

BAF WORKSHOP

*LTspice Basics +
Beyond for DIY Audio
Burning Amp Fest 2023
Edition*

Copyright 2023 Mike Rothacher

UNIT LABELS IN LTSPICE

- K or k = kilo = 10^3
- MEG = mega = 10^6
- G = giga = 10^9
- T = terra = 10^{12}
- m = milli = 10^{-3}
- u = micro = 10^{-6}
- n = nano = 10^{-9}
- p = pico = 10^{-12}
- F = femto = 10^{-15}

*Don't Forget!

Use MEG for mega, not M

Use 1 for 1 Farad, not 1F

LESSON 1: DRAW A BASIC SCHEMATIC

USEFUL SHORTCUTS

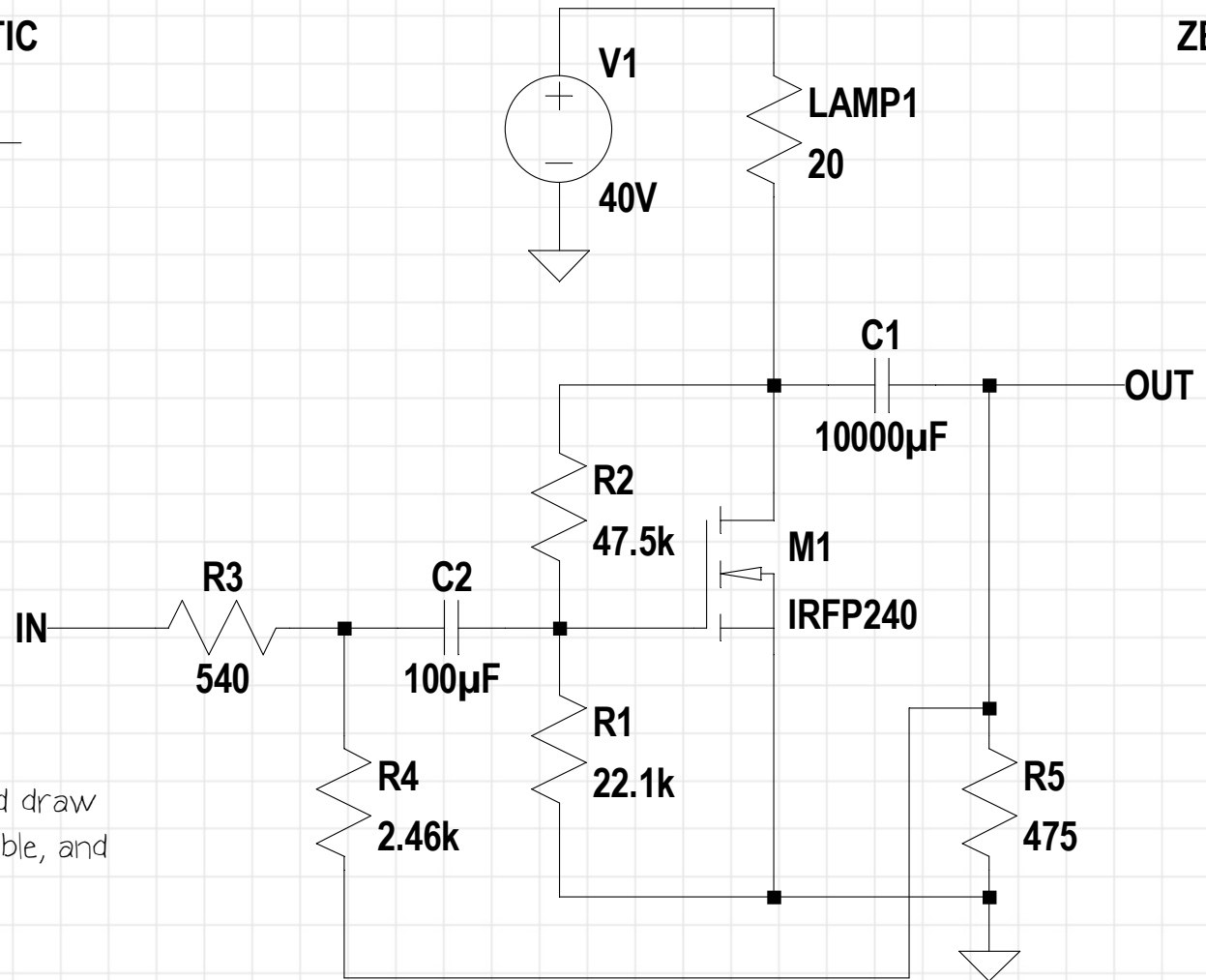
RESISTOR: R
CAP: C
INDUCTOR: I
DIODE: D

ROTATE: CTRL+R
MIRROR: CTRL+E

WIRE: F3
LABEL: F4
GROUND: G

Assignment:

Start a new schematic in LTspice and draw this circuit. Copy it as closely as possible, and prove you are fearless.



ZEN LITE

LESSON 2: DC OPERATING POINT ANALYSIS

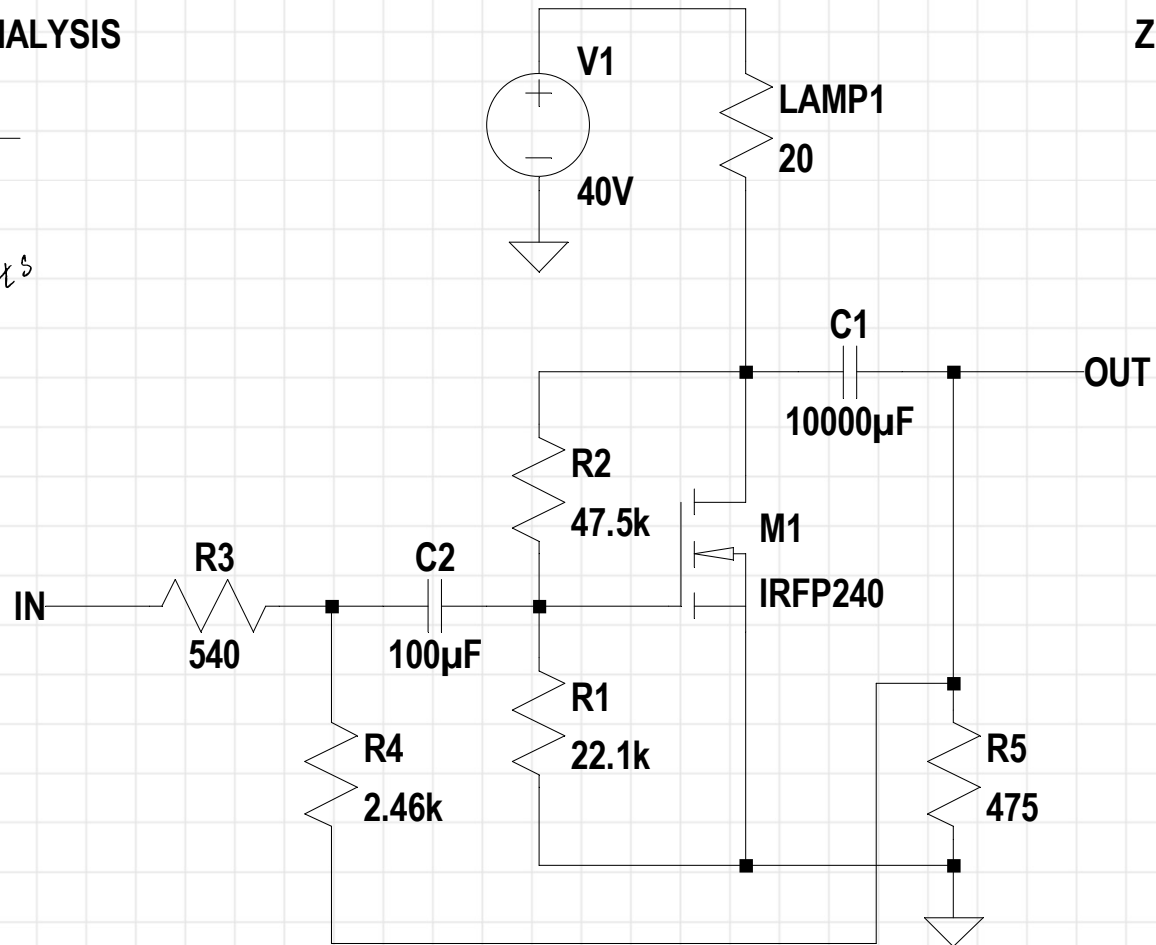
.OP DIRECTIVE

Calculates the DC voltage and current of each node under steady state conditions

.op

results

--- Operating Point ---		
V(n001):	40	voltage
V(n003):	14.5636	voltage
V(n005):	4.62437	voltage
V(n004):	7.05345e-011	voltage
V(out):	6.93969e-011	voltage
V(in):	7.05345e-011	voltage
Id(M1):	1.27161	device_current
Ig(M1):	-1.48813e-010	device_current
Is(M1):	-1.27161	device_current
I(C1):	-1.45636e-013	device_current
I(C2):	4.62437e-016	device_current
I(R5):	1.46099e-013	device_current
I(R4):	4.62437e-016	device_current
I(R3):	0	device_current
I(R1):	0.000209248	device_current
I(R2):	0.000209248	device_current
I(Lamp1):	1.27182	device_current
I(V1):	-1.27182	device_current



ZEN LITE

LESSON 3: TRANSIENT ANALYSIS

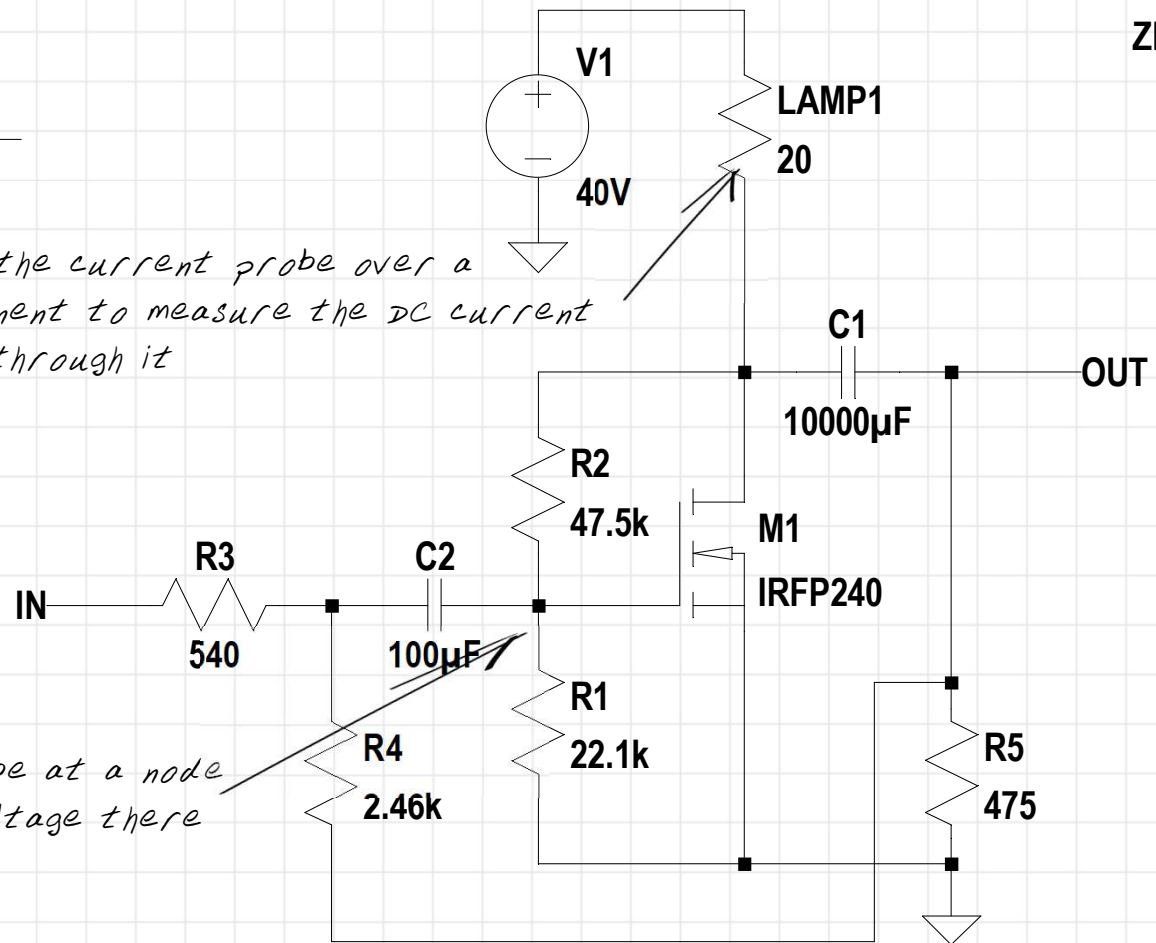
.TRAN DIRECTIVE

Nonlinear time-domain analysis

.tran 1

Move the current probe over a component to measure the DC current going through it

Point the voltage probe at a node to measure the DC voltage there



ZEN LITE

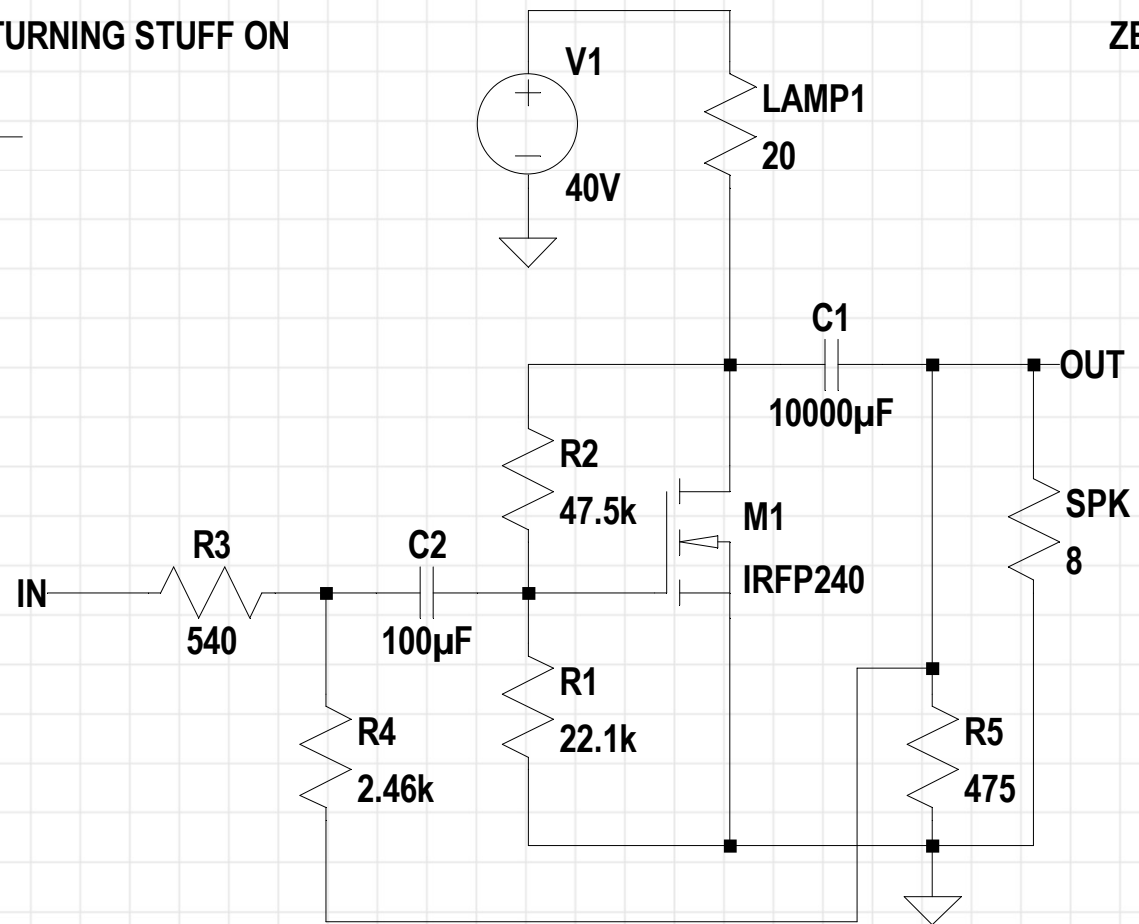
LESSON 4: TRANSIENT ANALYSIS - TURNING STUFF ON

.TRAN DIRECTIVE

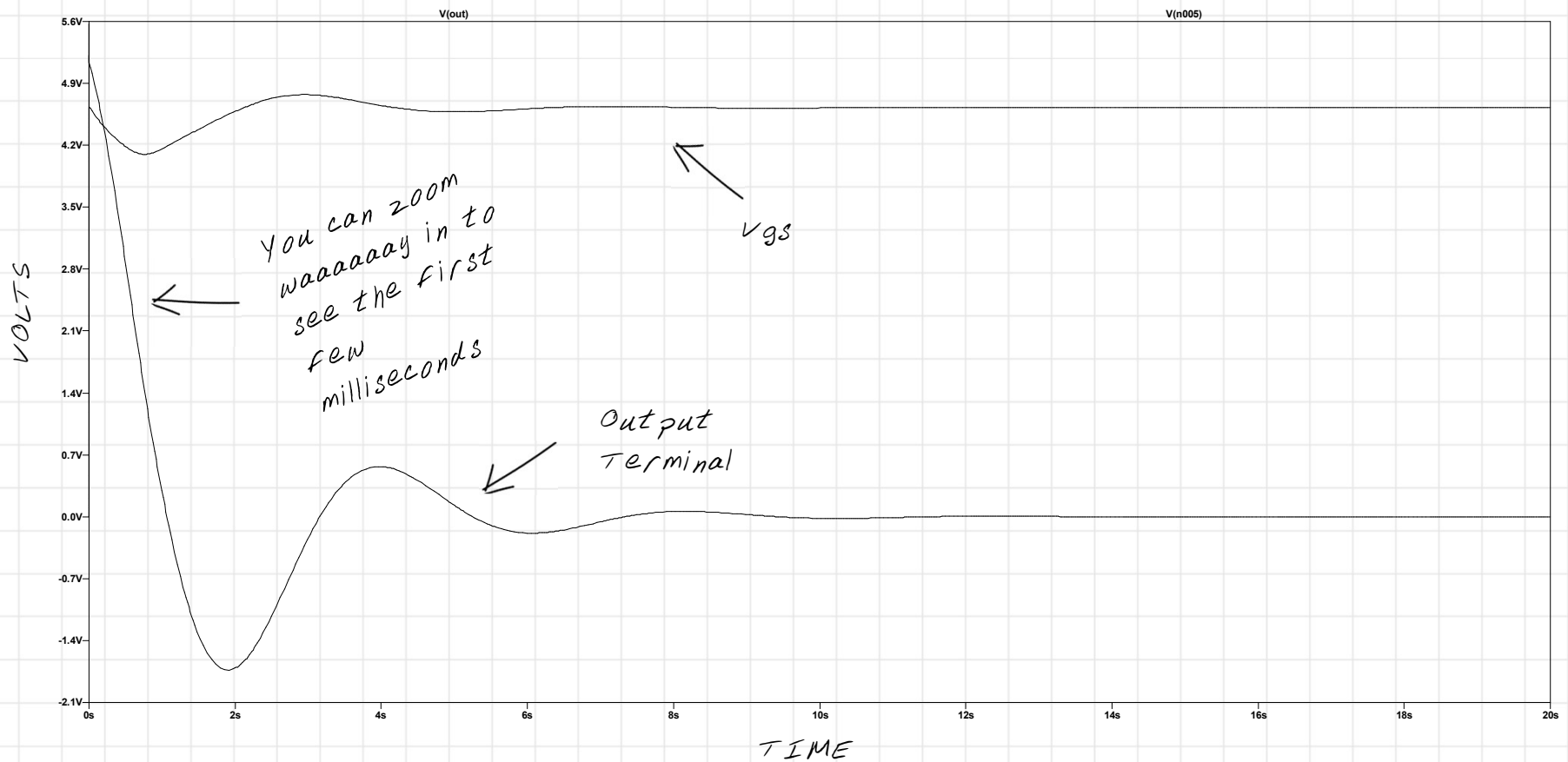
Nonlinear time-domain analysis

.tran 20 startup

*Extra Credit:
Change V1 to a piecewise
linear voltage that slowly
ramps up, and see if that
tames the thump :)*



