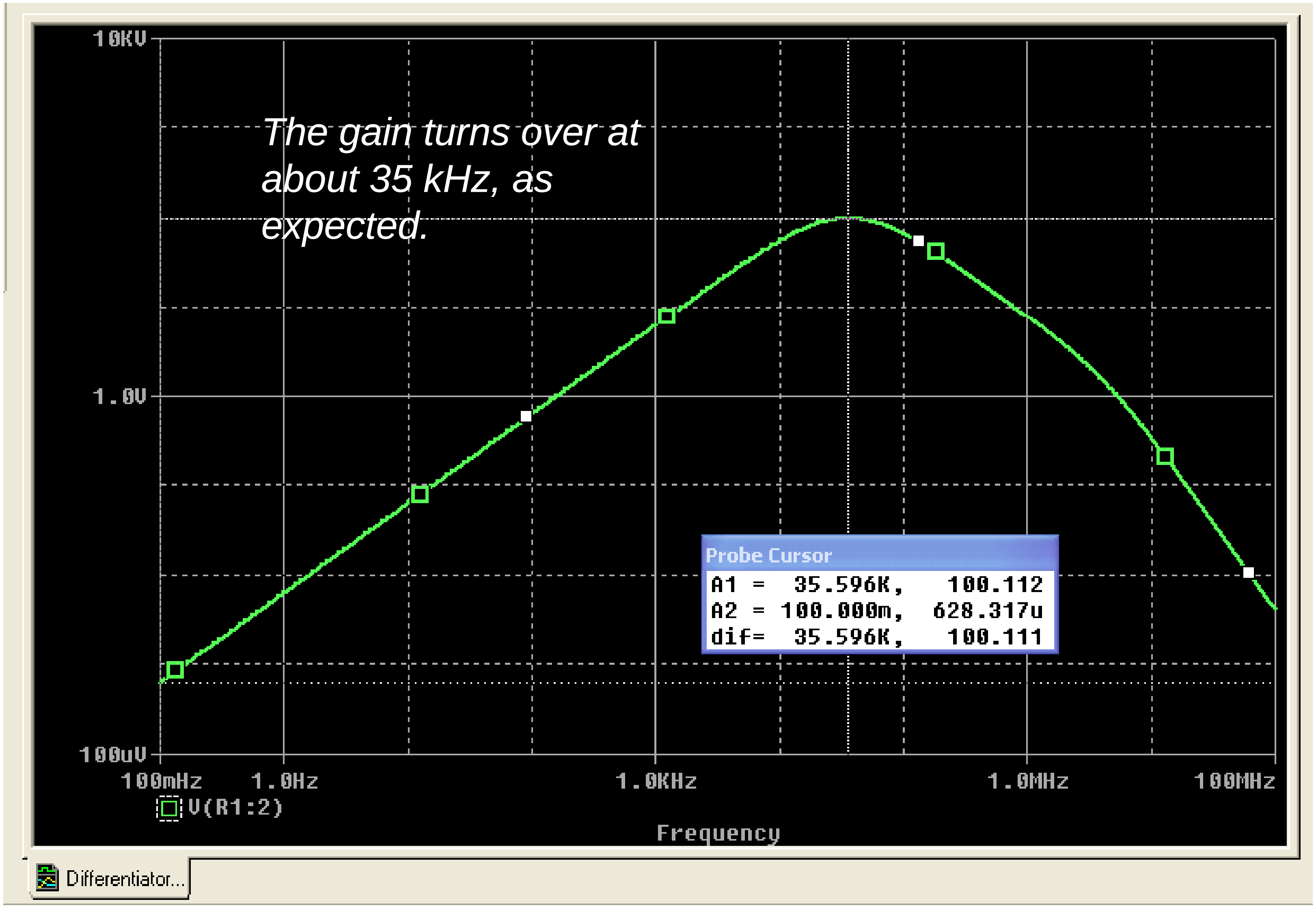
With 1k Resistor in Series with Cap



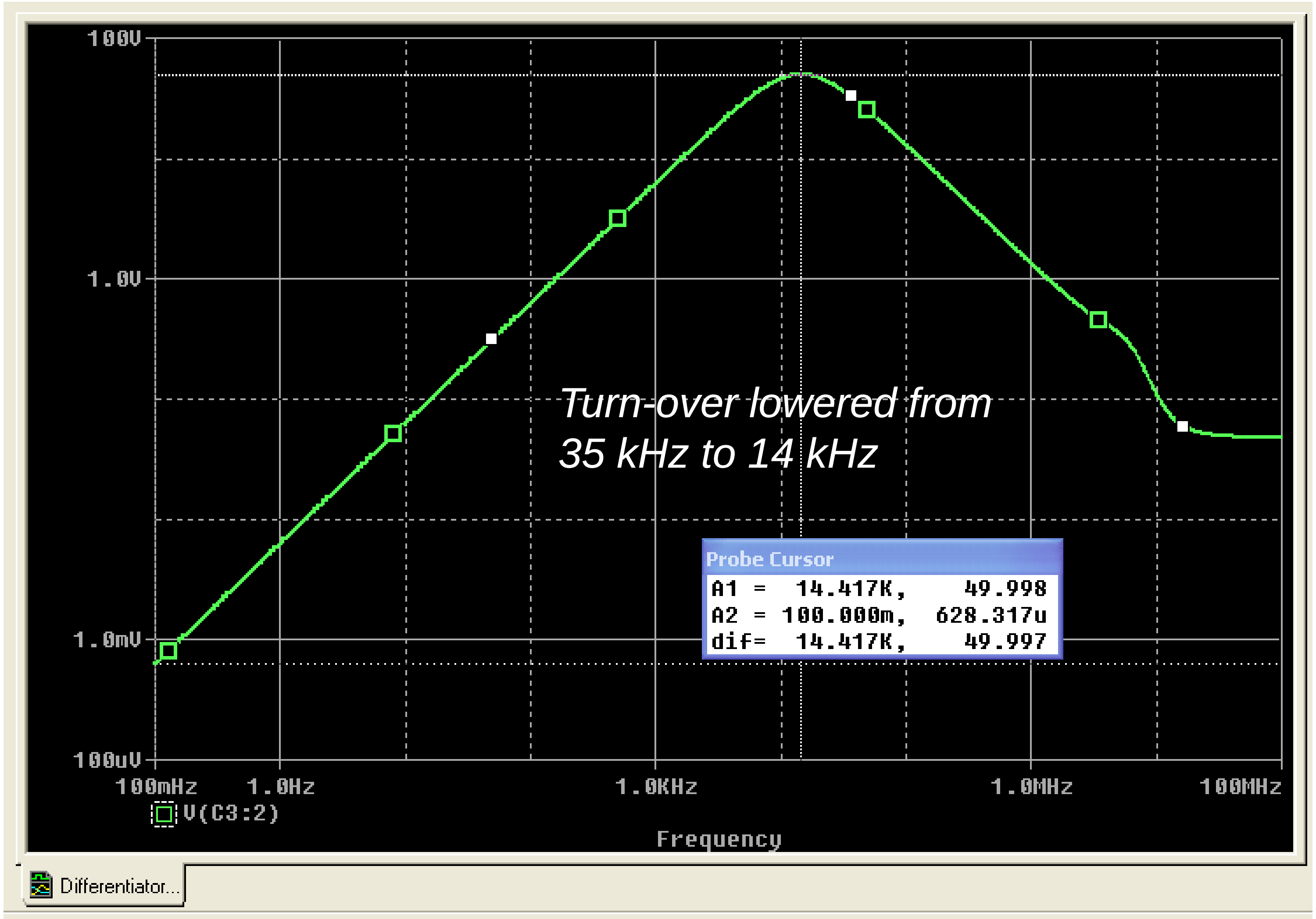
Lab Differentiator Circuit



Differentiator without feedback capacitor



Differentiator with feedback capacitor



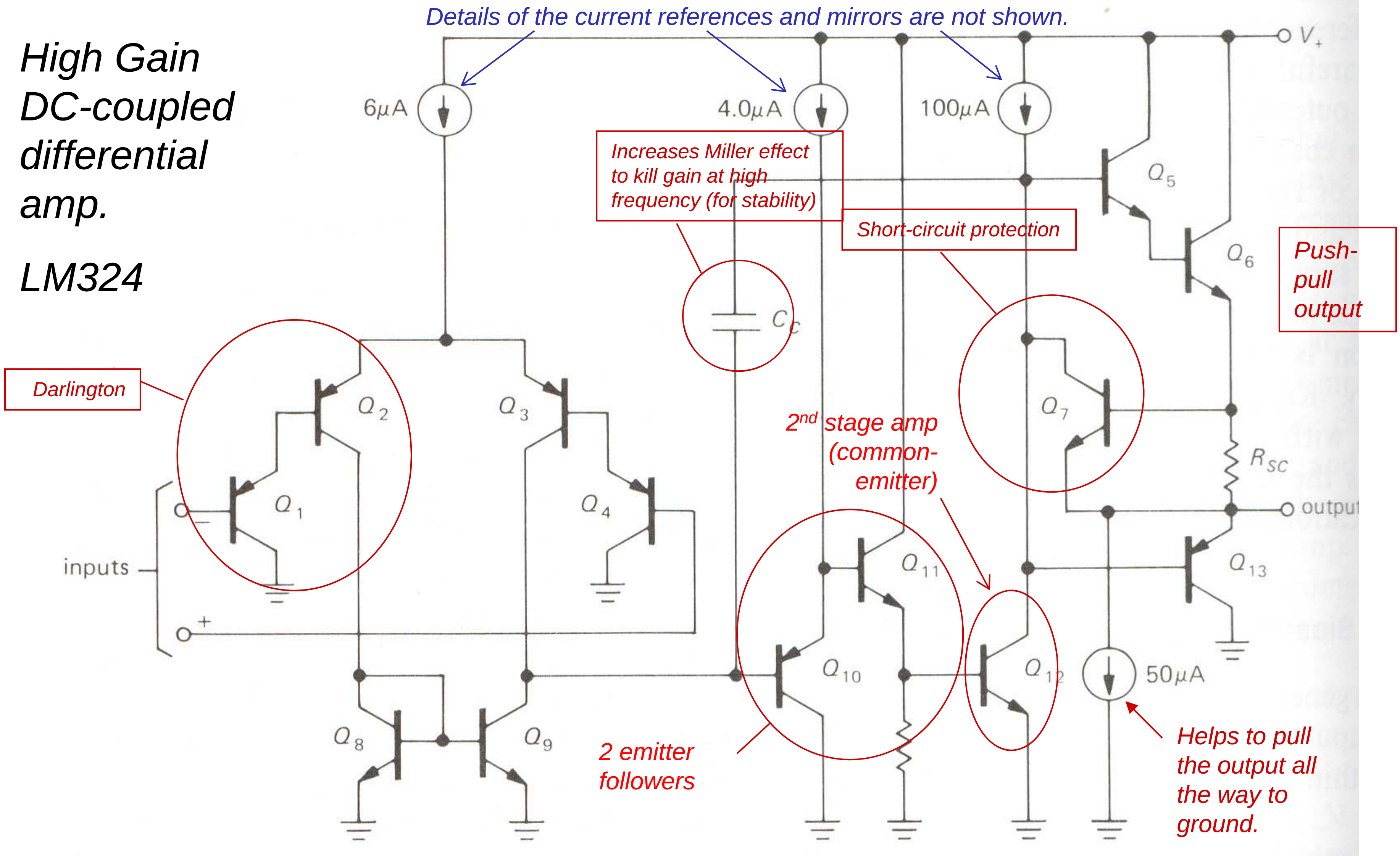
Input and Output Impedance

- *Differential input impedance*
  - *For a non-inverting amp, it is boosted by a factor of (1+AB) to near infinity due to negative voltage feedback. Thus it becomes an insignificant parameter. (Remember: AB="loop gain".)*