Zen Lite Turn On



LESSON 5: TRANSIENT ANALYSIS - TURNING STUFF OFF

ZEN LITE

.TRAN DIRECTIVE

Nonlinear time-domain analysis

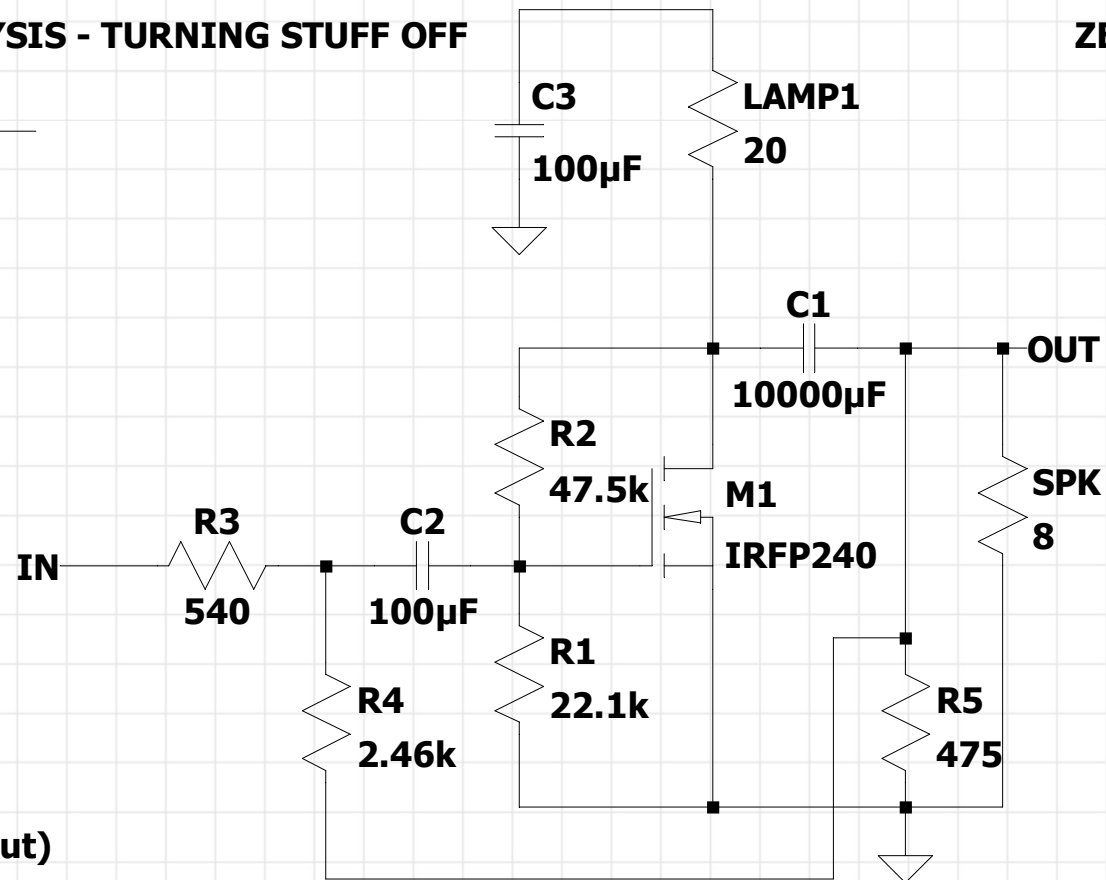
.tran 3

.IC v(n001) 40V

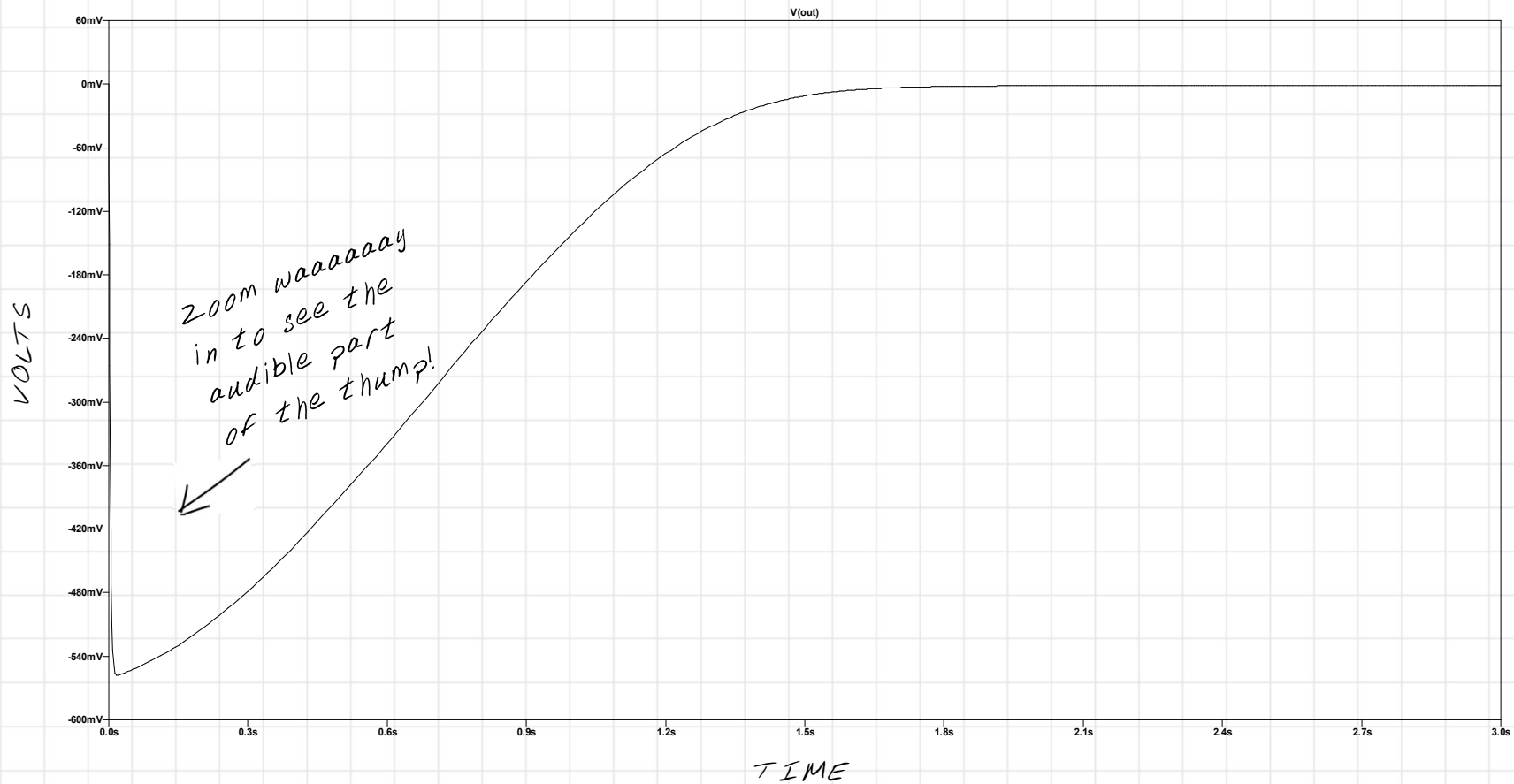
*Super deluxe bonus!
Wanna hear it for
yourself?*



.wave off.wav 16 44.1K V(out)



Zen Lite Turn Off



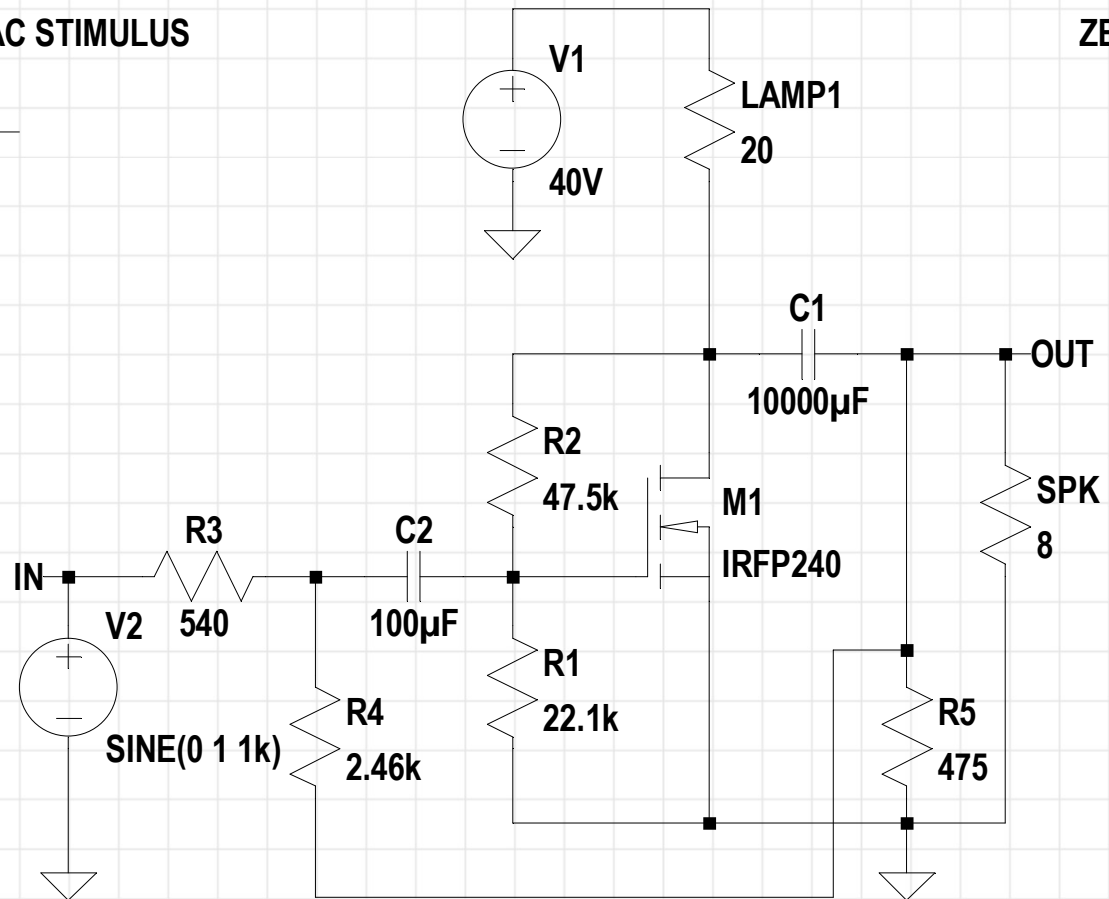
LESSON 6: TRANSIENT ANALYSIS - AC STIMULUS

ZEN LITE

.TRAN DIRECTIVE

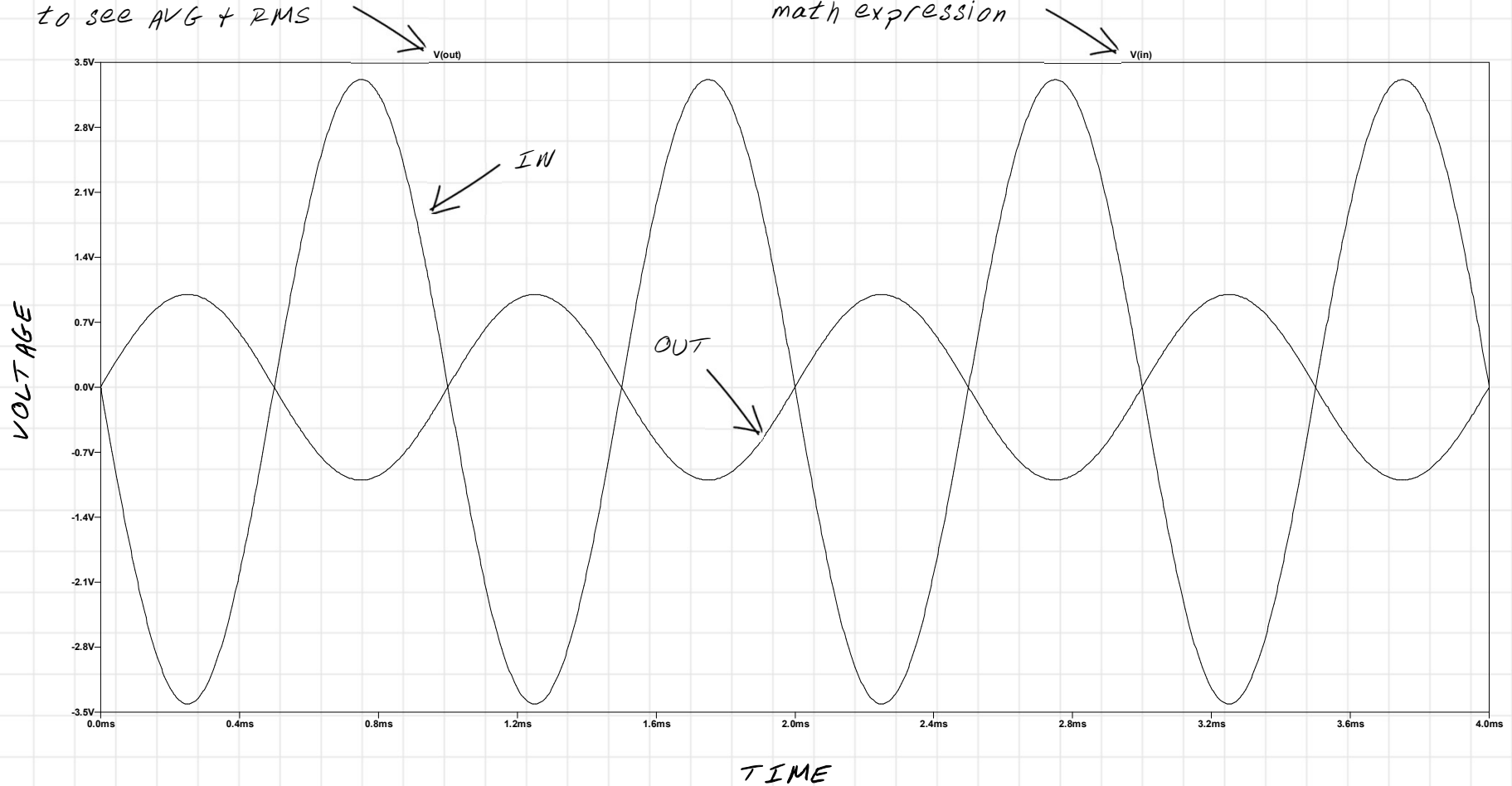
Nonlinear time-domain analysis

.tran .004



CTRL+CLICK on a label
to see AVG + RMS

RIGHT CLICK on a label to change
color, attach a cursor, or change its
math expression

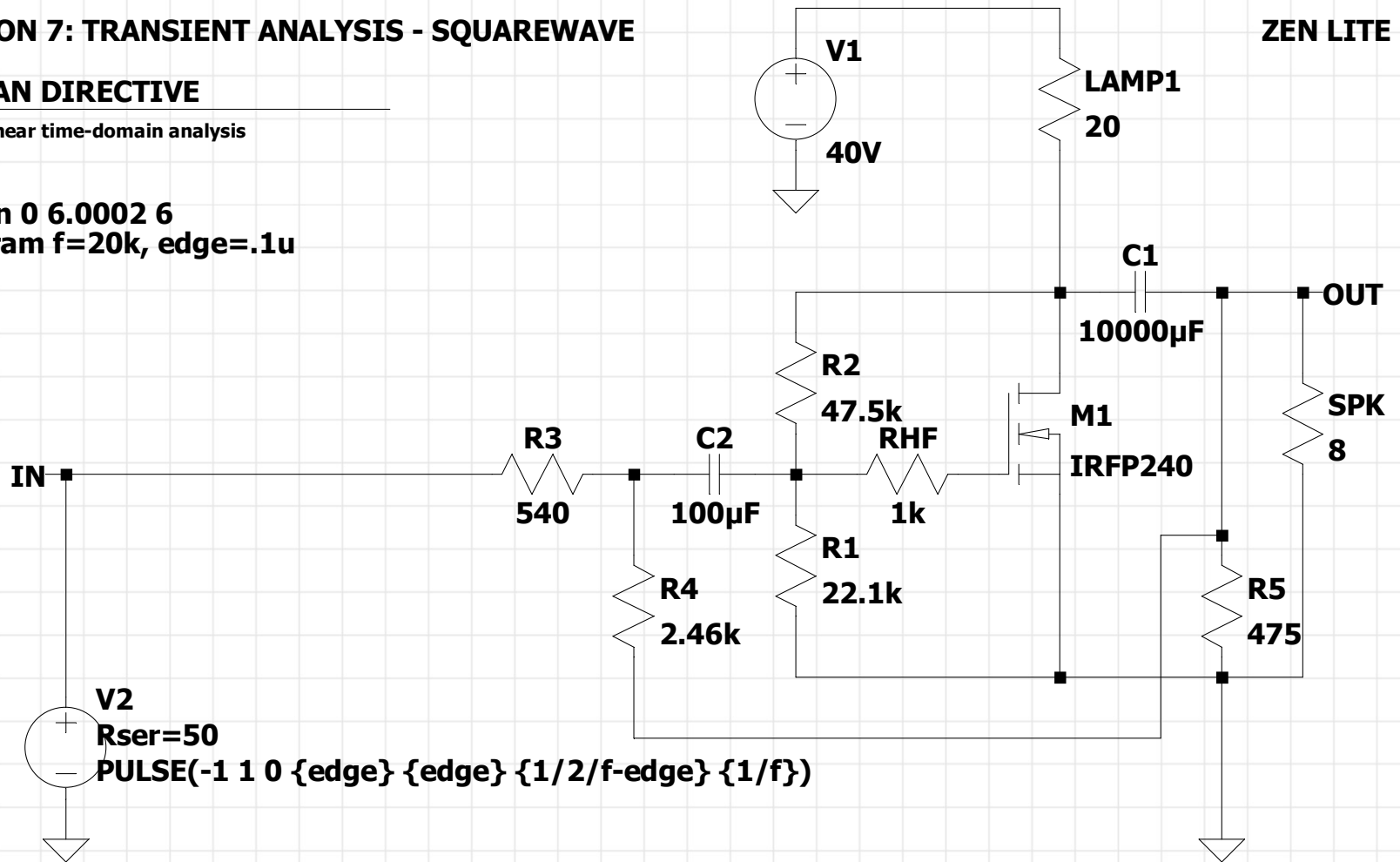


LESSON 7: TRANSIENT ANALYSIS - SQUAREWAVE

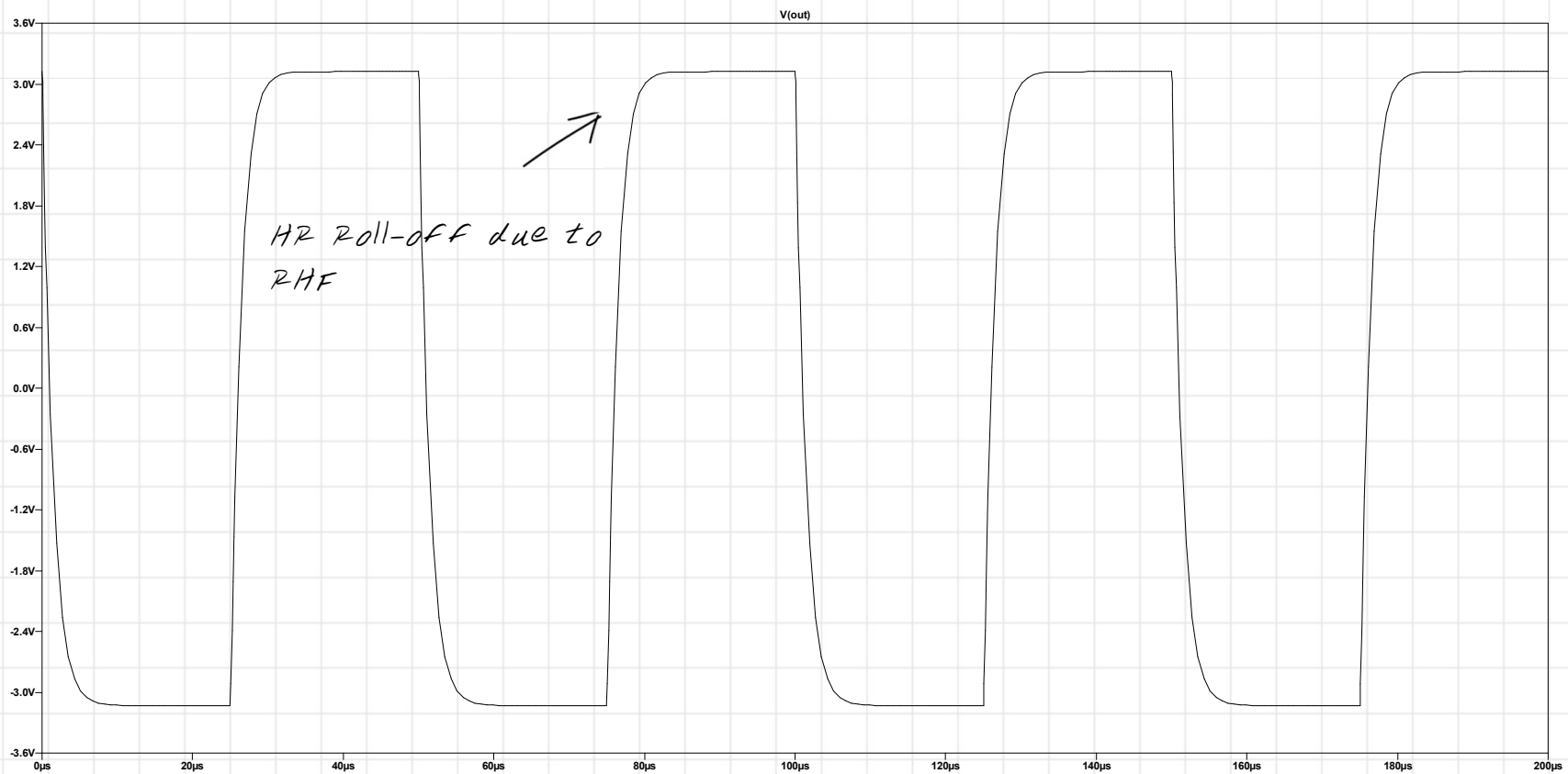
.TRAN DIRECTIVE

Nonlinear time-domain analysis

```
.tran 0 6.0002 6  
.param f=20k, edge=.1u
```



20kHz Squarewave Response

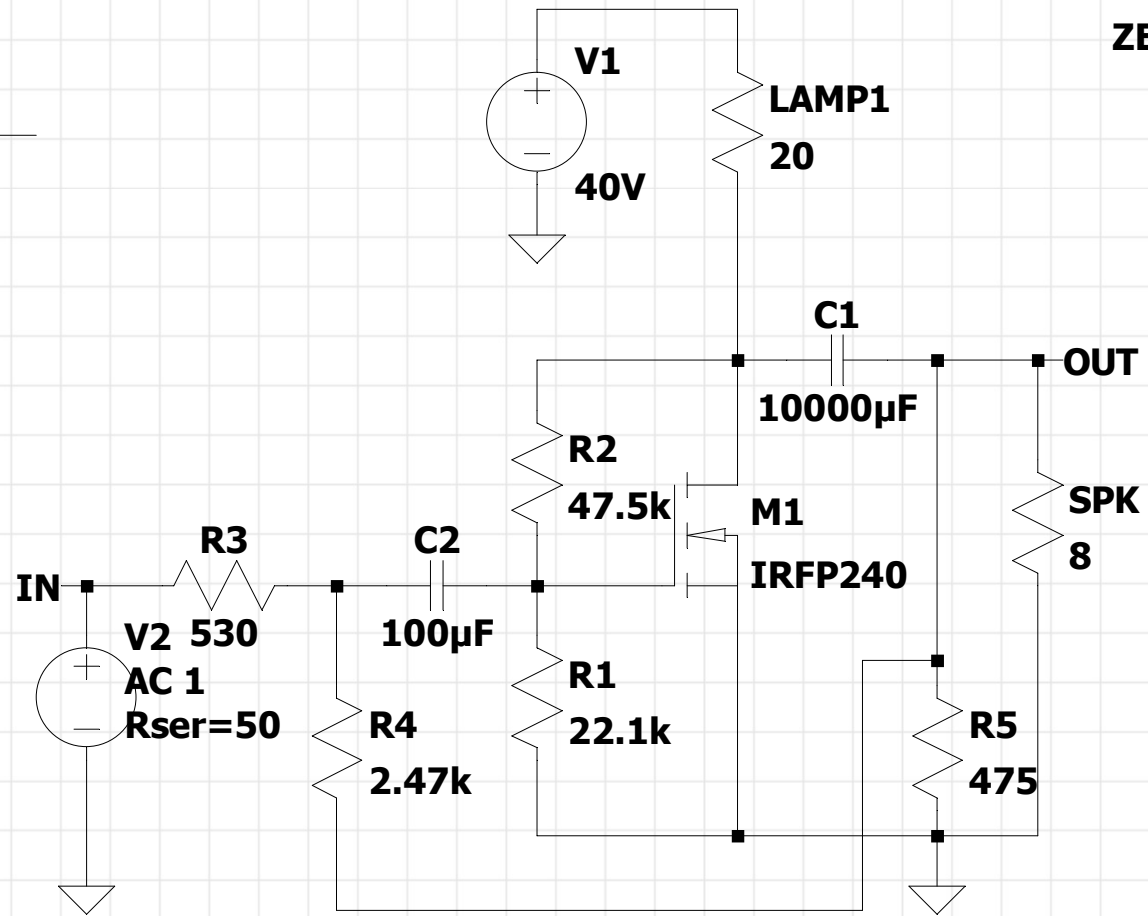


LESSON 8: AC ANALYSIS

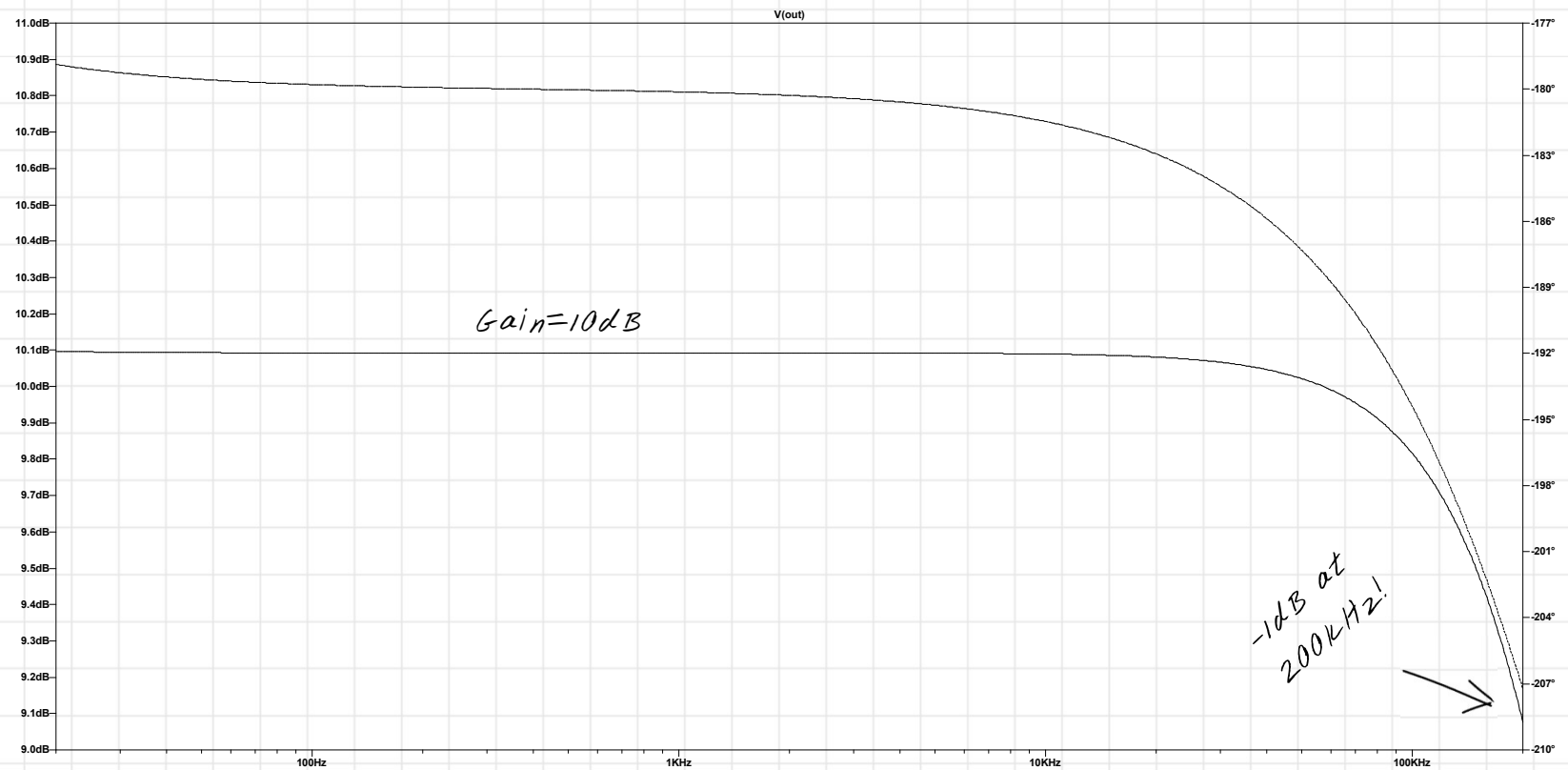
.AC DIRECTIVE

Nonlinear time-domain analysis

.ac oct 100 20 200k



Frequency Response

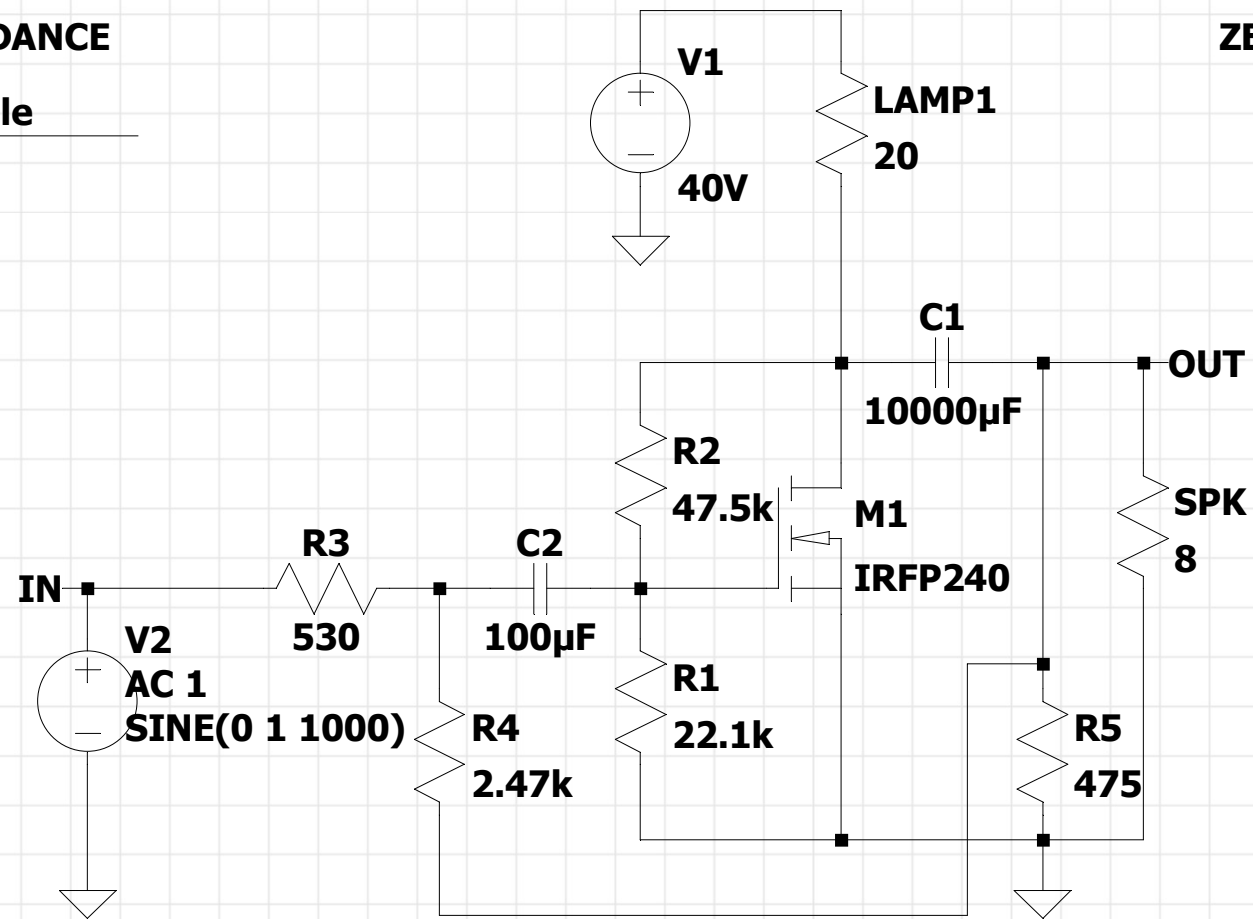


LESSON 9: INPUT IMPEDANCE

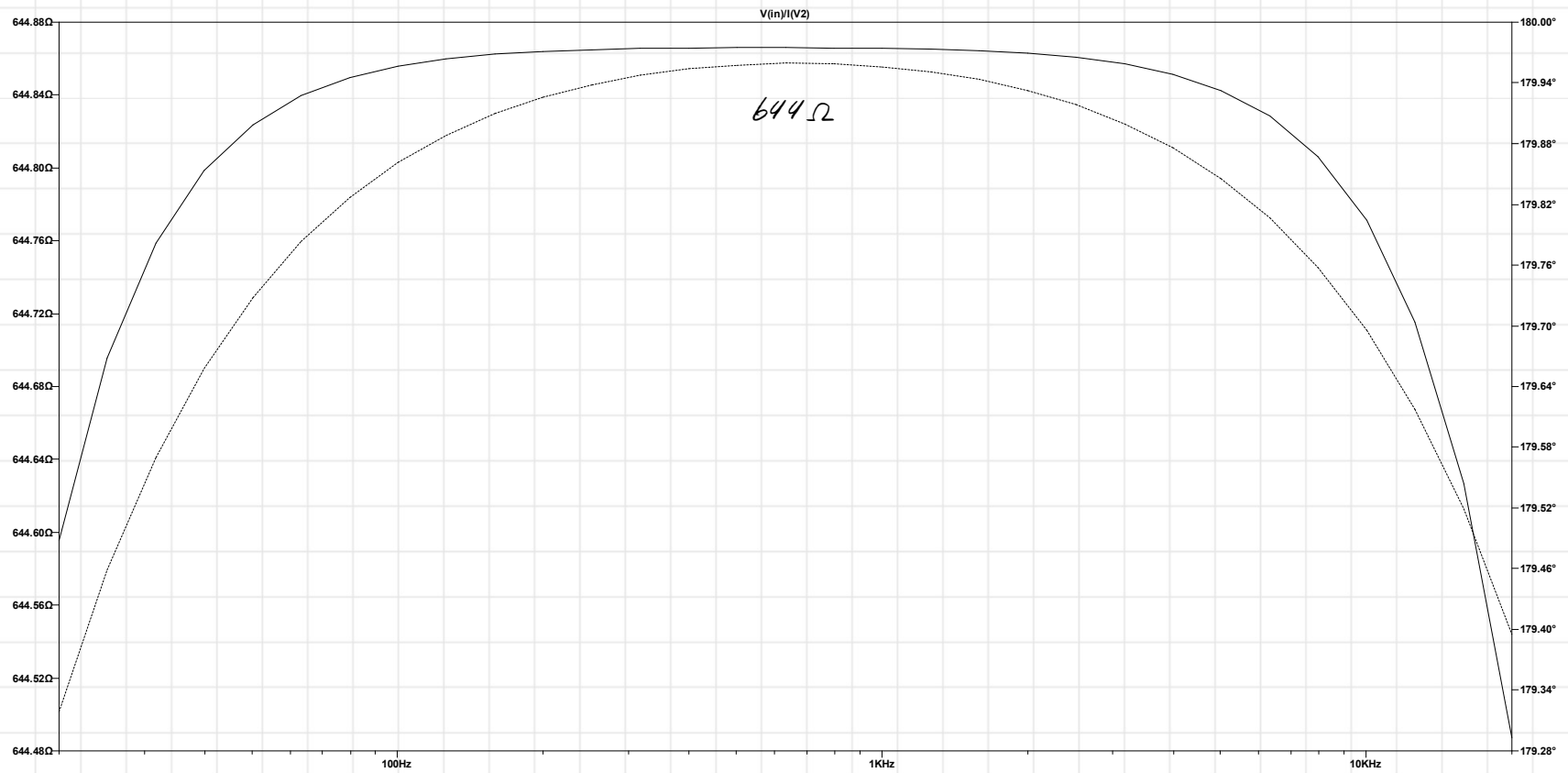
V(IN)/I(V2) Linear Scale

Input impedance vs. frequency

.ac dec .02 20 20000



Input Impedance vs. Frequency

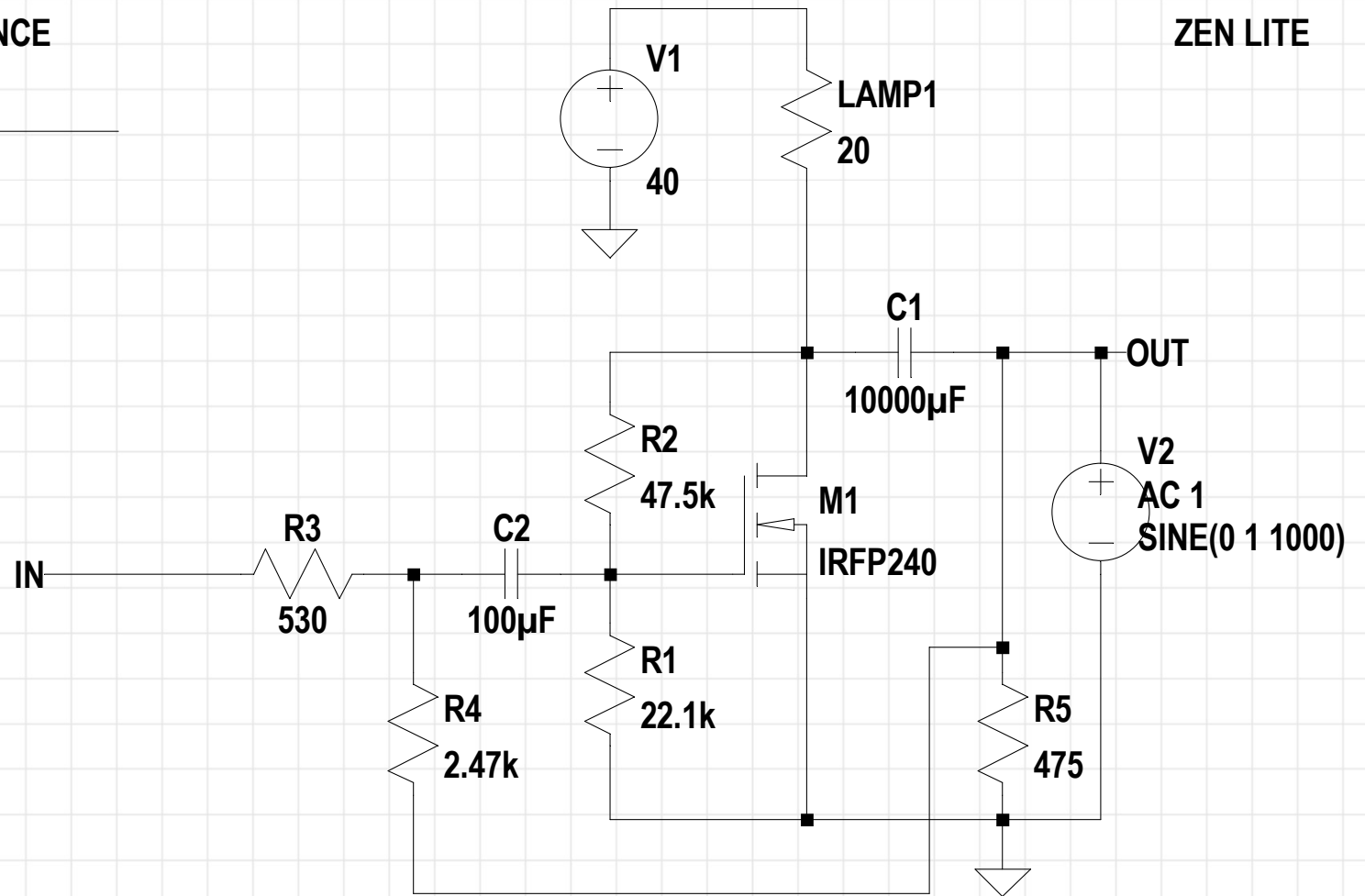


LESSON 10: OUTPUT IMPEDANCE

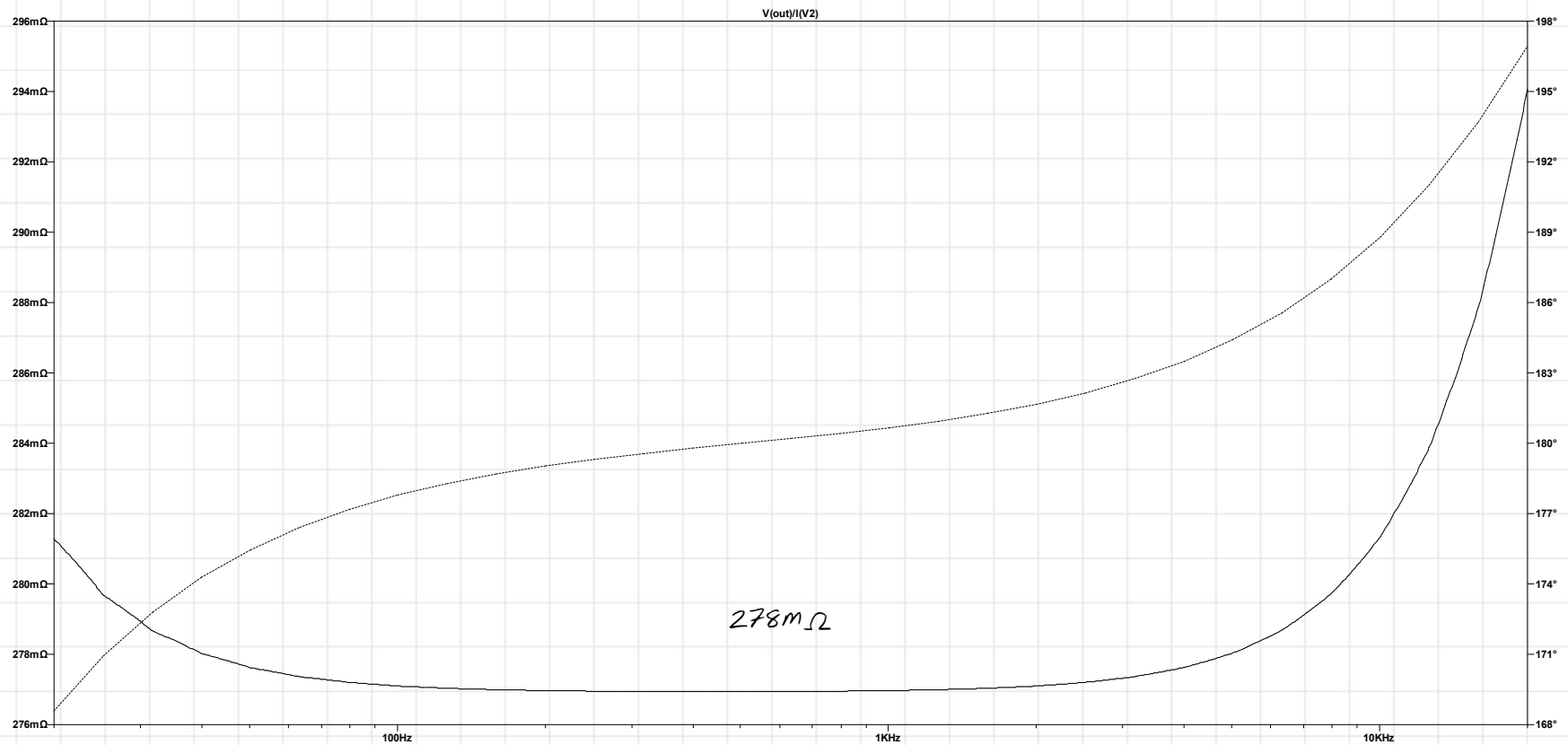
$V(\text{OUT})/I(\text{V2})$ Linear Scale