- *Output impedance: 40 ohms for the 411 without feedback*
  - *For a real application the output impedance depends on the feedback network (low for V source; high for I source)*
  - *With negative voltage feedback the output impedance drops by a factor of 1/(1+AB) to such a low value as to become insignificant.* ***The maximum current drive of the output stage is then the much more relevant parameter.***
- *Maximum output current and output swing*
  - *411 can go from V_{EE}+2V to V_{CC}–2V with a 1 kohm load*
  - *Single-supply op-amps (e.g. LM358) can swing from ground to close to the positive rail (but typically they can only reach ground if they don't have to sink too much current, e.g. <50 μA).*

Op-Amp Example (Single Supply)

High Gain DC-coupled differential amp.

LM324

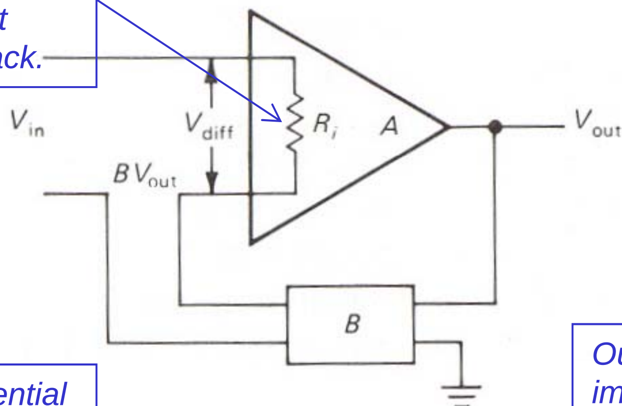


Input and Output Impedance

- *Non-inverting amplifier (voltage, or series, feedback)*
  - *Z_{in} gets increased by (1+AB)*
  - *Z_{out} gets decreased by 1/(1+AB)*

$$G = \frac{V_{out}}{V_{in}} = \frac{A}{1+AB}$$

Input impedance without feedback.