Output impedance vs. frequency

.ac dec .02 20 20000



Output Impedance vs. Frequency



LESSON 10A: OUTPUT IMPEDANCE IRL

V(OUT)/I(V2) Linear Scale

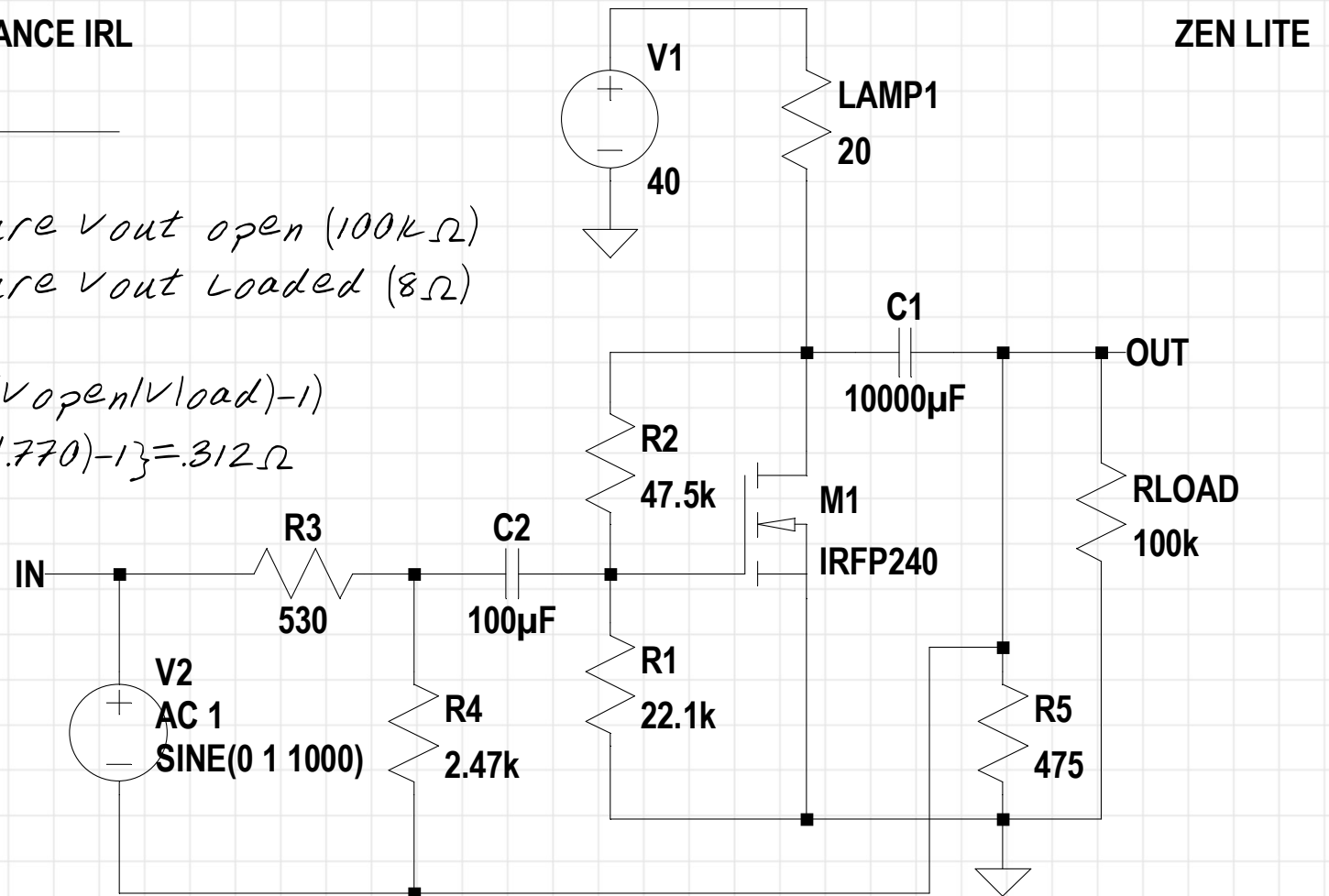
Output impedance vs. frequency

.tran .02

1. Measure V_{out} open ($100k\Omega$)
2. Measure V_{out} Loaded (8Ω)

$$Z_{out} = R_{load} * ((V_{open}/V_{load}) - 1)$$

$$Z_{out} = 8 * \{(.800/.770) - 1\} = .312\Omega$$

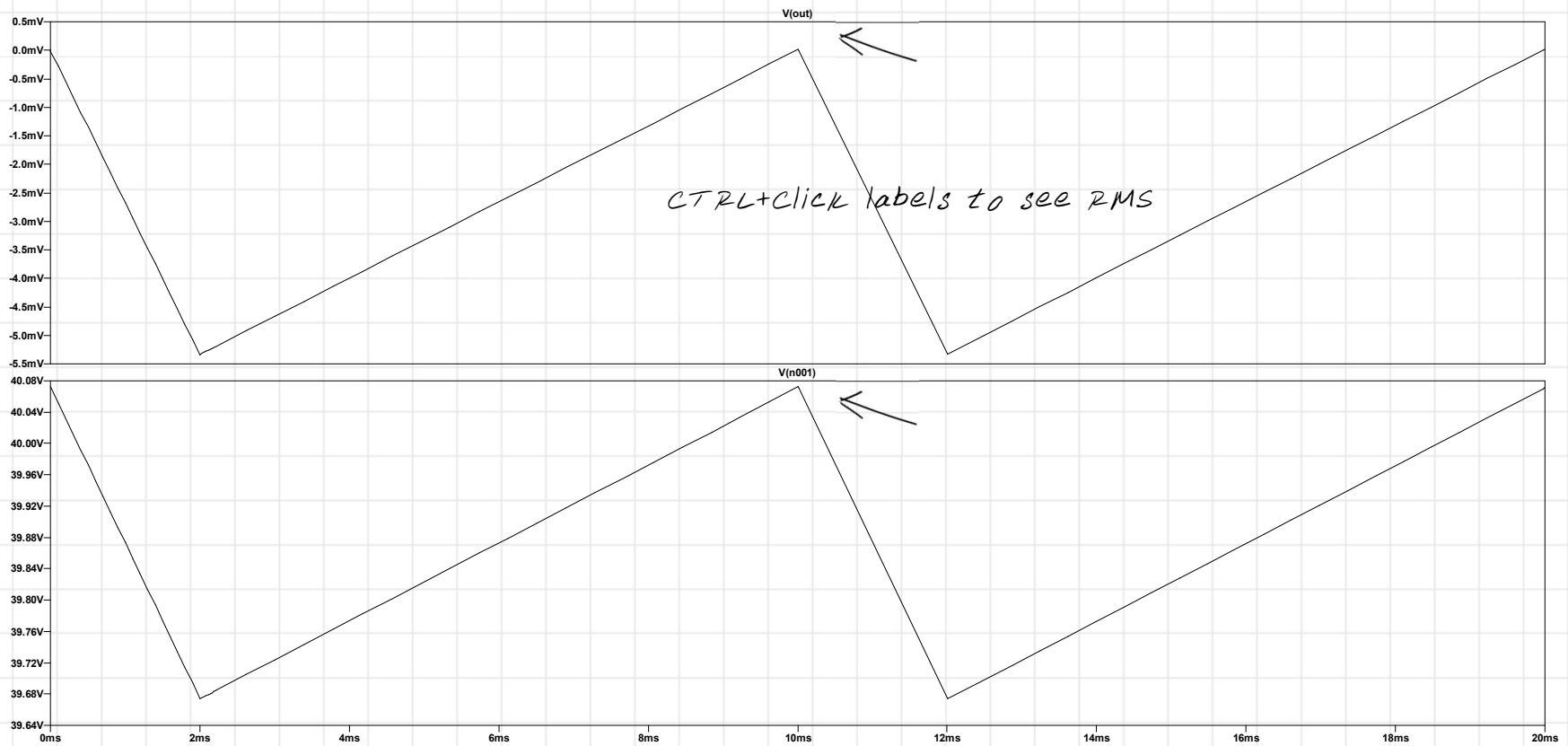


ZEN LITE

.tran .02



Ripple Rejection

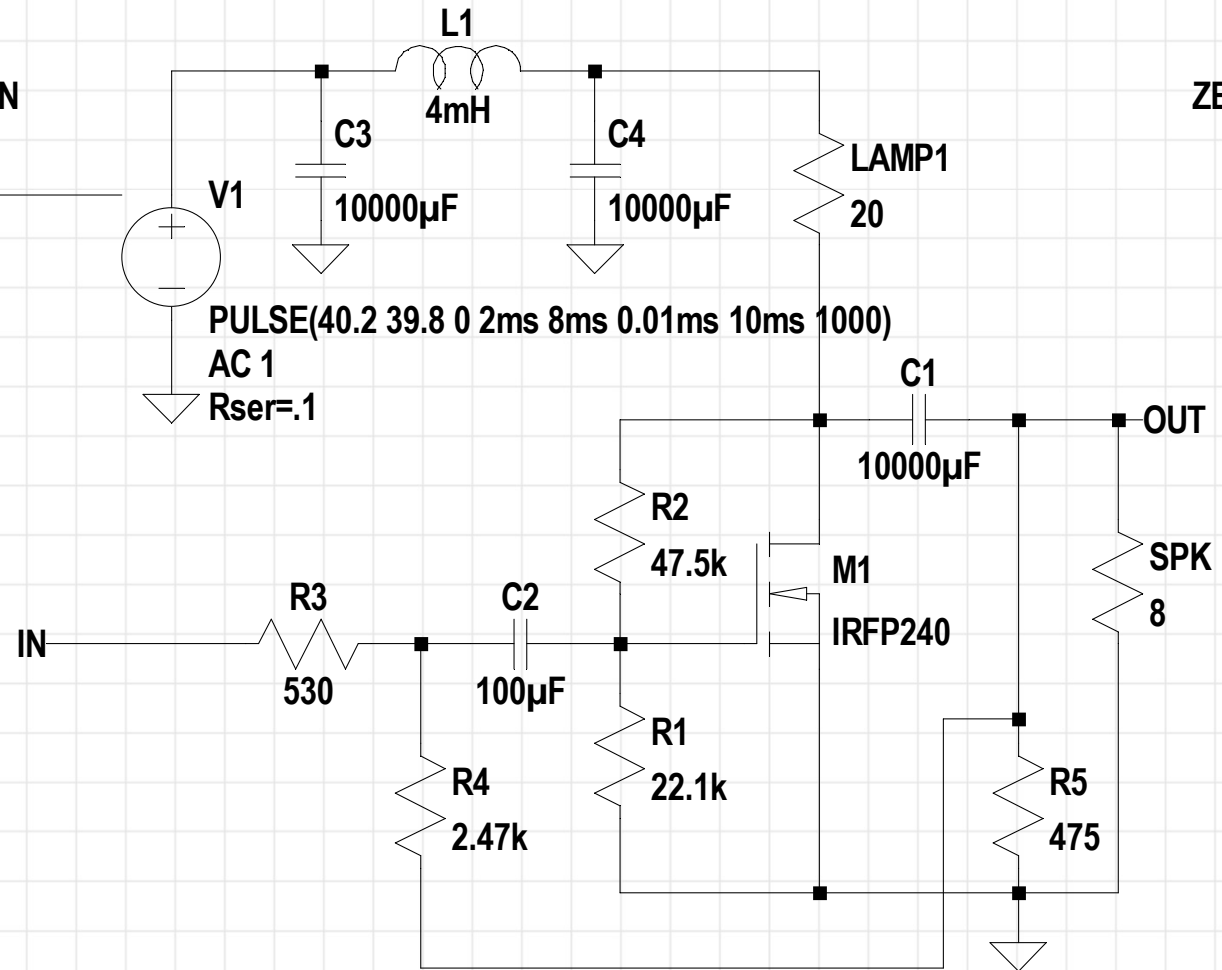


LESSON 11 RIPPLE REJECTION

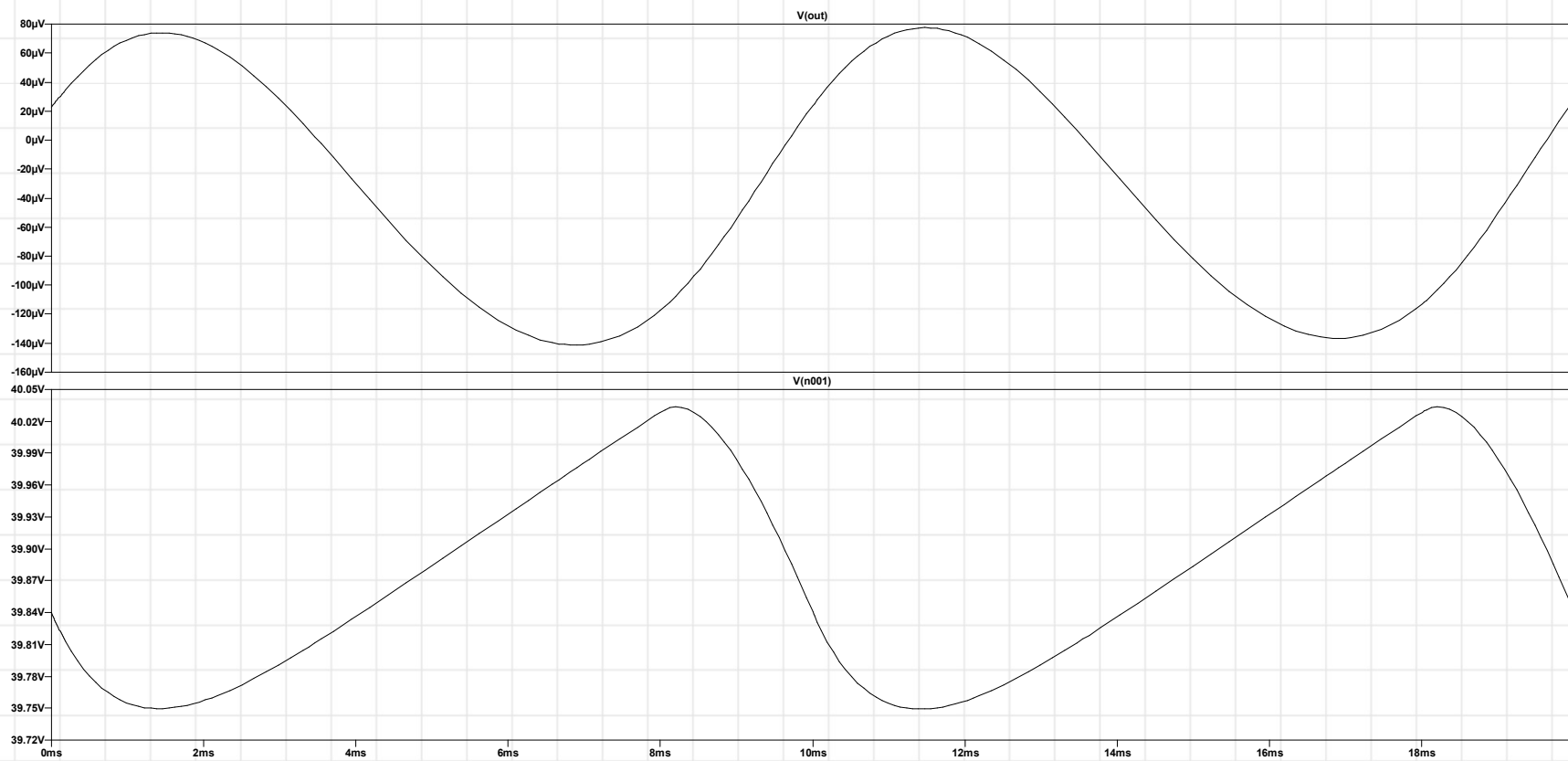
With Filtering

ZEN LITE

.tran 0 8.02 8



With Filtering

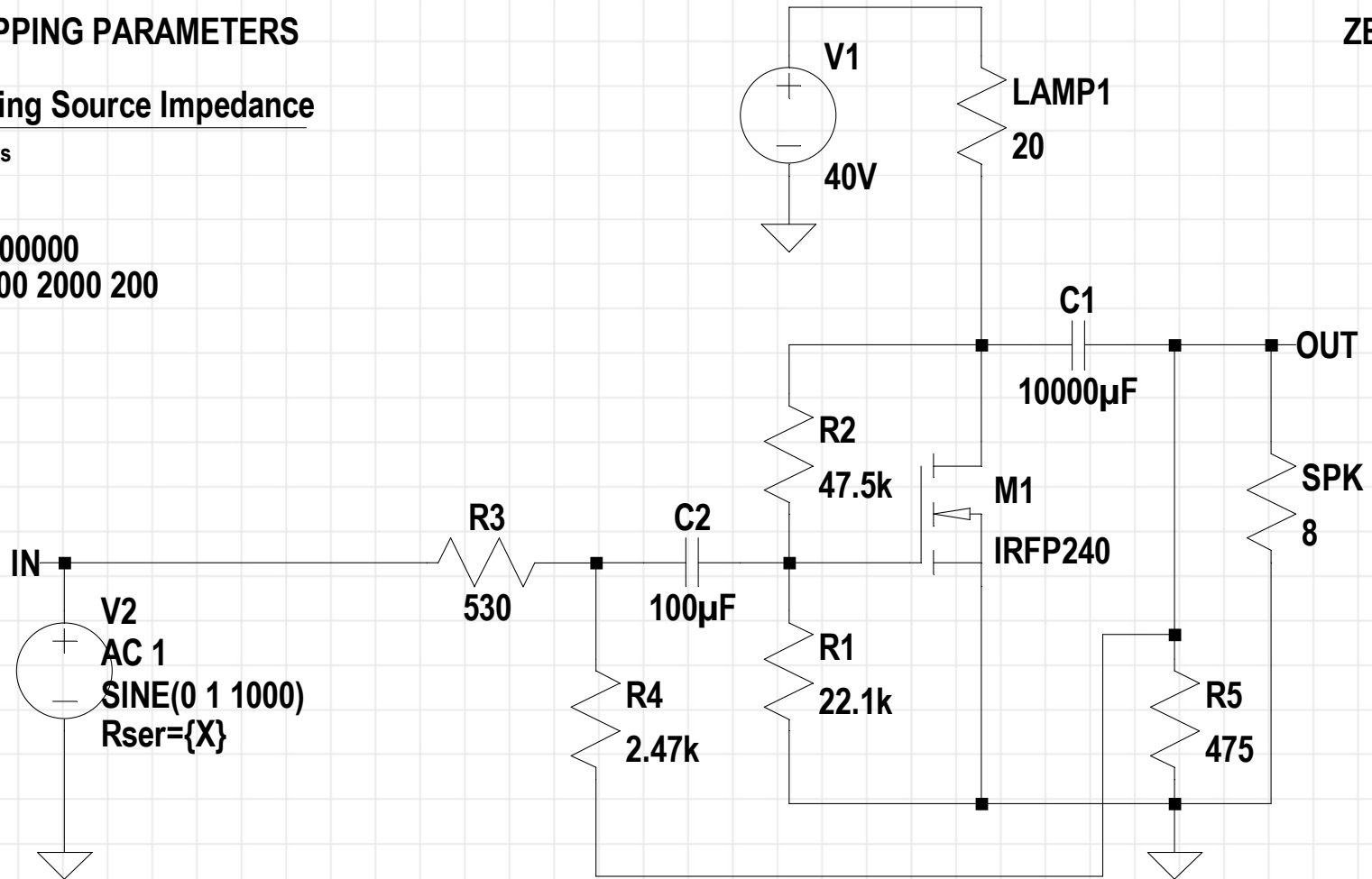


LESSON 12: STEPPING PARAMETERS

Example: Stepping Source Impedance

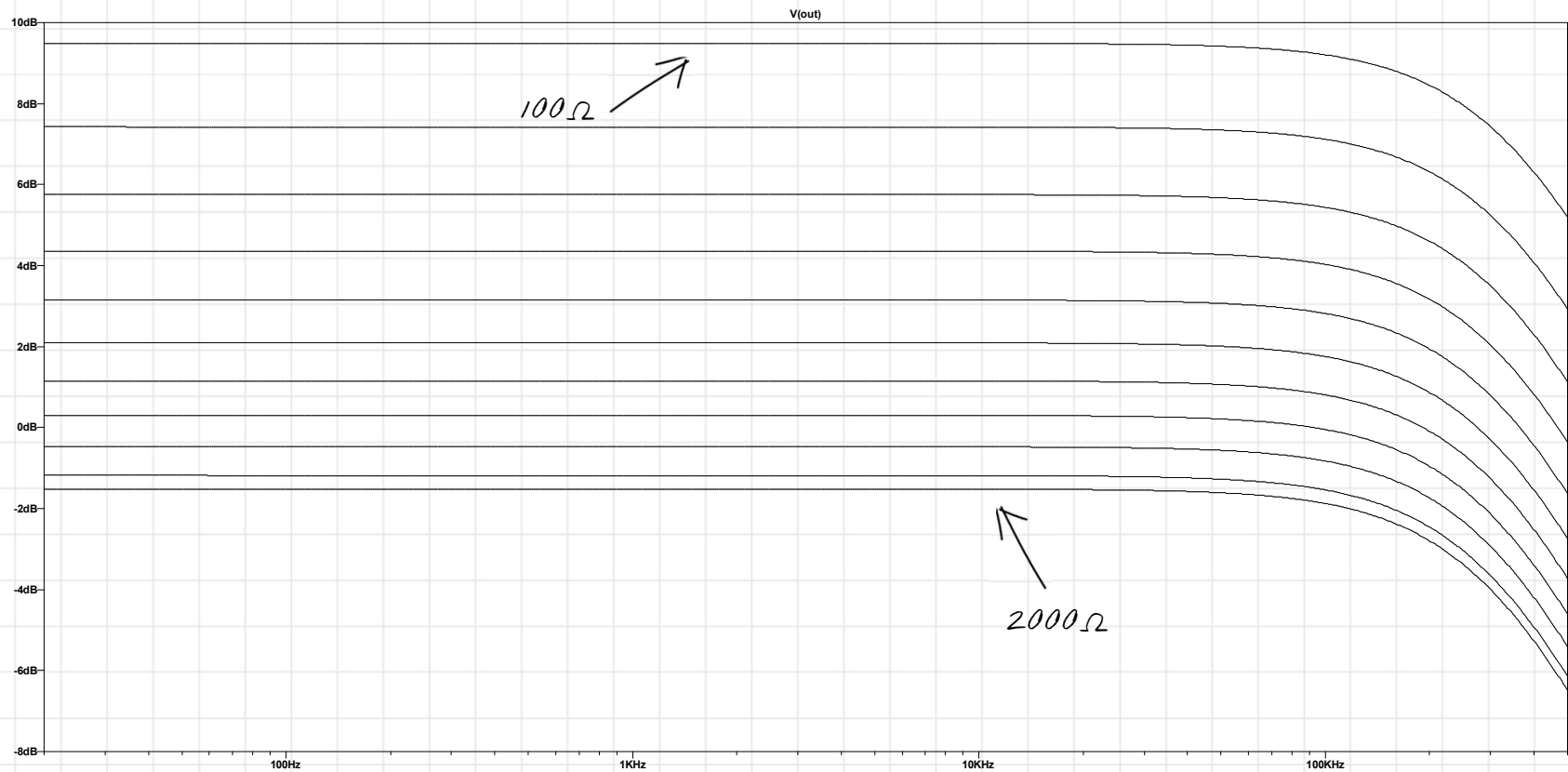
Source Impedance Effects

```
.ac dec 100 20 500000  
.step param X 100 2000 200
```



ZEN LITE

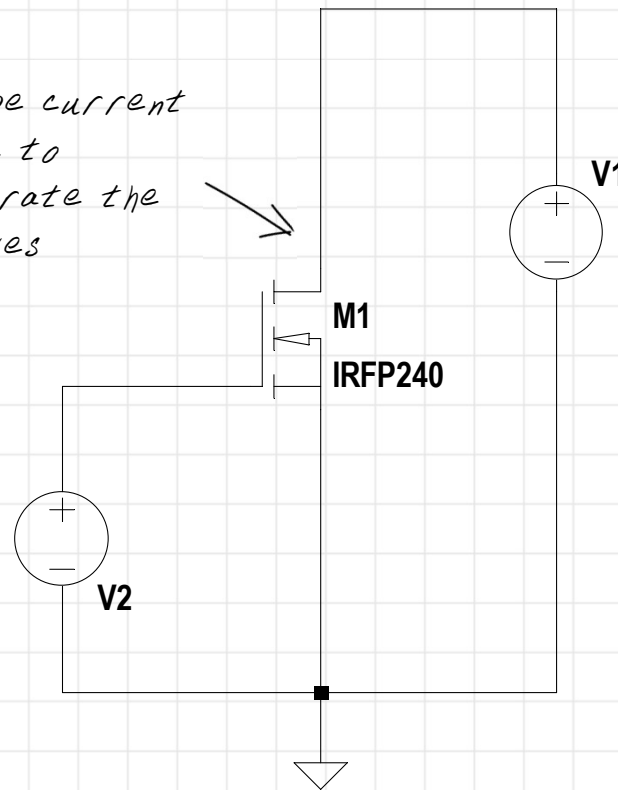
Source Impedance Effects



LESSON 13: DEVICE CHARACTERISTICS

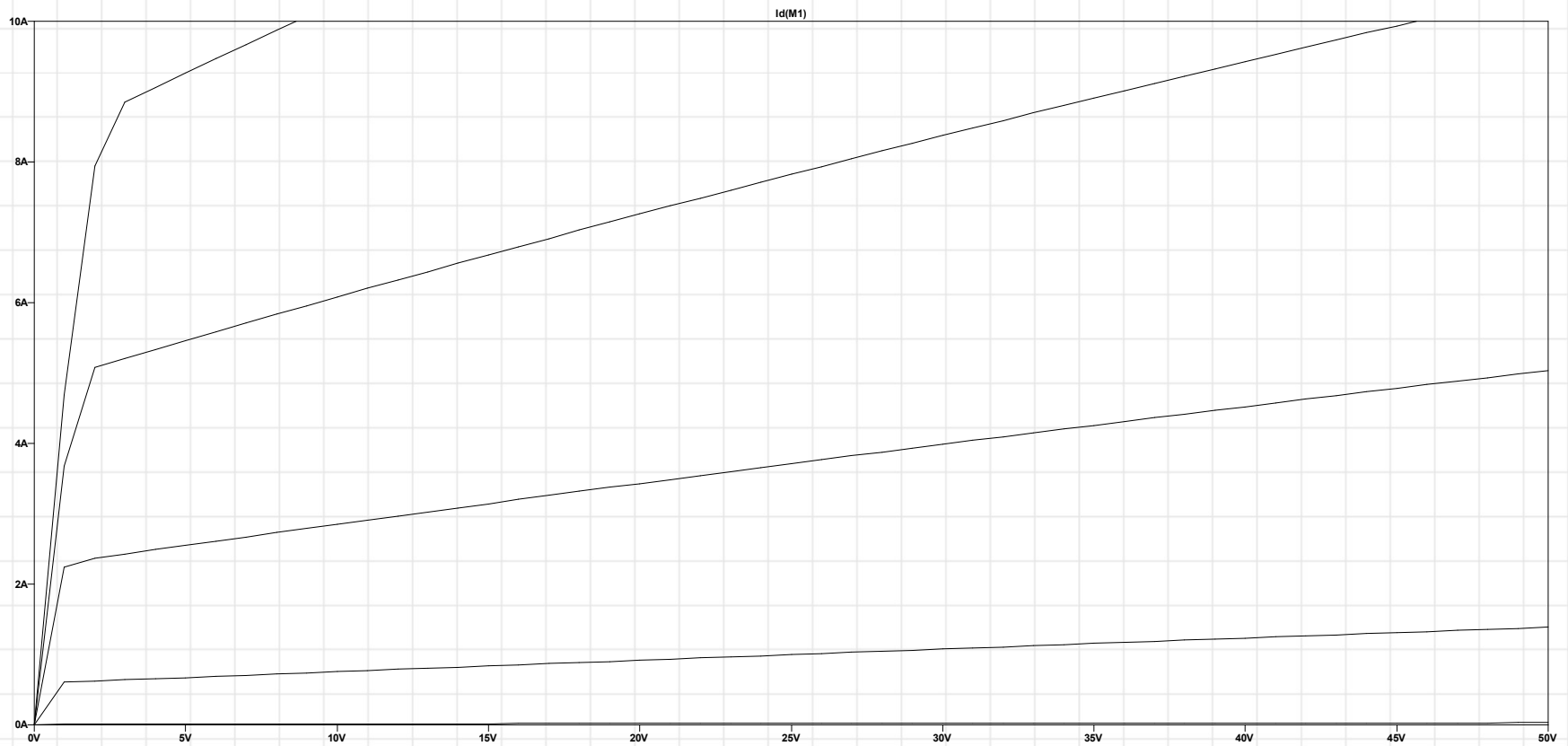
.dc V1 0 50 1 V2 4 6 .5

*Probe current
here to
generate the
curves*



PLOT DEVICE IV CURVES

IRFP240 BUILT-IN MODEL





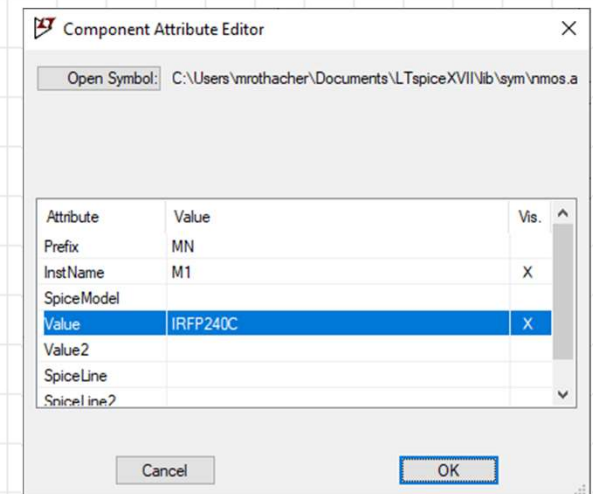
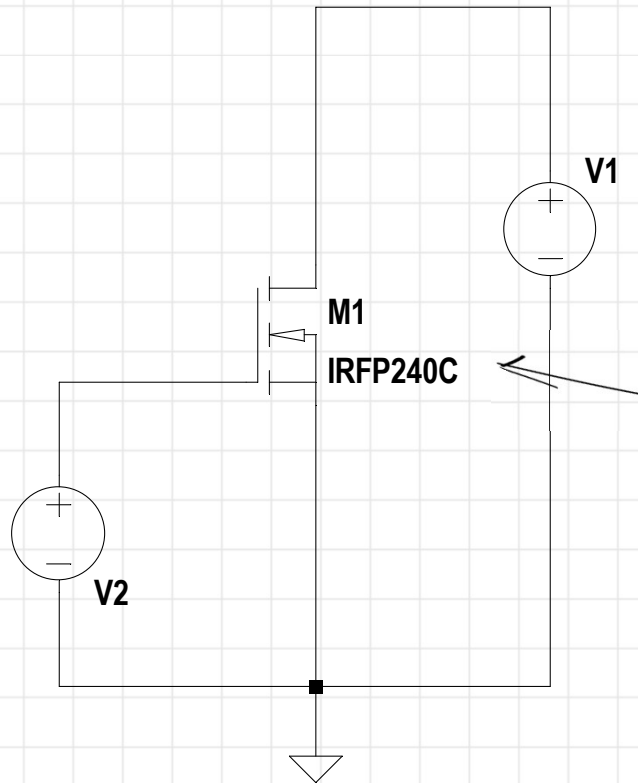
The Mysteries of Negative Feedback Revealed



Characteristic	Type of Negative Feedback			
	voltage series	voltage shunt	current series	current shunt
Sampling mixing				
voltage Gain	decreases	decreases	decreases	decreases
Bandwidth	increases	increases	increases	increases
Harmonic distortion	decreases	decreases	decreases	decreases
Noise	decreases	decreases	decreases	decreases
Input Resistance	increases	decreases	increases	decreases
Output Resistance	decreases	decreases	increases	increases
	"Triodey"		"Pentodey"	

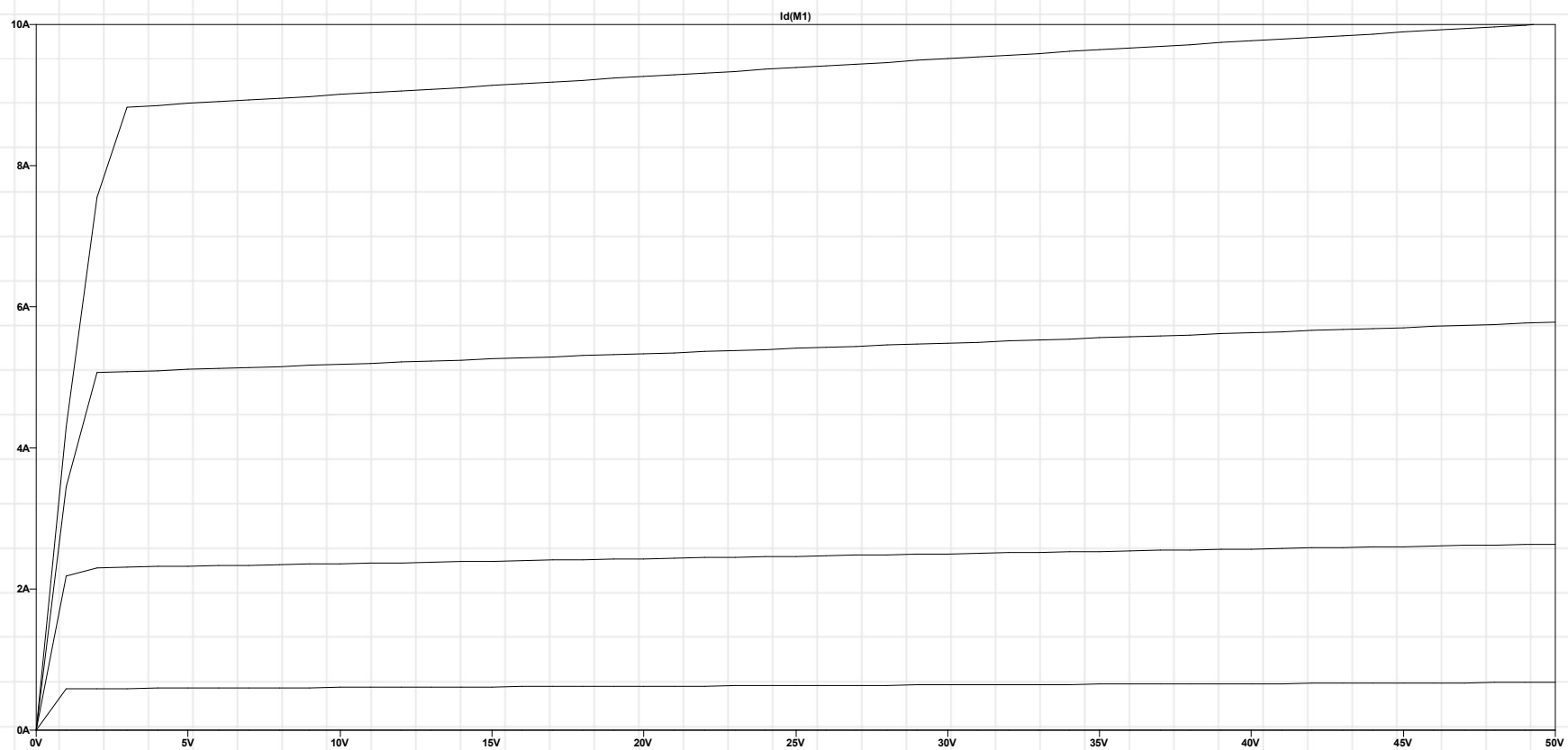
LESSON 14: CUSTOM MODELS

```
.inc cordell-models.txt  
.dc V1 0 50 1 V2 4 6 .5
```



PLOT DEVICE IV CURVES

IRFP240C CORDELL MODEL

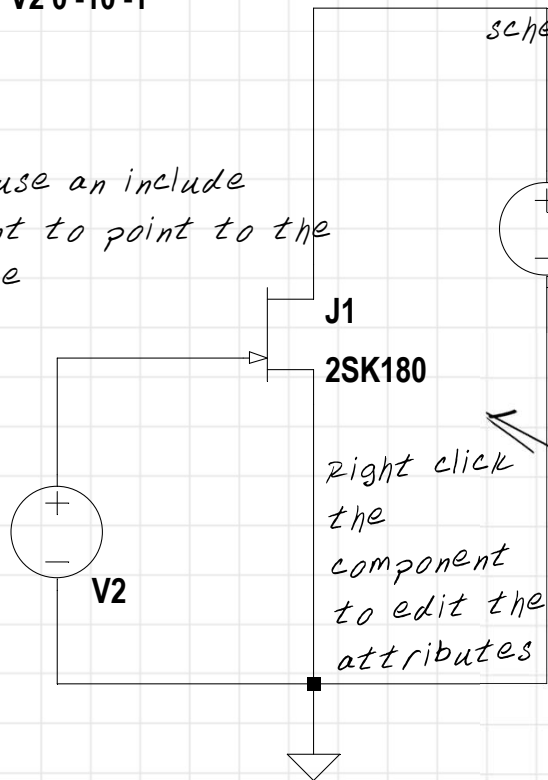


LESSON 14A: CUSTOM MODELS SUBCKT

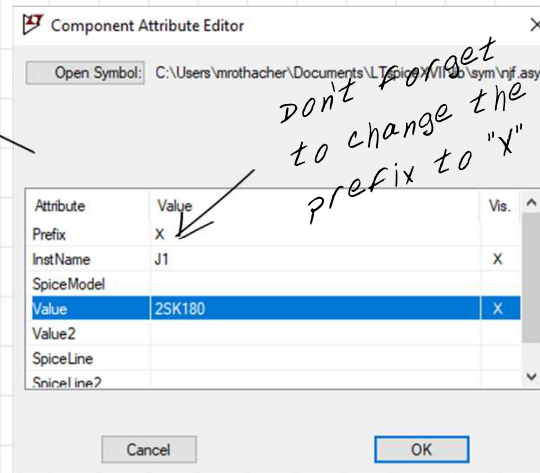
```
;inc 2sk180.txt
.dc V1 0 50 1 V2 0 -10 -1
```

You can use an include statement to point to the model file

Or you can just paste the model text right into the schematic



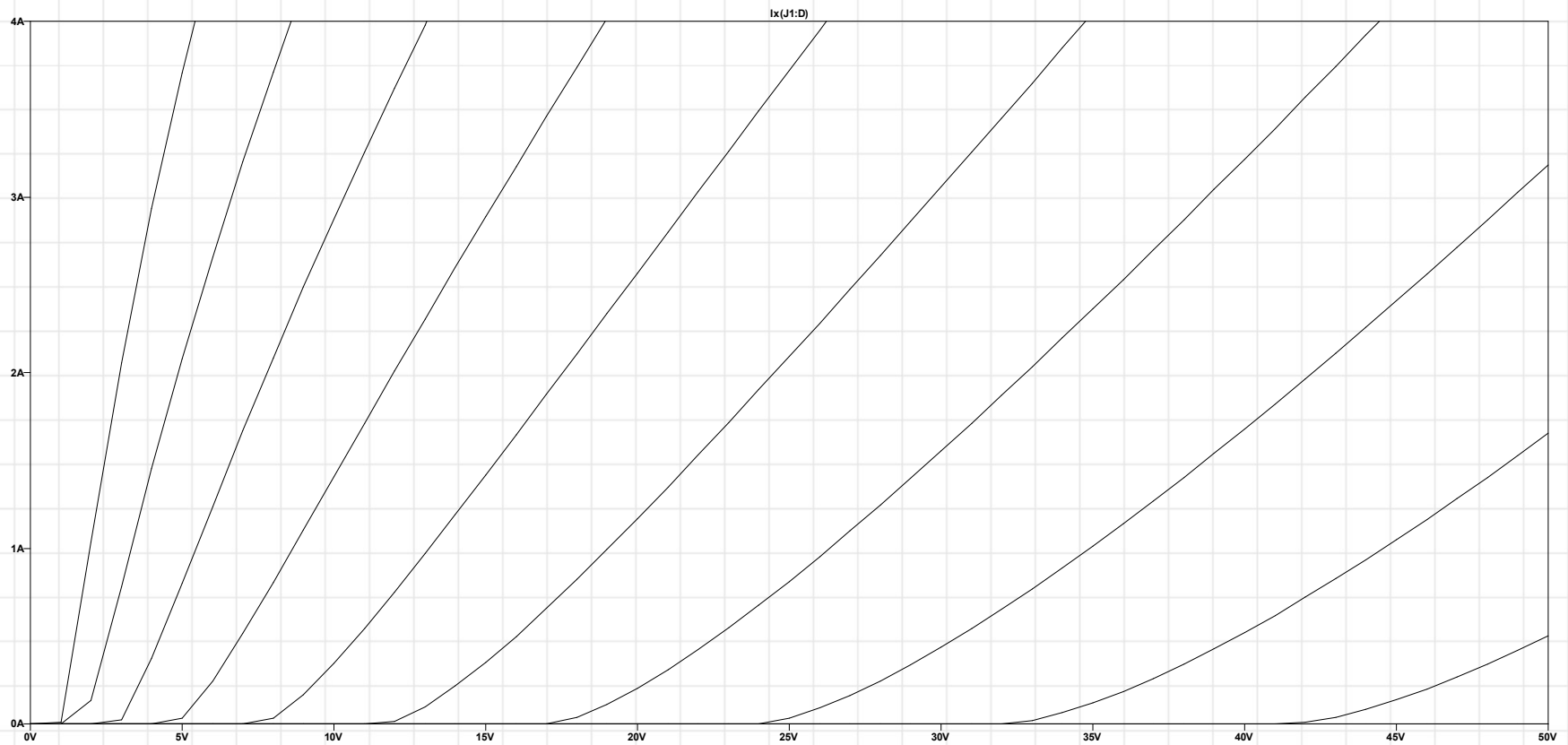
Right click the component to edit the attributes



```
*-----
*2SK180
*GENERATED BY SIT MODELER @ PASSDIY.TV
*MODEL RANGE: 100V, 5A
*-----
.SUBCKT 2SK180 D G S ; Drain Gate Source
+ PARAMS: MU=17 X=1.5 K=0.67 N=1.76 VCT=0 RG=2MEG
*-----
B1 D S I=K*PWR(URAMP((V(G,S)+VCT)+(N*LN(V(D,S))+(V(D,S)/MU))),X)
*FOR MULTISIM COMMENT OUT ABOVE LINE (*) AND UNCOMMENT NEXT LINE
*B1 D S I=K*PWR(MAX((V(G,S)+VCT)+(N*LN(V(D,S))+(V(D,S)/MU)),0),X)
R1 G S {RG}
CGS G S 2000P
CGD G D 2000P
CDS G S 0P
.ENDS 2SK180
*-----
```