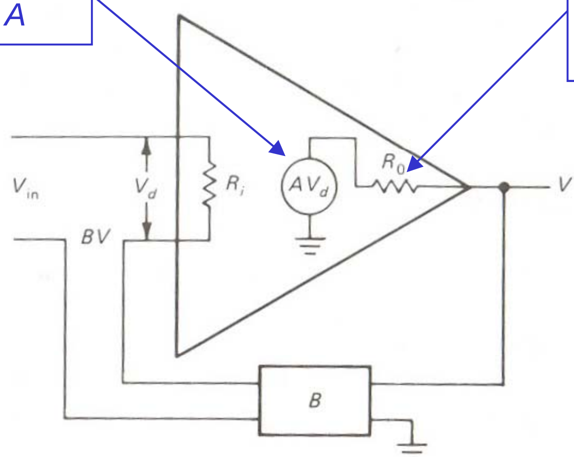


$$I_{in} = \frac{V_{in} - BV_{out}}{R_i} = \frac{V_{in}}{R_i \cdot (1+AB)}$$

Z_{in}

Differential gain = A

Output impedance without feedback.



Suppose $V_{in} = 0$ and apply V at output.

Amp sees $0 - BV$ across its 2 inputs.

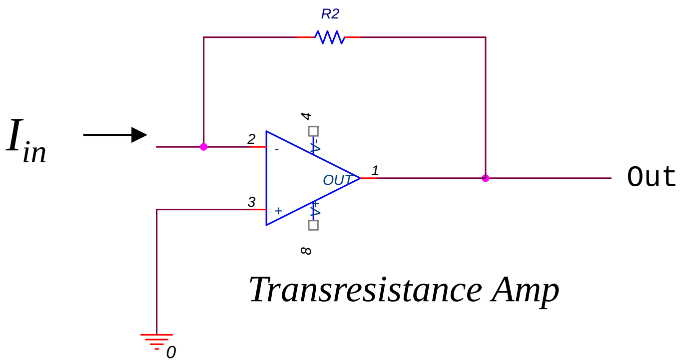
$$I_{out} = \frac{V - (-ABV)}{R_0} = V \cdot \frac{1+AB}{R_0}$$

$1/Z_{out}$

Input and Output Impedance

- *Inverting amp (shunt feedback)*

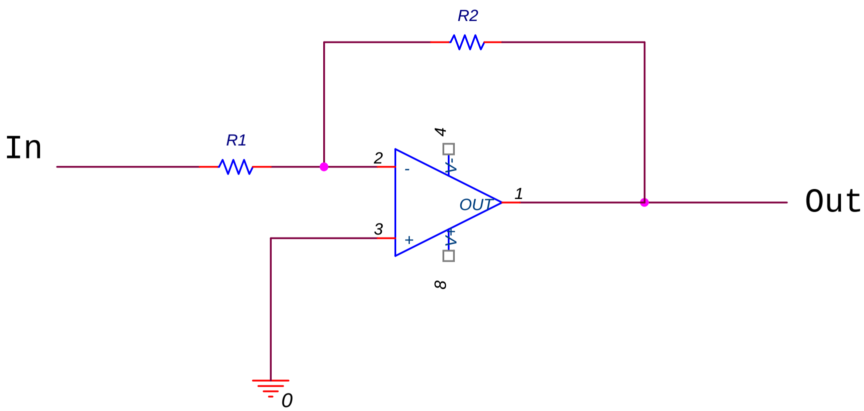
Z_{in} reduced by 1/(1+A)



Transresistance Amp

$$I_{in} = \frac{V_{in} - V_{out}}{R_2} = \frac{V_{in} \cdot (1 + A)}{R_2}$$

Impedance into the amp input itself is so high that we can ignore it here. It is in parallel with $R_2/(1+A)$, which is tiny.