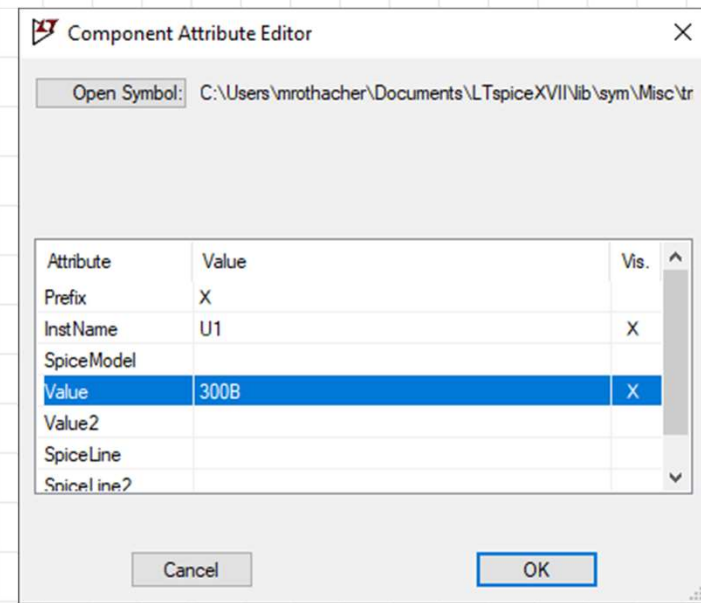
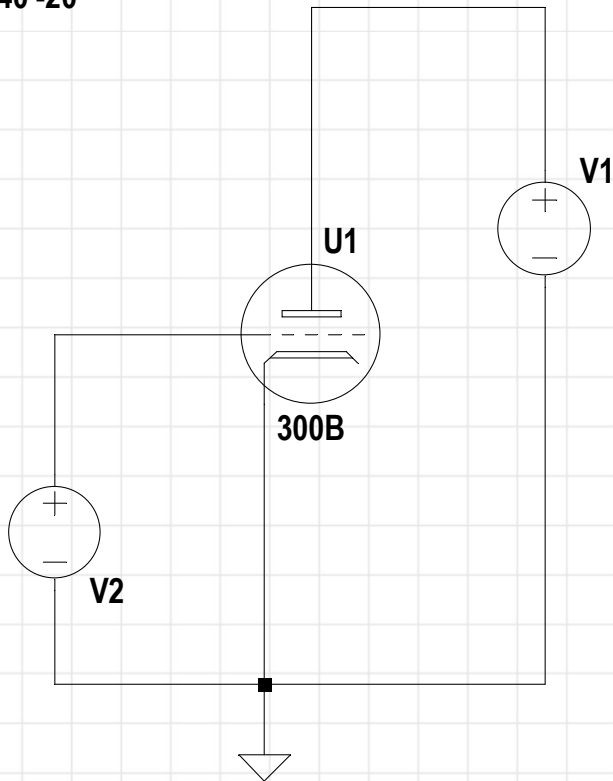
PLOT DEVICE IV CURVES

2SK180 Rothacher SIT Model



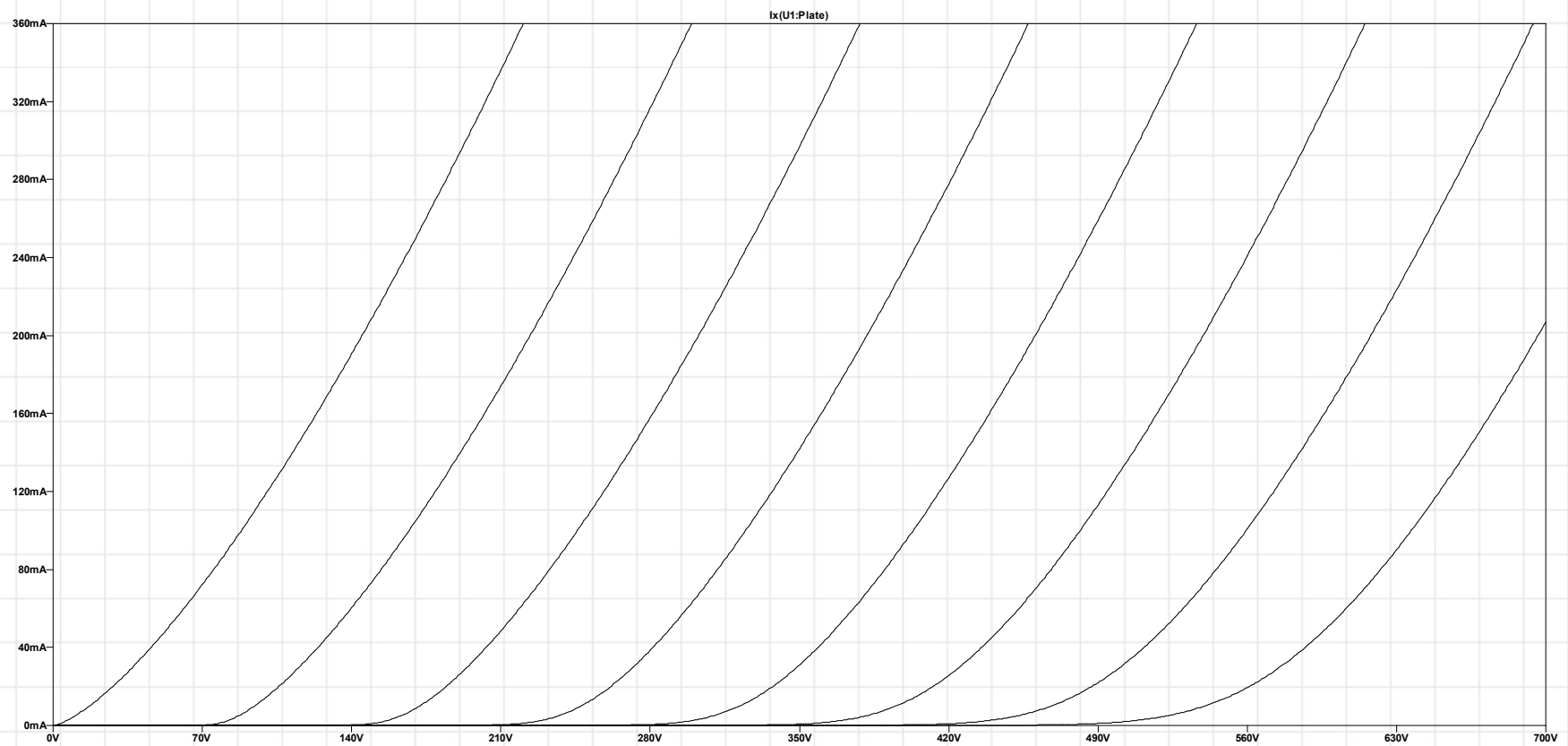
LESSON 15: TUBES

.lib Tube.lib
.dc V1 0 700 1 V2 0 -140 -20



PLOT DEVICE IV CURVES

300B Koren Model

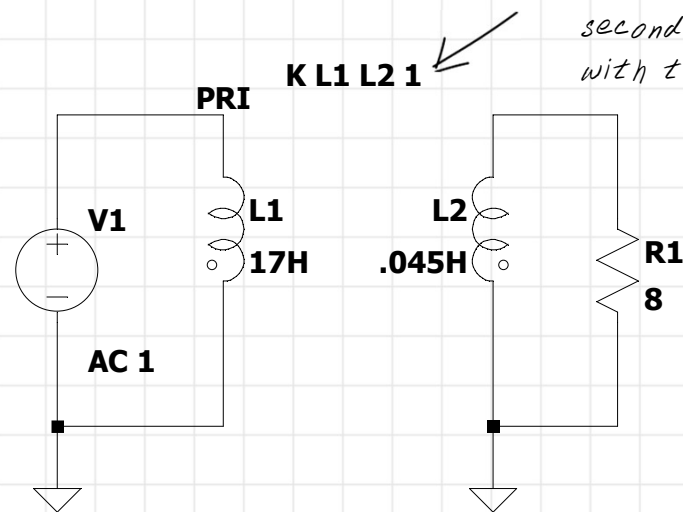


LESSON 16 - TRANSFORMERS

Add trace V(pri)/I(v1) linear scale

.ac dec 100 20 20000

Note:
Inductance
ratio is the
same as
impedance
ratio



To measure the coupling coefficient of a real transformer, measure the inductance of the primary with the secondary open, then measure again with the secondary shorted.

$$K = \text{SQRT}(1 - (L_{\text{short}} / L_{\text{open}}))$$

$$\text{Voltage Transformation Ratio} = W_{\text{sec}} / W_{\text{pri}}$$

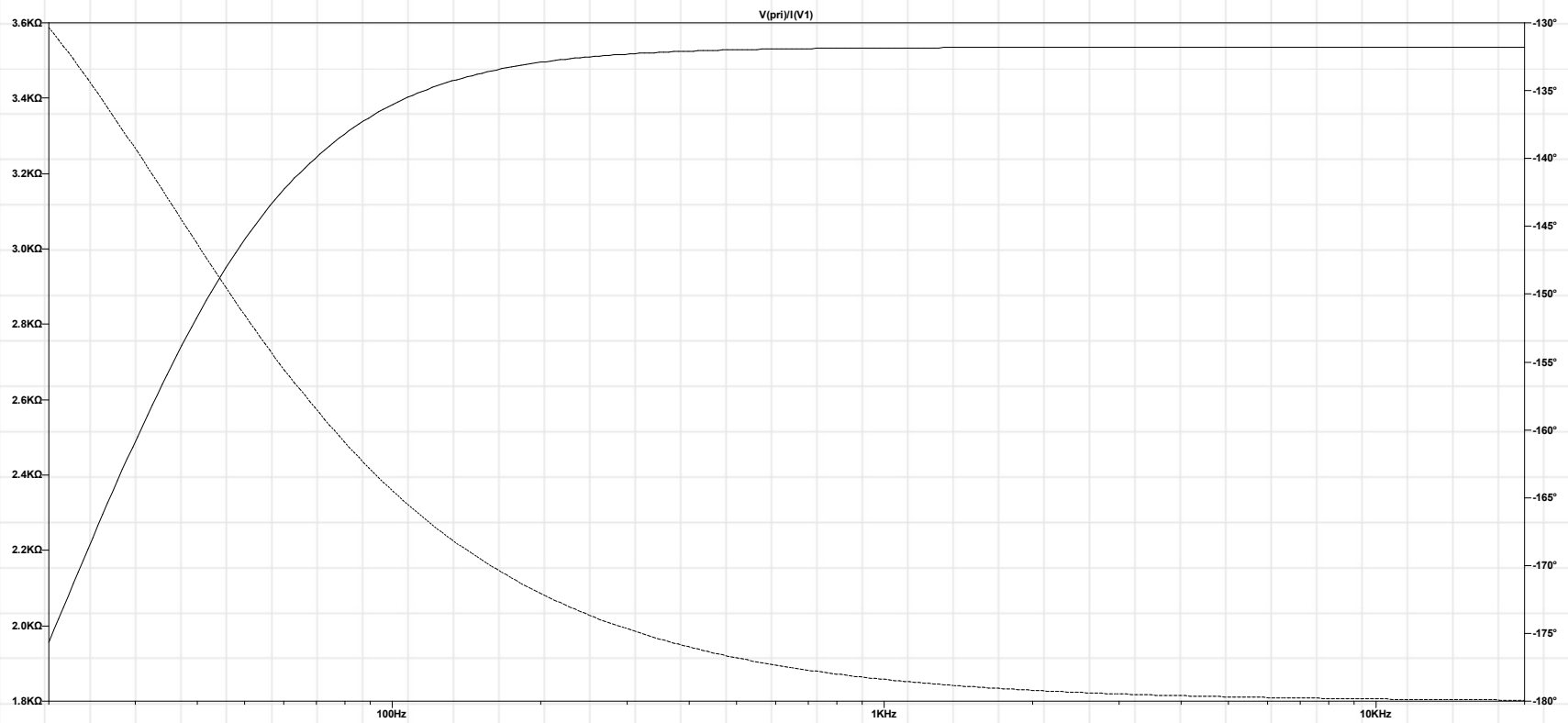
$$\text{Current Transformation Ratio} = W_{\text{pri}} / W_{\text{sec}}$$

$$\text{Impedance Transformation Ratio} = (W_{\text{sec}} / W_{\text{pri}})^2$$

Where W = number of turns in winding

UBT-3

UBT-3 Primary Impedance

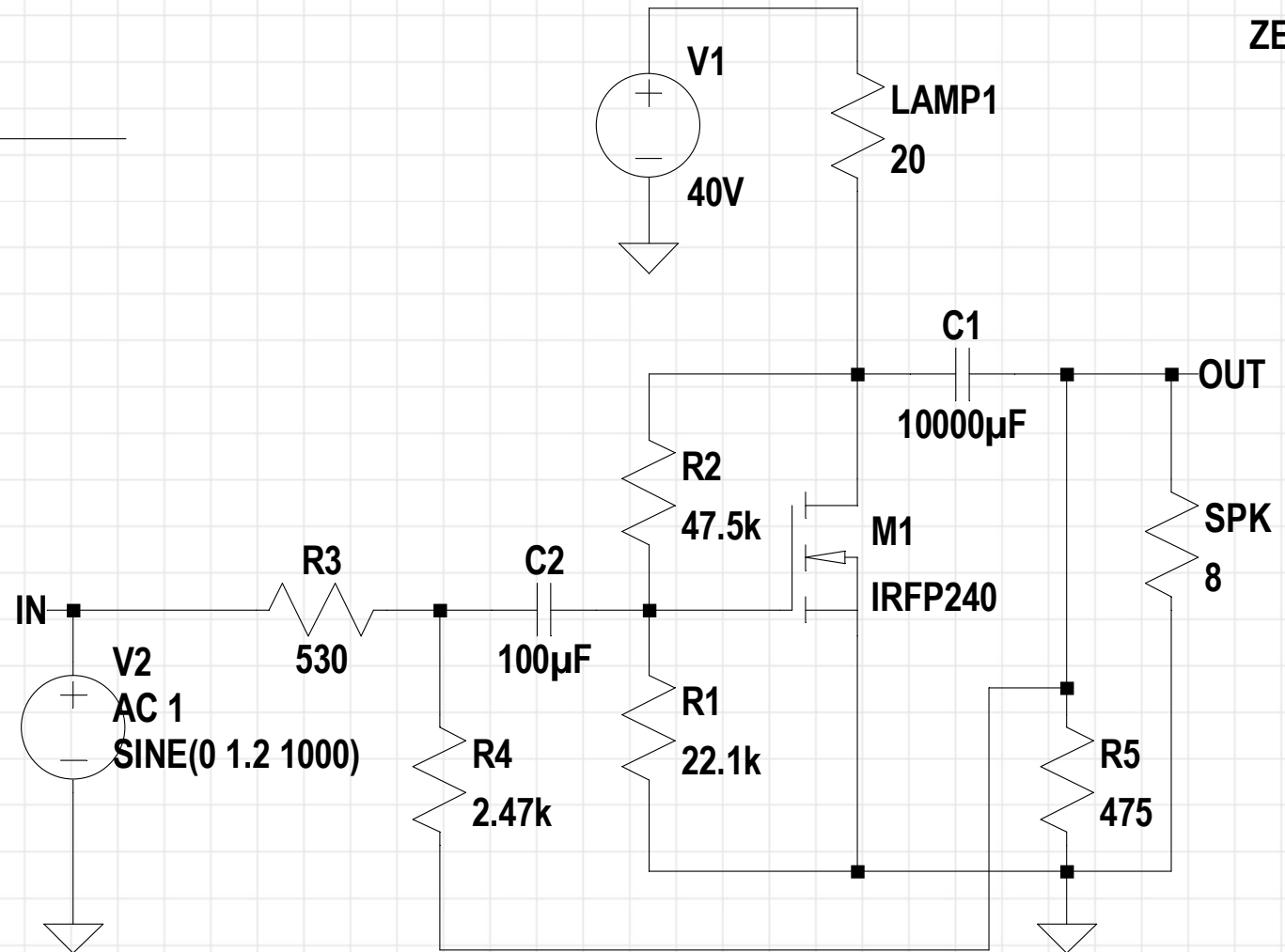


LESSON 17: THD ANALYSIS

USING .FOUR

Output impedance vs. frequency

```
.tran .02  
.four 1kHz v(out)
```



Fourier Analysis Results From Error Log

Fourier components of V(out)
DC component:-0.0353229

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component	Phase [degree]	Normalized Phase [deg]
1	1.000e+03	4.088e+00	1.000e+00	179.88°	0.00°
2	2.000e+03	3.911e-02	9.566e-03	89.01°	-90.86°
3	3.000e+03	7.889e-03	1.930e-03	-179.10°	-358.97°
4	4.000e+03	1.255e-03	3.069e-04	-92.98°	-272.86°
5	5.000e+03	1.508e-04	3.688e-05	19.81°	-160.06°
6	6.000e+03	6.340e-05	1.551e-05	75.68°	-104.19°
7	7.000e+03	6.428e-05	1.572e-05	-18.91°	-198.79°
8	8.000e+03	4.110e-05	1.005e-05	149.66°	-30.21°
9	9.000e+03	9.482e-05	2.319e-05	143.08°	-36.80°

Total Harmonic Distortion: 0.976316% (0.977848%)

Measured amplitude
Measured Amplitude

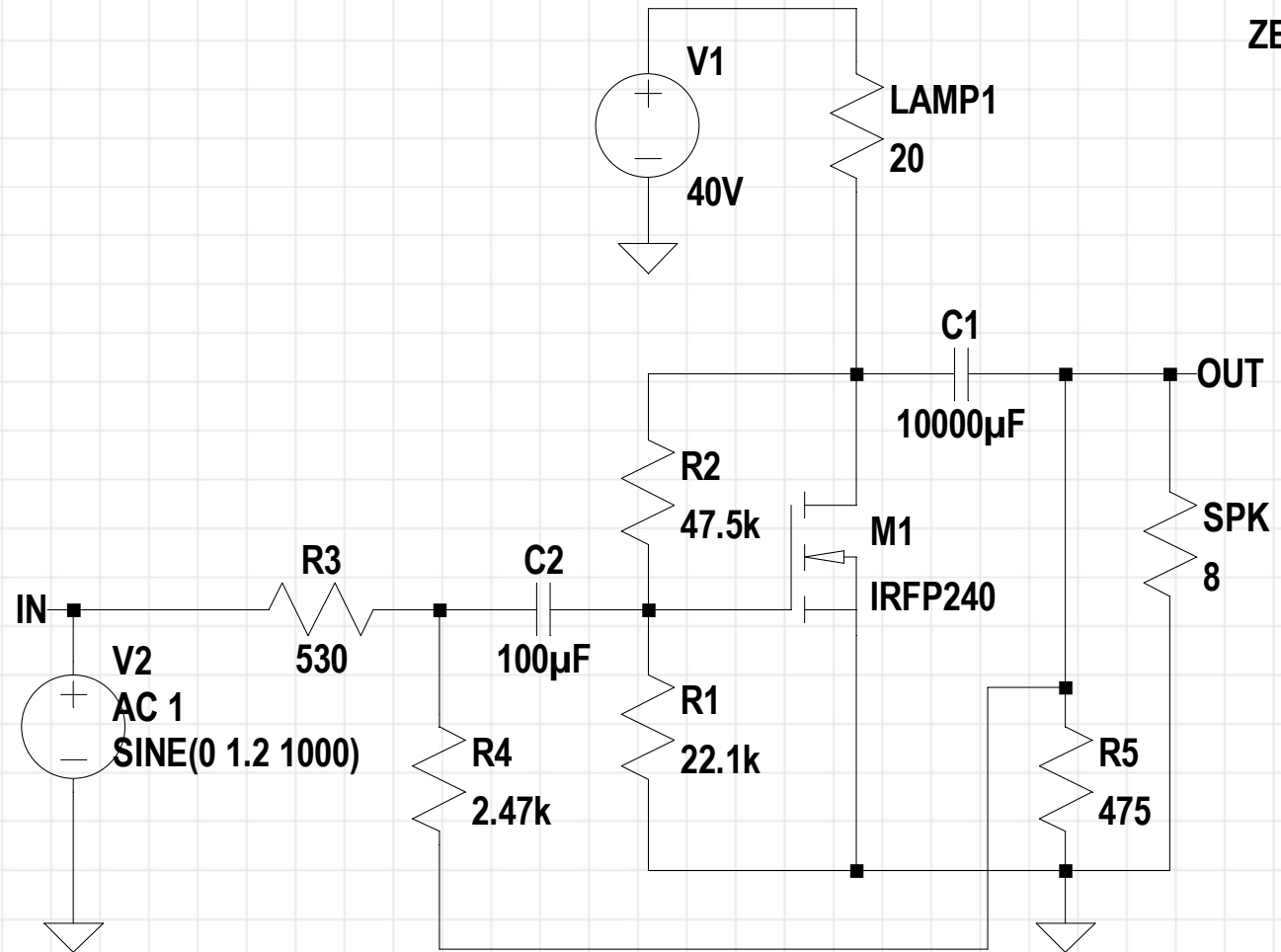
Amplitude normalized
to one

THD as computed
from this data

THD all harmonics + noise

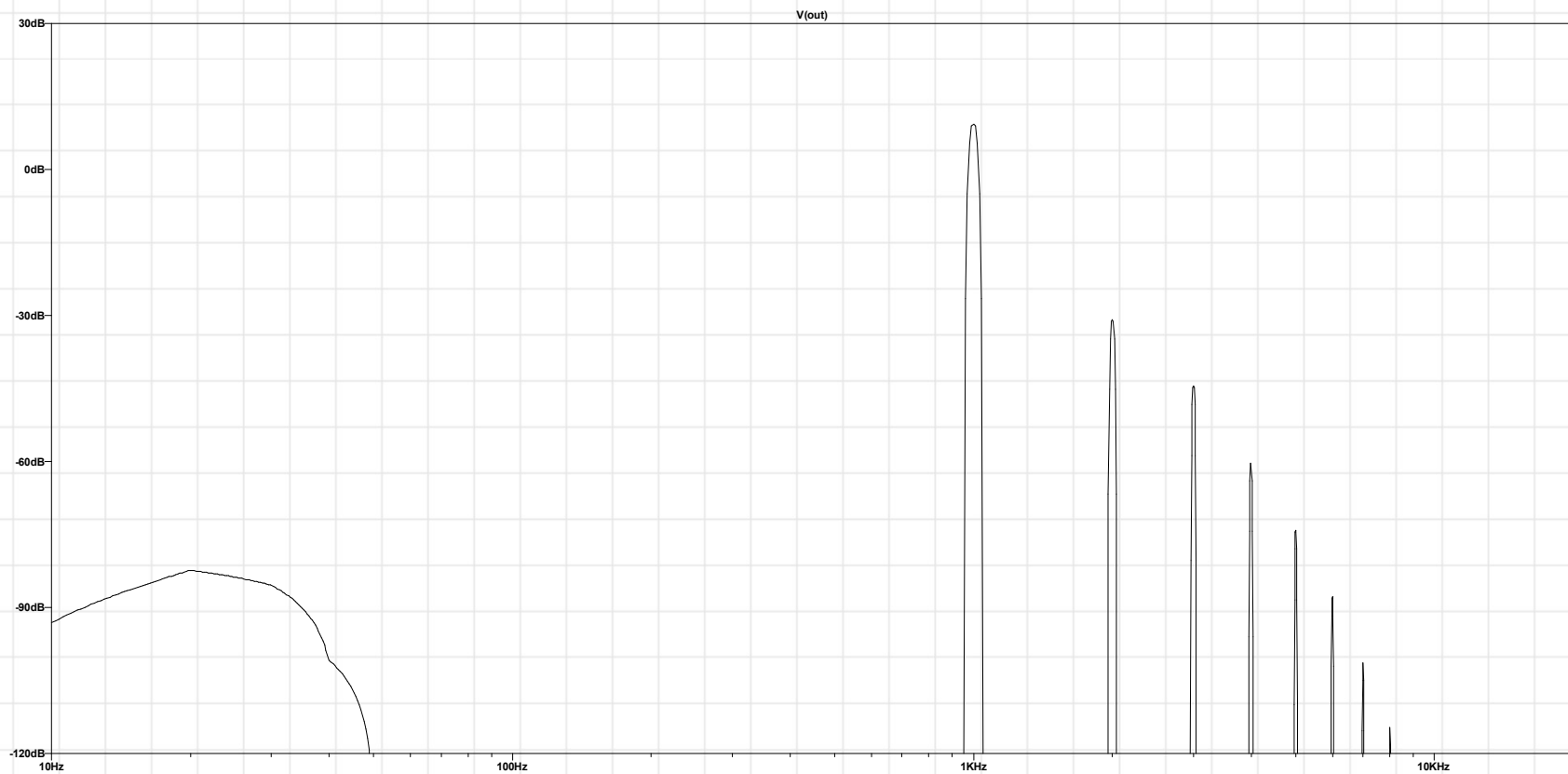
LESSON 18: FFT VIEW

.tran 0 2.1 2 100n
.options plotwinsize=0



ZEN LITE

FFT (FLAT TOP WINDOW APPLIED)