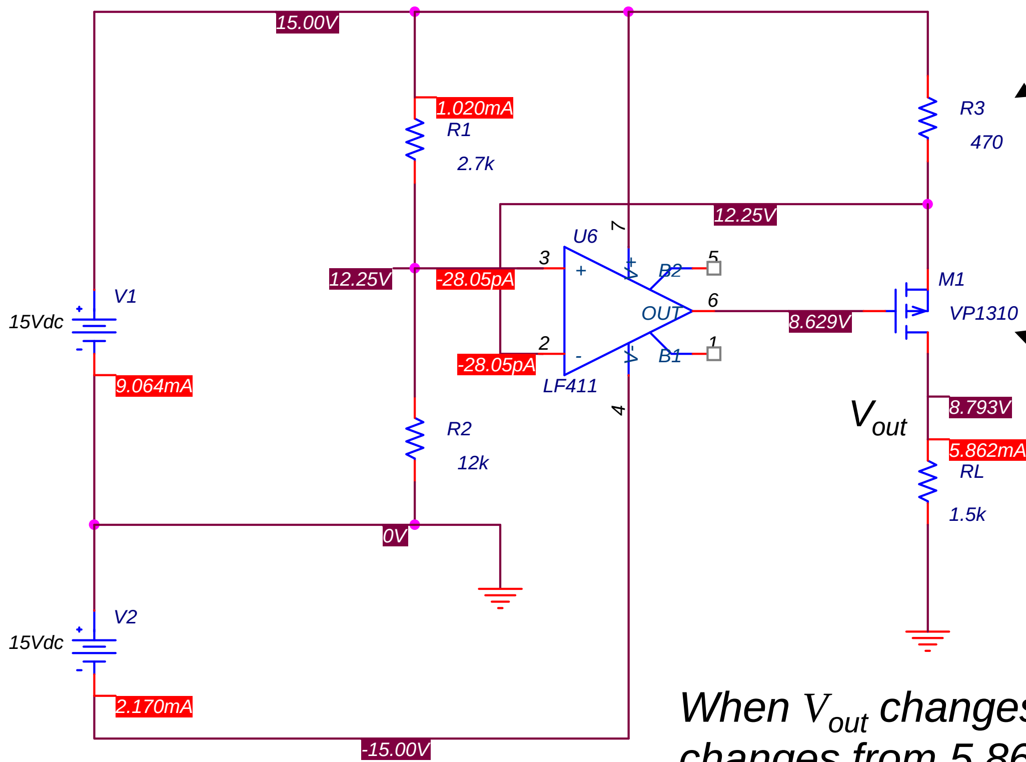


$$Z_{in} = R_1 + \frac{R_2}{1 + A} \approx R_1$$

*The **output** impedance of the inverting amp is the same as for the non-inverting amp. In both cases the voltage is sampled at the output and fed back.*

Output Impedance

- *Current source (current sampling)*



The feedback is using R3 to sample the output ***current***.

The op-amp output uses the MOSFET g_m *to control the current.*

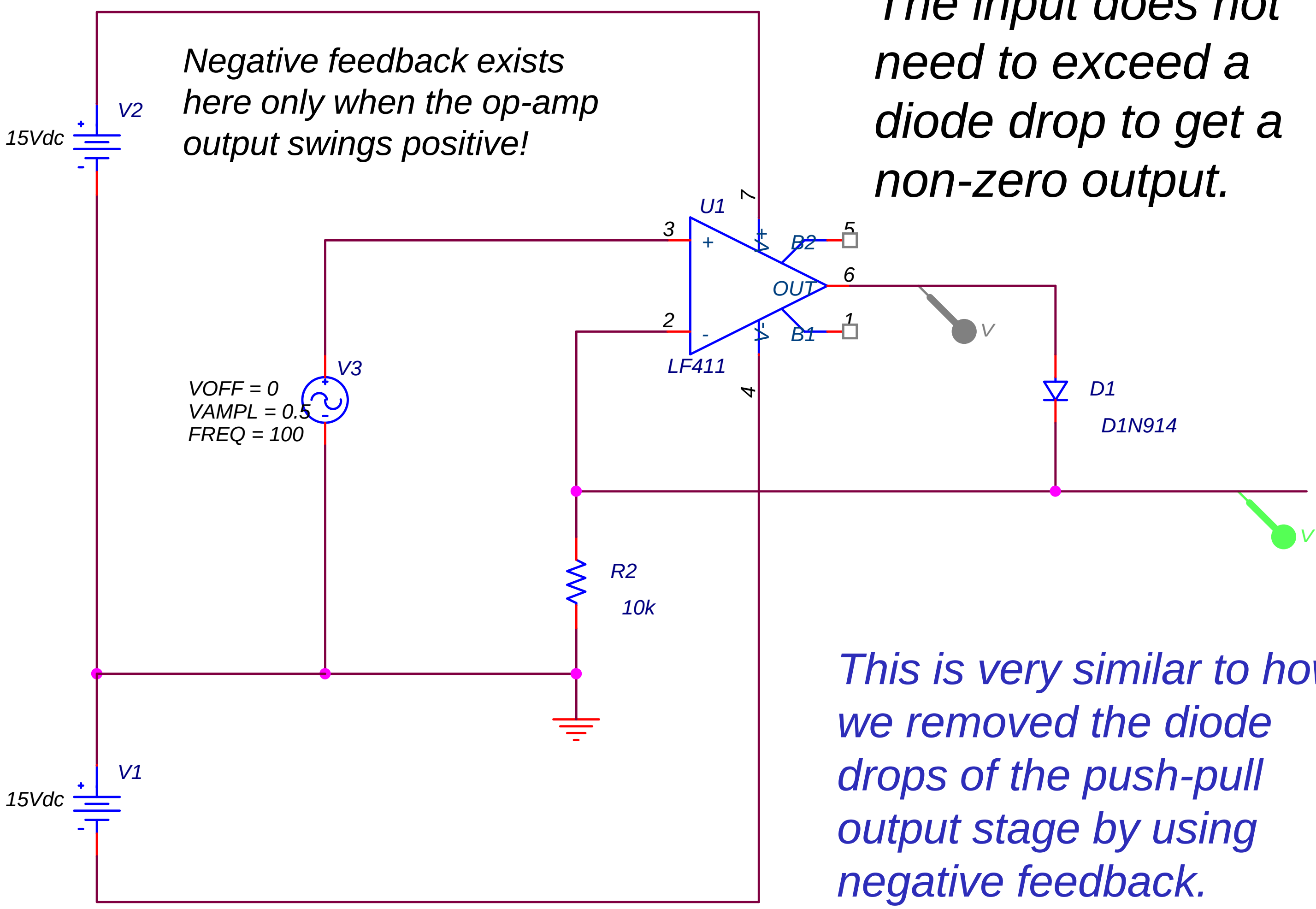
When V_{out} *changes from 0 to 11.5V, the current changes from 5.86209625 mA to 5.86209775 mA.*

$$Z_{out} = \frac{11.5}{1.5 \times 10^{-9}} = 7.7\ \mathrm{G\Omega}!!$$

Some additional circuits studied in the lab:

ACTIVE RECTIFIERS

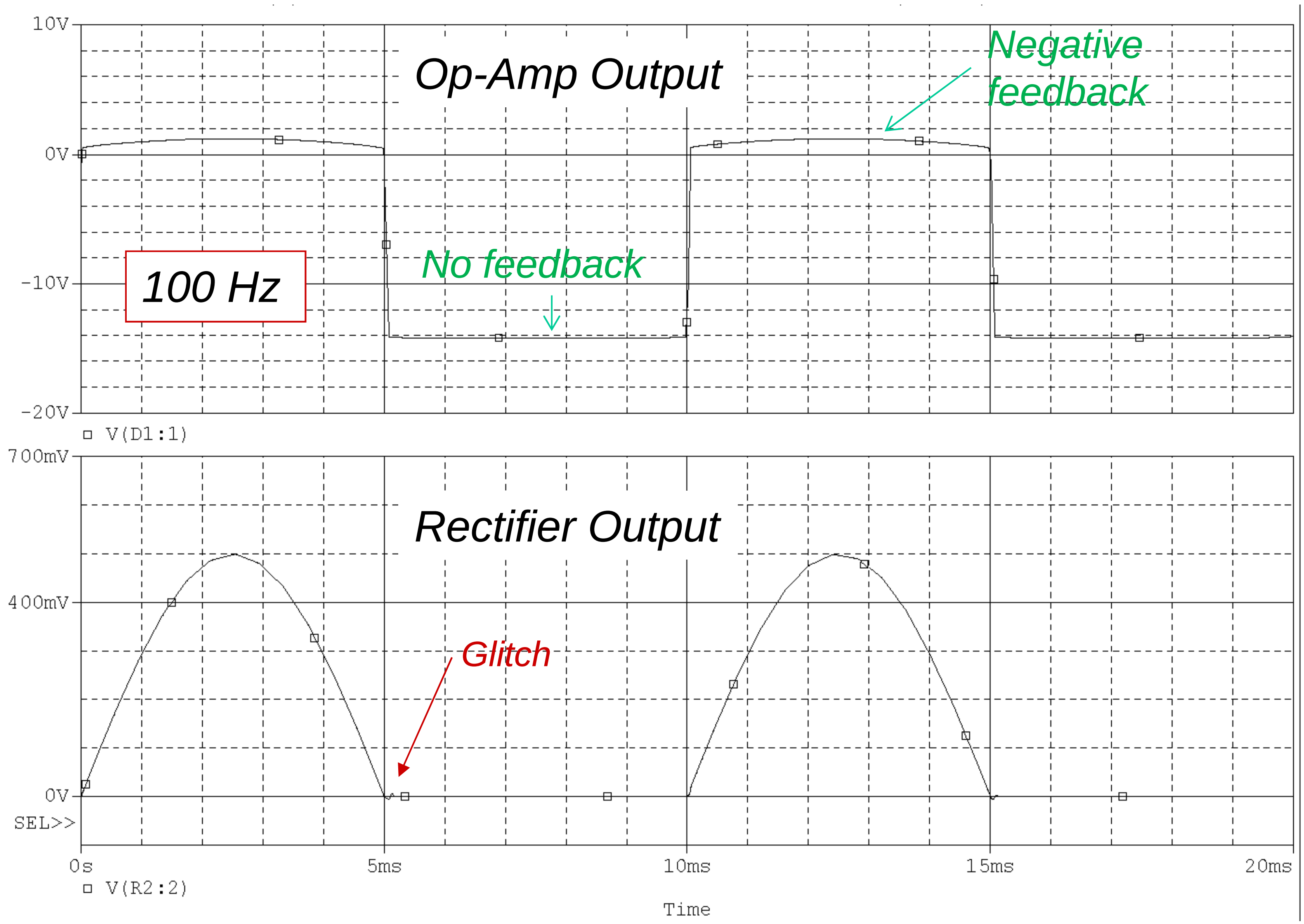