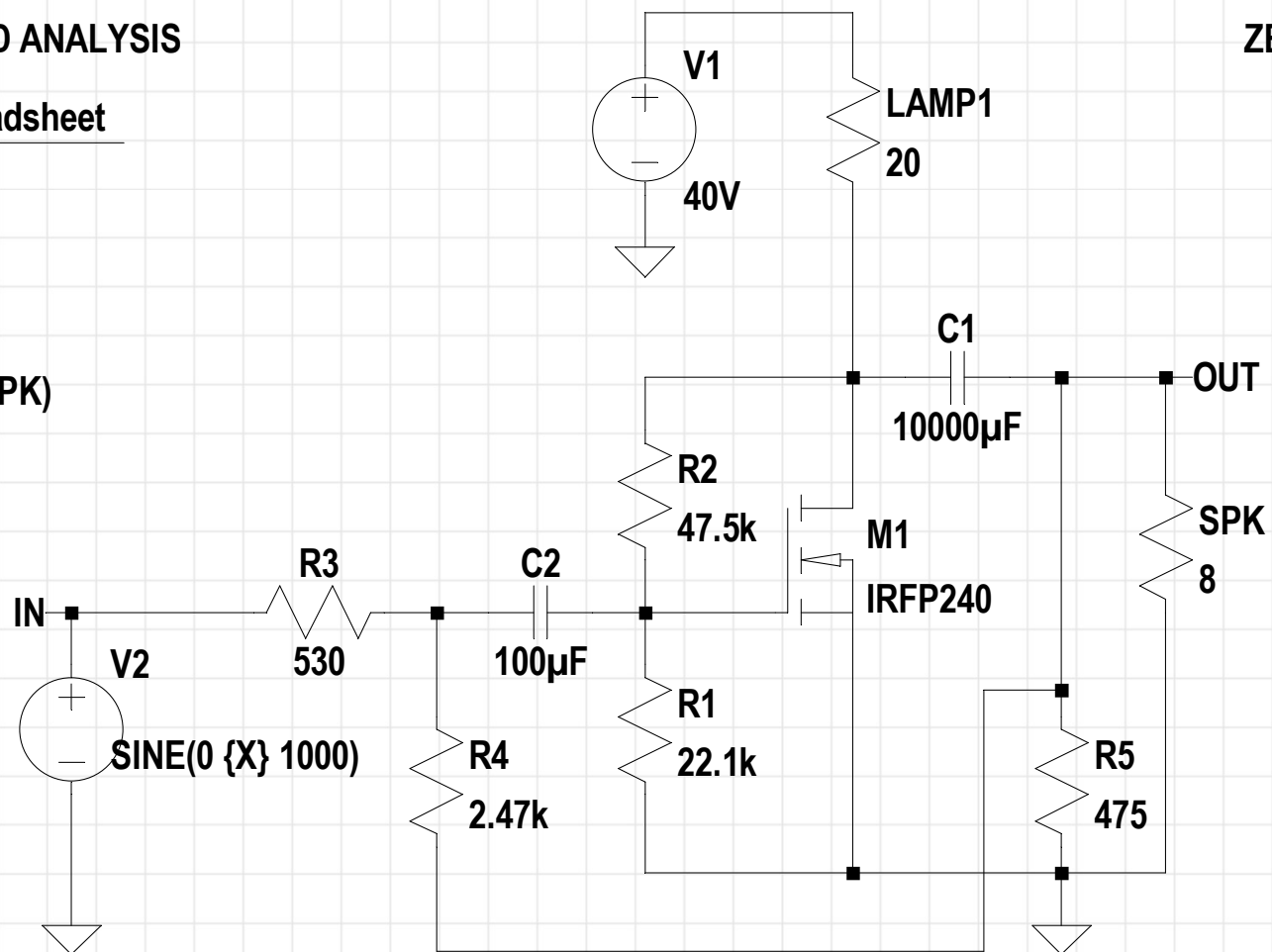


LESSON 19: AUTOMATING THD ANALYSIS

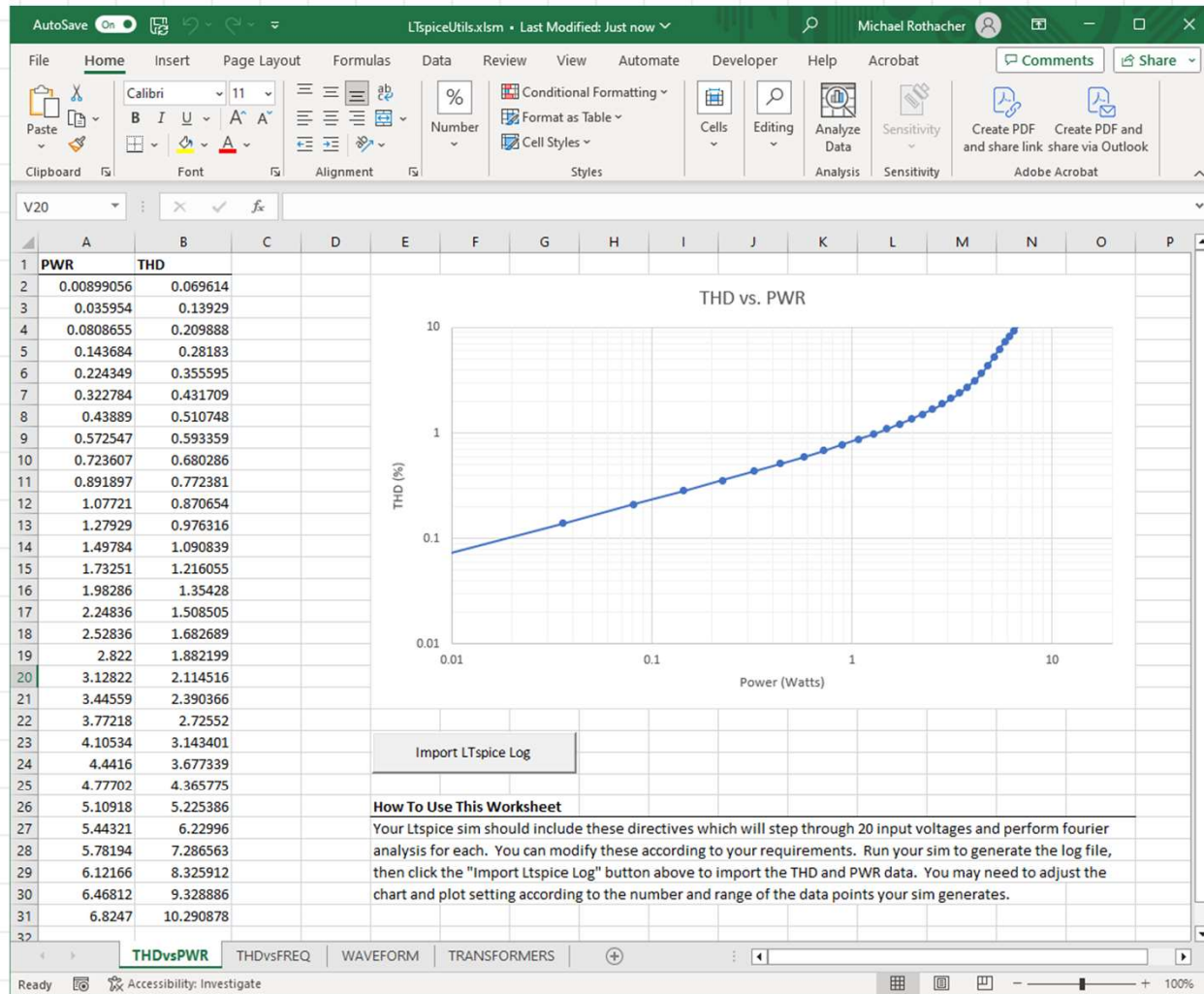
USING My LTspiceUtils Spreadsheet

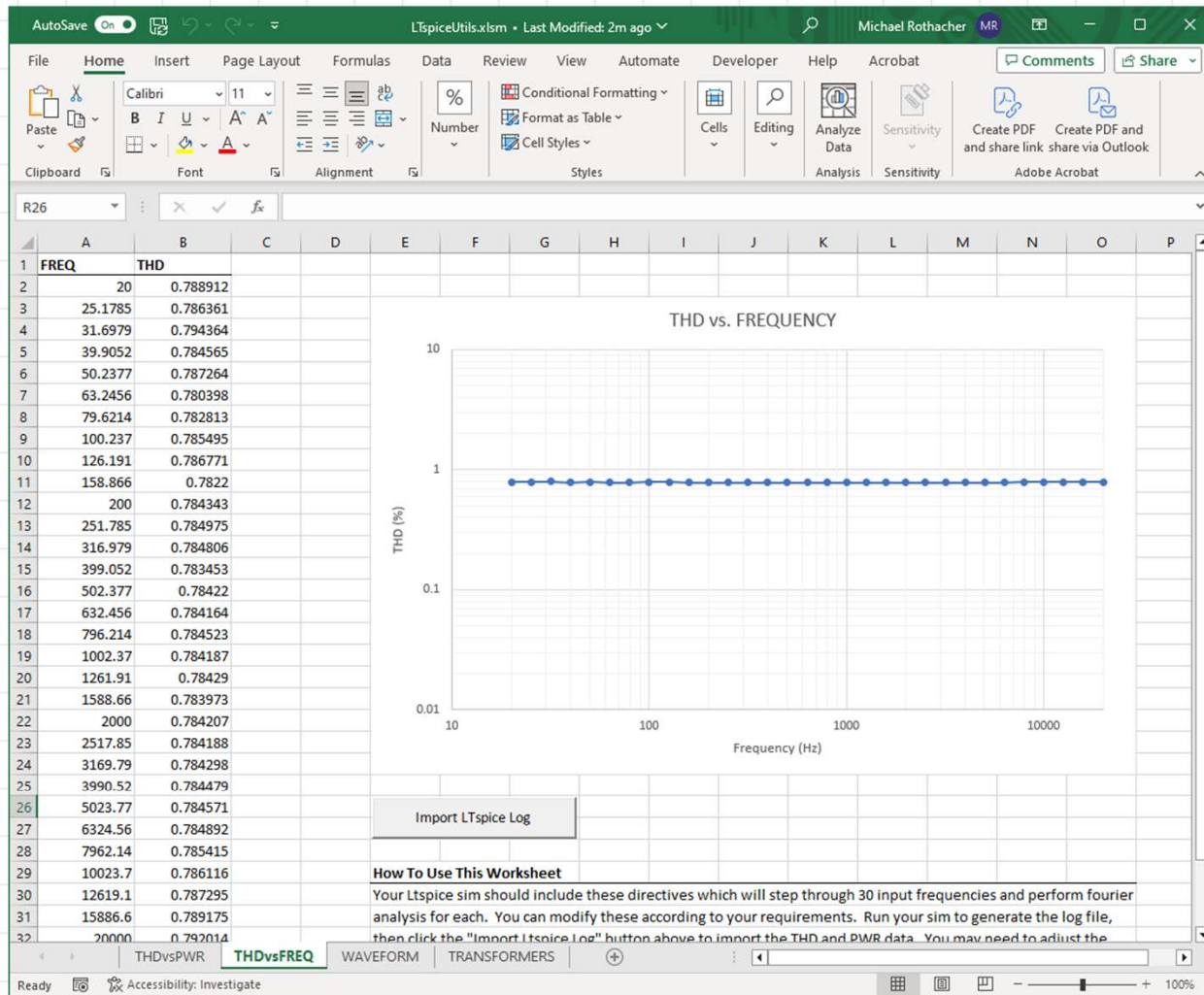
THD vs. Power

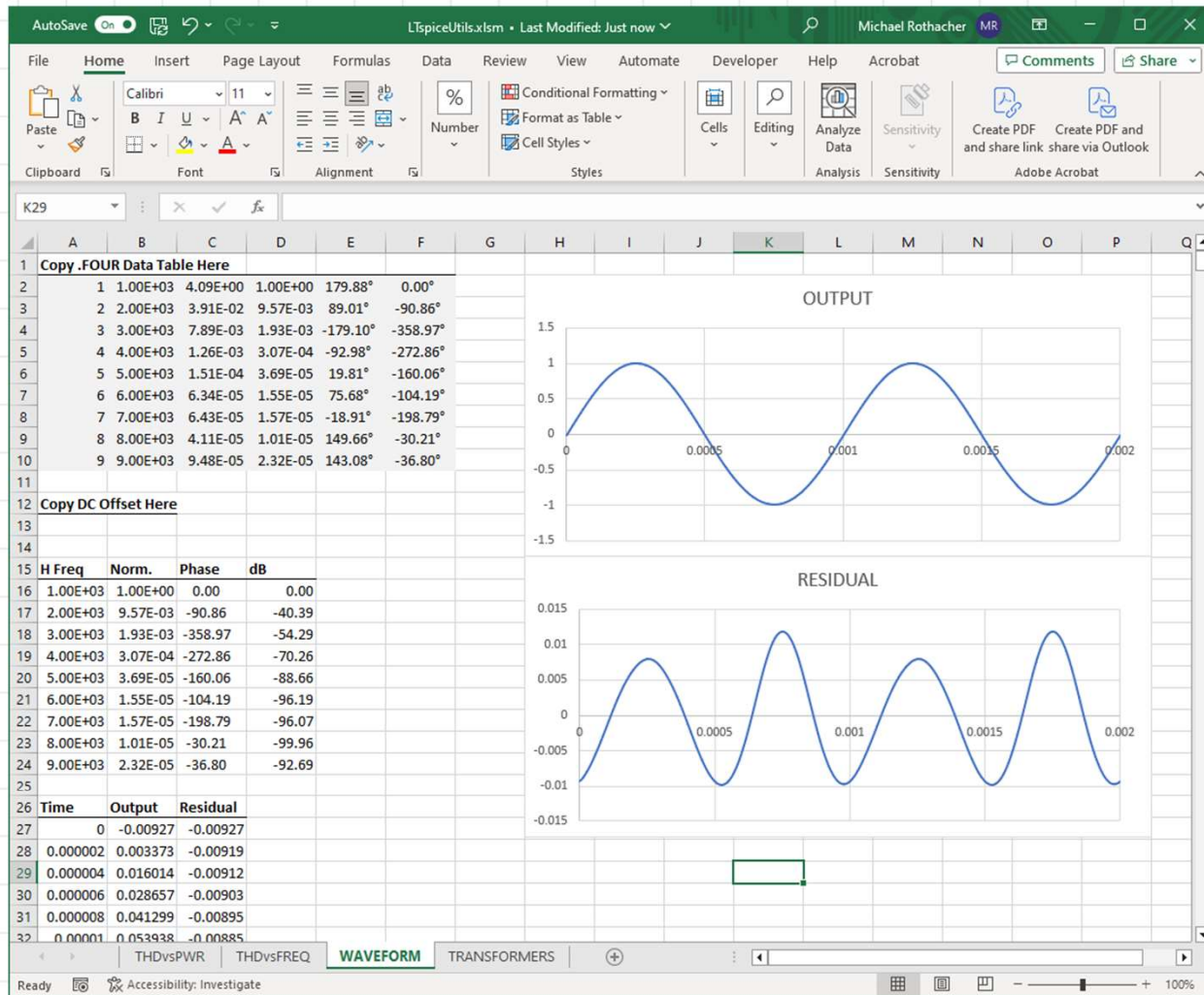
```
.tran .02  
.four 1kHz v(OUT)  
.step param X .1 3 .1  
.meas power RMS V(OUT)*I(SPK)
```



ZEN LITE







LESSON 20: GENERIC FR LOUDSPEAKER LOAD

Impedance Plot - Add trace $V(IN)/I(R1)$

.ac oct 100 20 20k

NOTES:

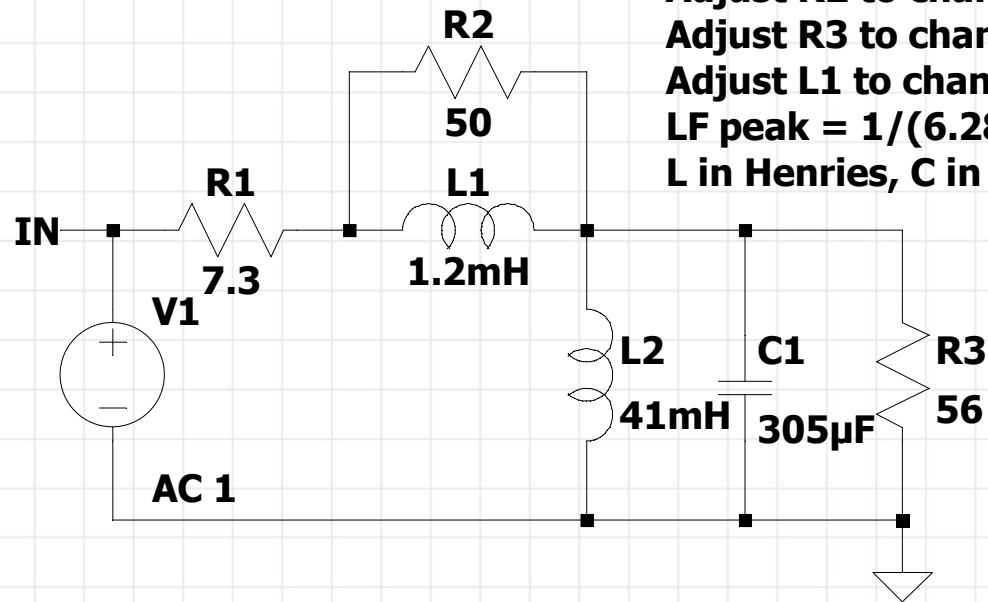
Adjust R2 to change HF Zmax (approx. $R1+R2$)

Adjust R3 to change LF Zmax (approx. $R3+R1$)

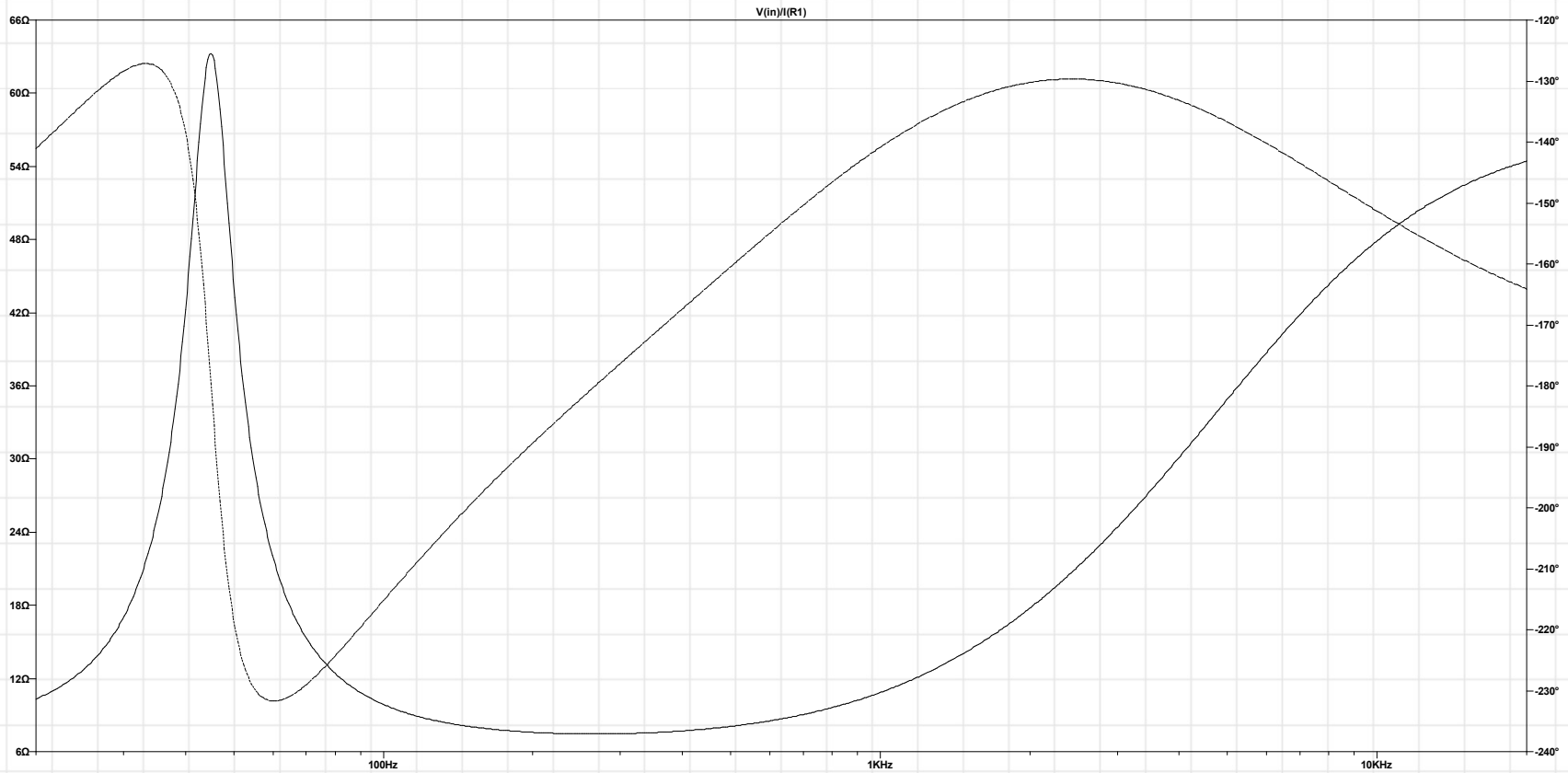
Adjust L1 to change where HF rise starts

LF peak = $1/(6.28 * \text{SQRT}(L2 * C1))$

L in Henries, C in Farads



Generic FR Speaker Load



LESSON 21: T/S PARAMETERS

Impedance Plot - Add trace $V(IN)/I(Re)$

Thiele/Small parameters (commonly abbreviated T/S parameters, or TSP) are a set of electromechanical parameters that define the specified low frequency performance of a loudspeaker driver.