Active ½ Wave Rectifier



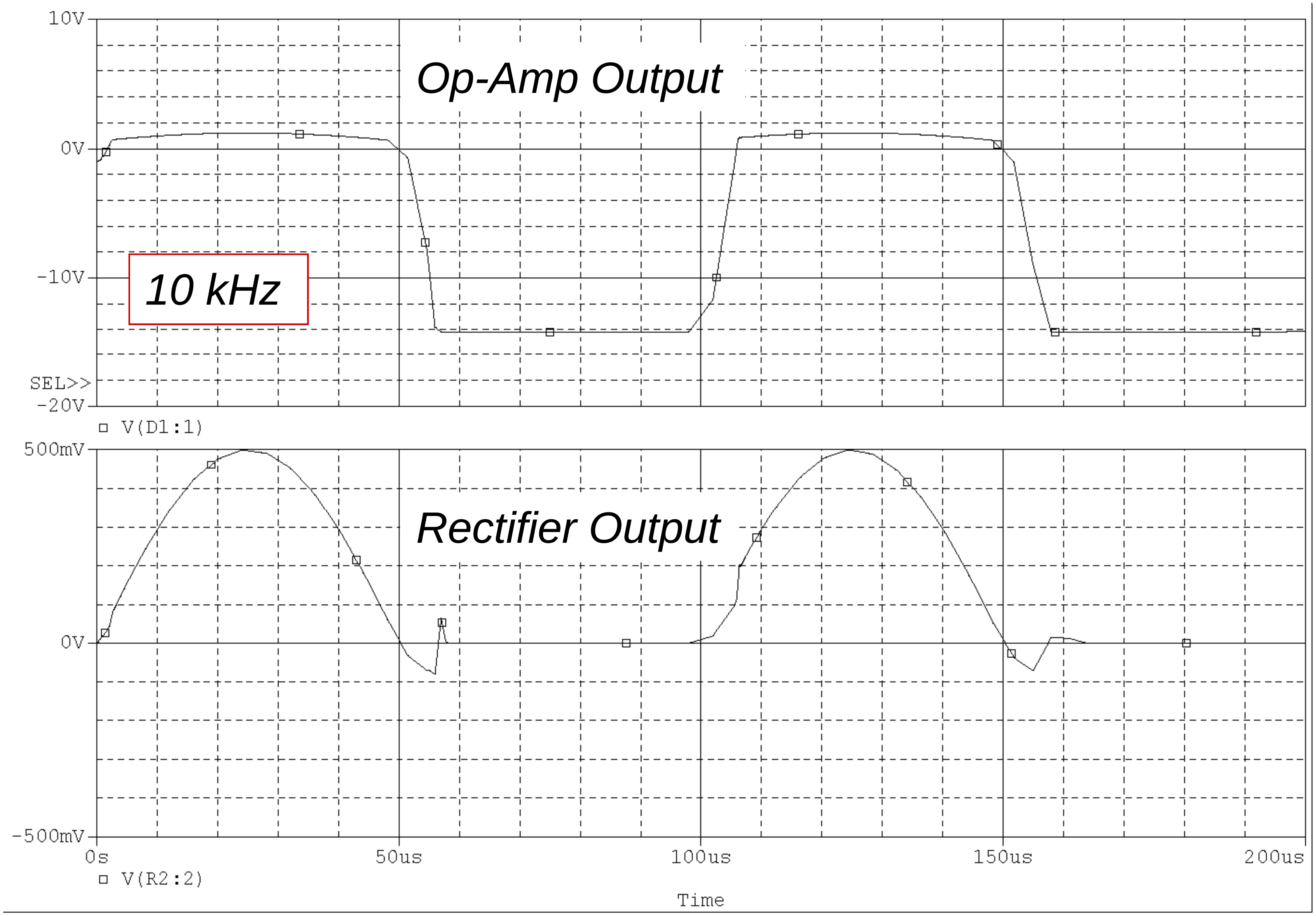
The input does not need to exceed a diode drop to get a non-zero output.

This is very similar to how we removed the diode drops of the push-pull output stage by using negative feedback.

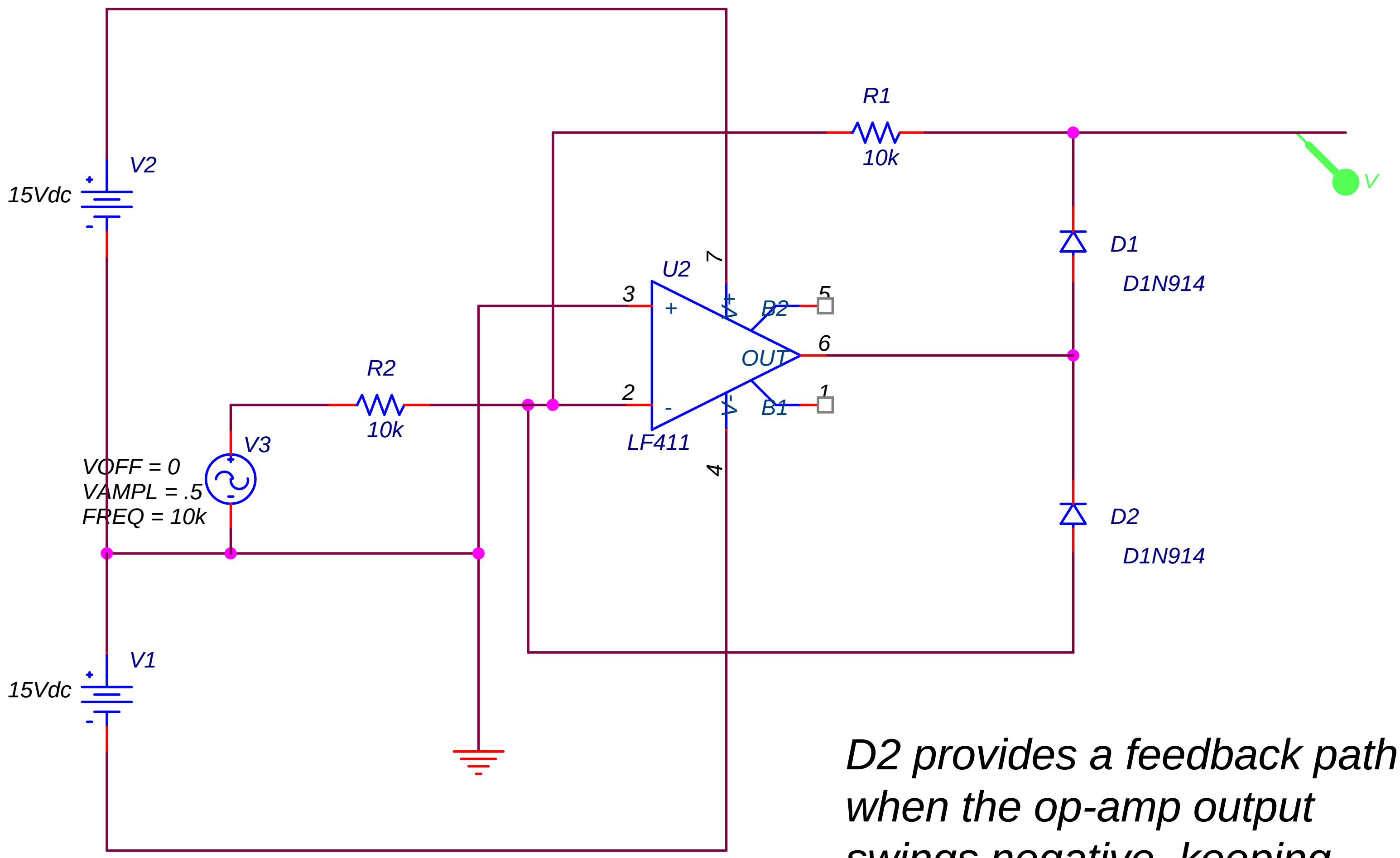
Active Rectifier Transient Simulation



Active Rectifier Transient Simulation



Improved Active ½ Wave Rectifier



D2 provides a feedback path when the op-amp output swings negative, keeping the op amp from trying to swing all the way to V_{EE}.

Improved Active Rectifier