.ac oct 100 5 2000

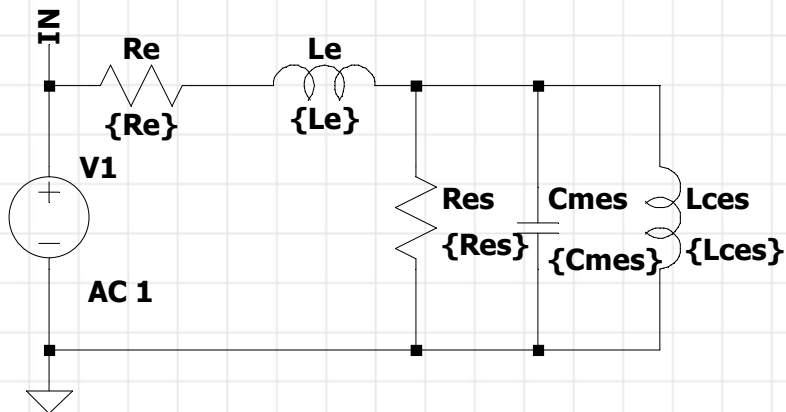
Thiele/Small Parameters

Notes: S_d is in cm sq. V_{as} in litres

.param $F_s=45$ $Q_{ms}=4.83$ $V_{as}=37$ $M_{ms}=22.2$ $Q_{es}=.63$ $R_e=7.3$ $C_{ms}=4.83$ $Q_{ts}=.56$ $L_e=1.2mH$ $SPL=90$ $BL=8.5$ $S_d=49.6$

Constants

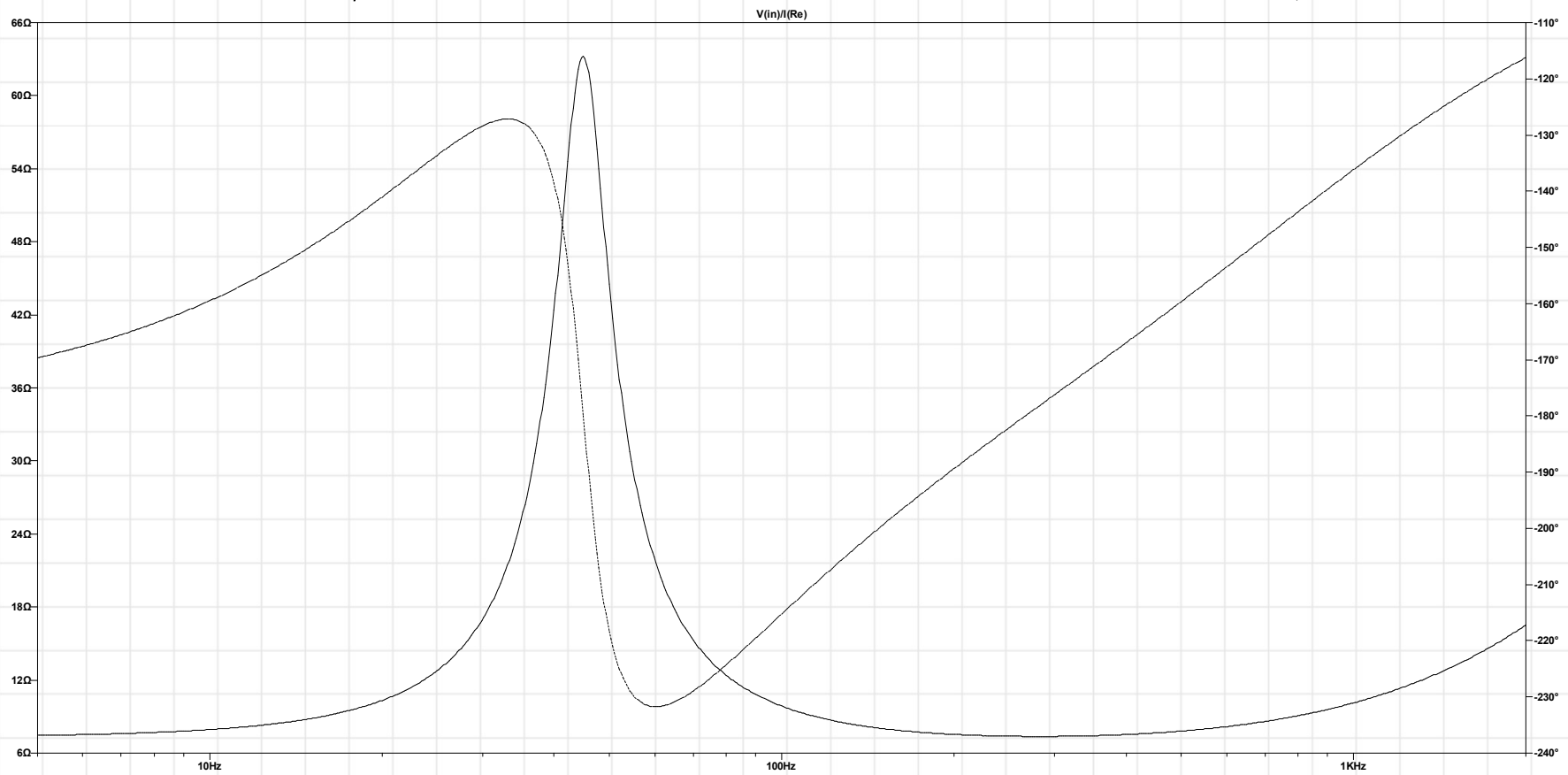
.param $c=344$ $\rho=1.18$ $\pi=3.14$



```
.param Res = Qms/Qes*Re
.param Cmes = Qes/(2*pi*Fs*Re)
.param Lces = Re/(2*pi*Fs*Qes)

.measure ac Res_param = 'Res'
.measure ac Cmes_param = 'Cmes'
.measure ac Lces_param = 'Lces'
```


Impedance Plot (From TS Parameters)



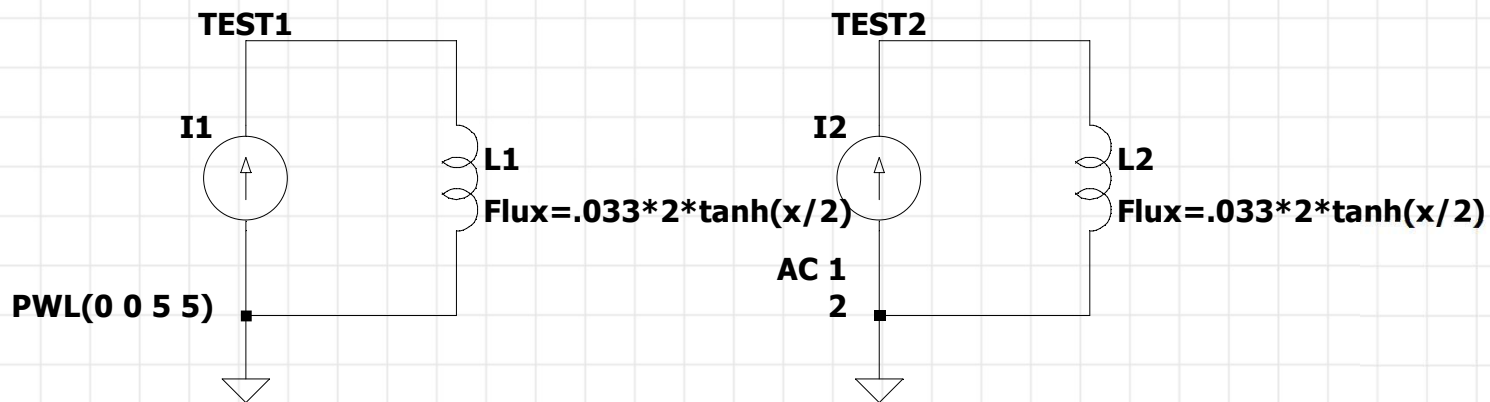
LESSON 22: NON-LINEAR INDUCTOR

TEST1: Run transient sim and add trace V(test1)/1V

TEST2: Run ac sim and add trace V(test2)/I(L2)

.tran 5

.ac dec 100 20 200

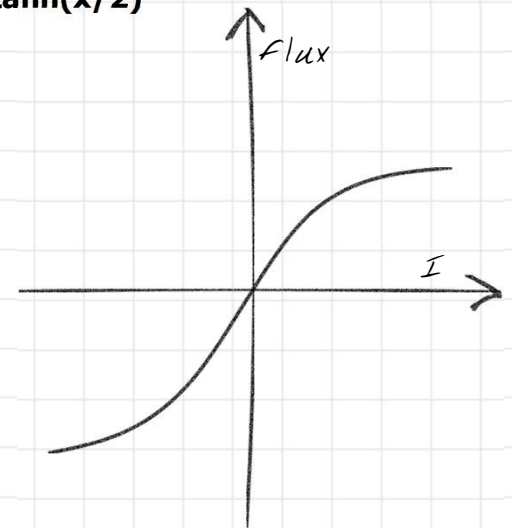


NOTES:

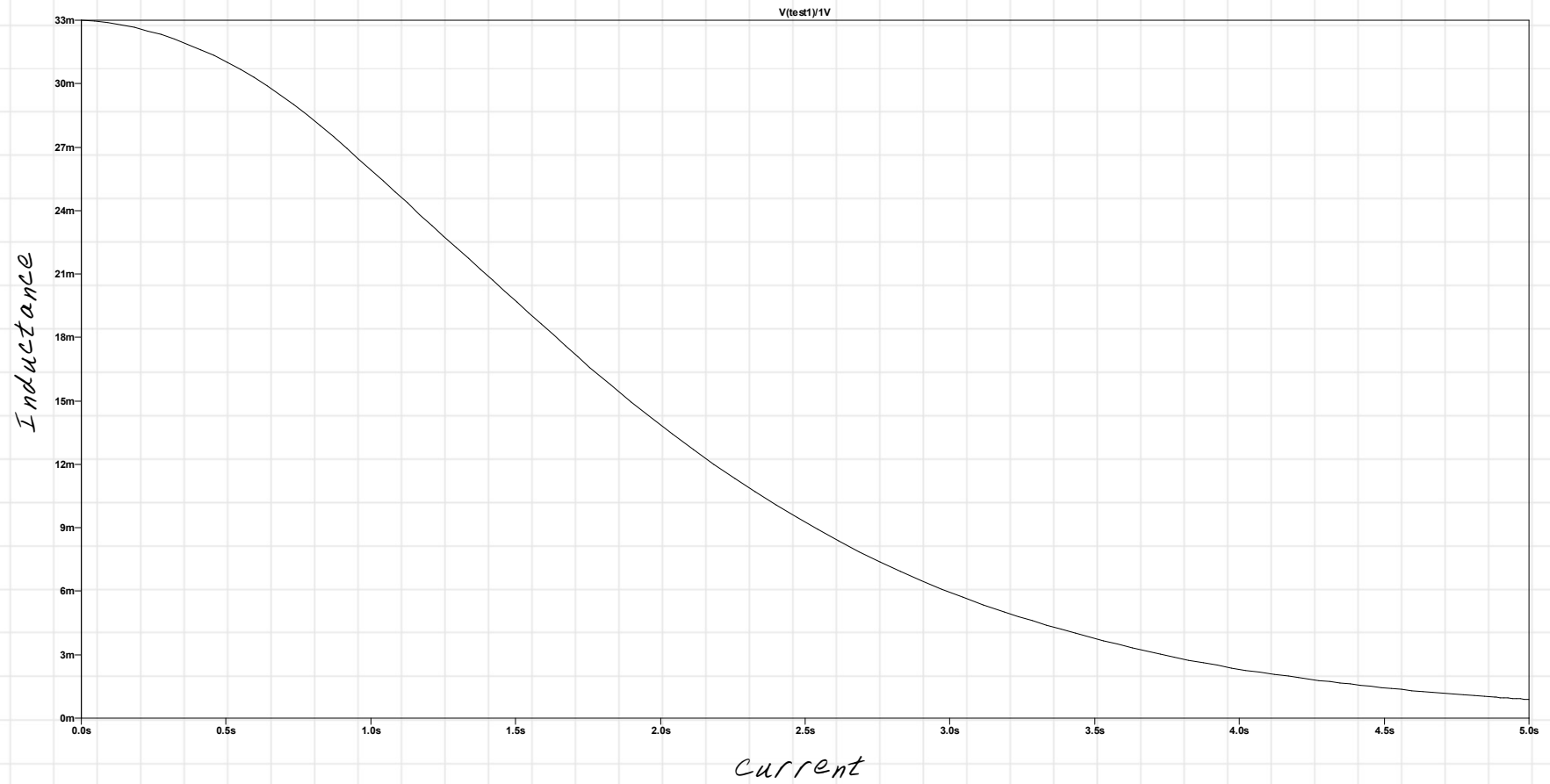
The voltage across an inductor is $V = -L \cdot (dI/dt)$

$\text{flux} = \{L \cdot I_s\} \cdot \tanh(x/\{I_s\})$; L= inductance and I_s = "saturation" current

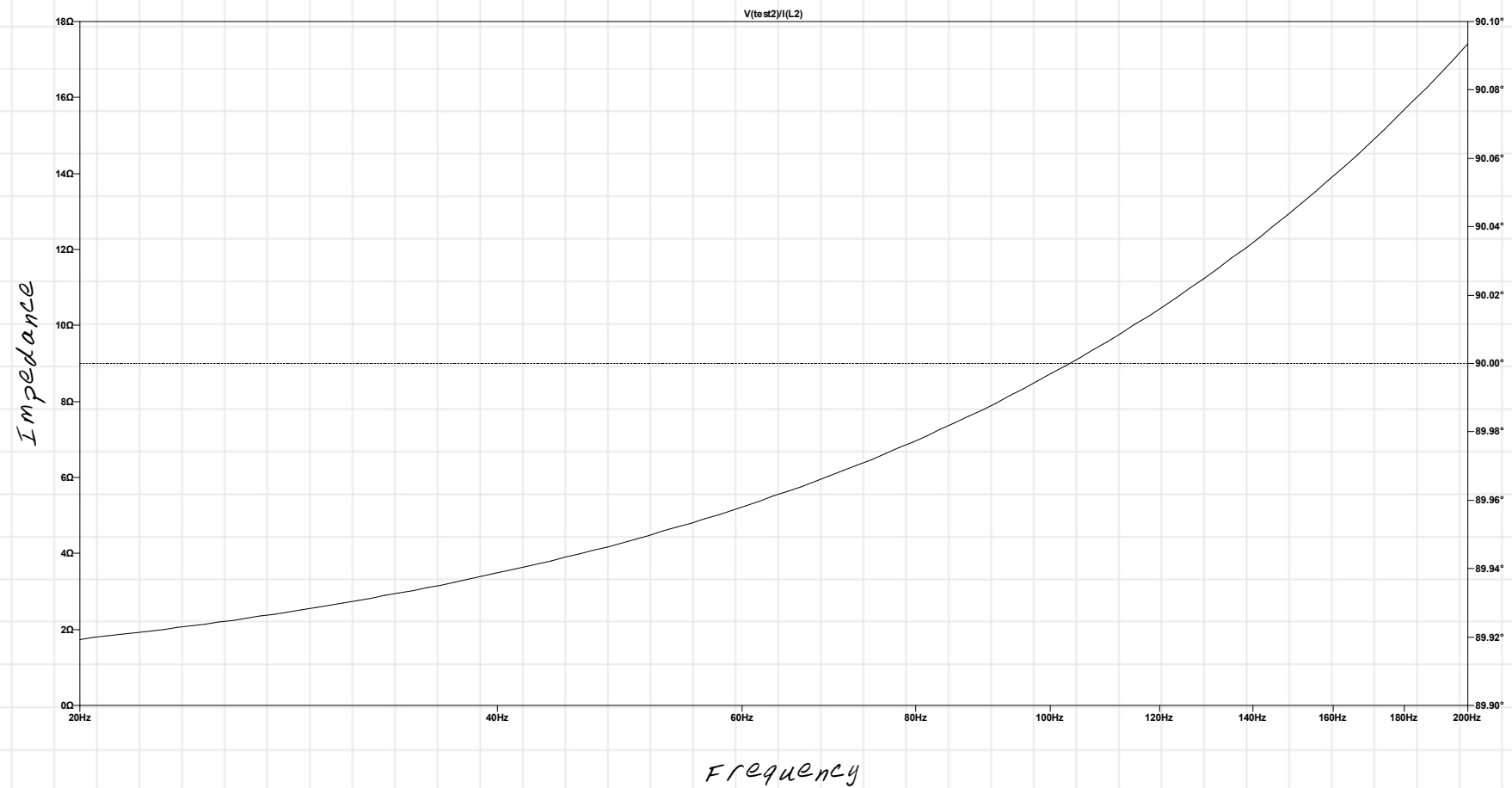
$L = Z / (6.28 \cdot \text{frequency})$



SATURATION



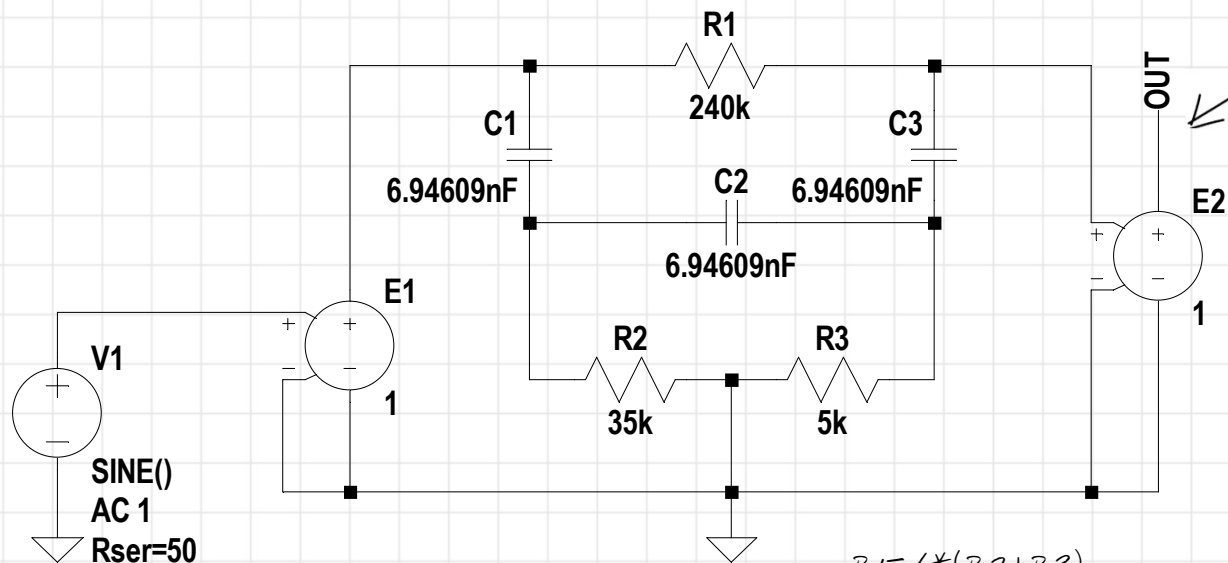
SATURATION EFFECT ON IMPEDANCE



LESSON 23: EXAMPLE NOTCH FILTER

HALL NOTCH

.ac dec 100 20 20000

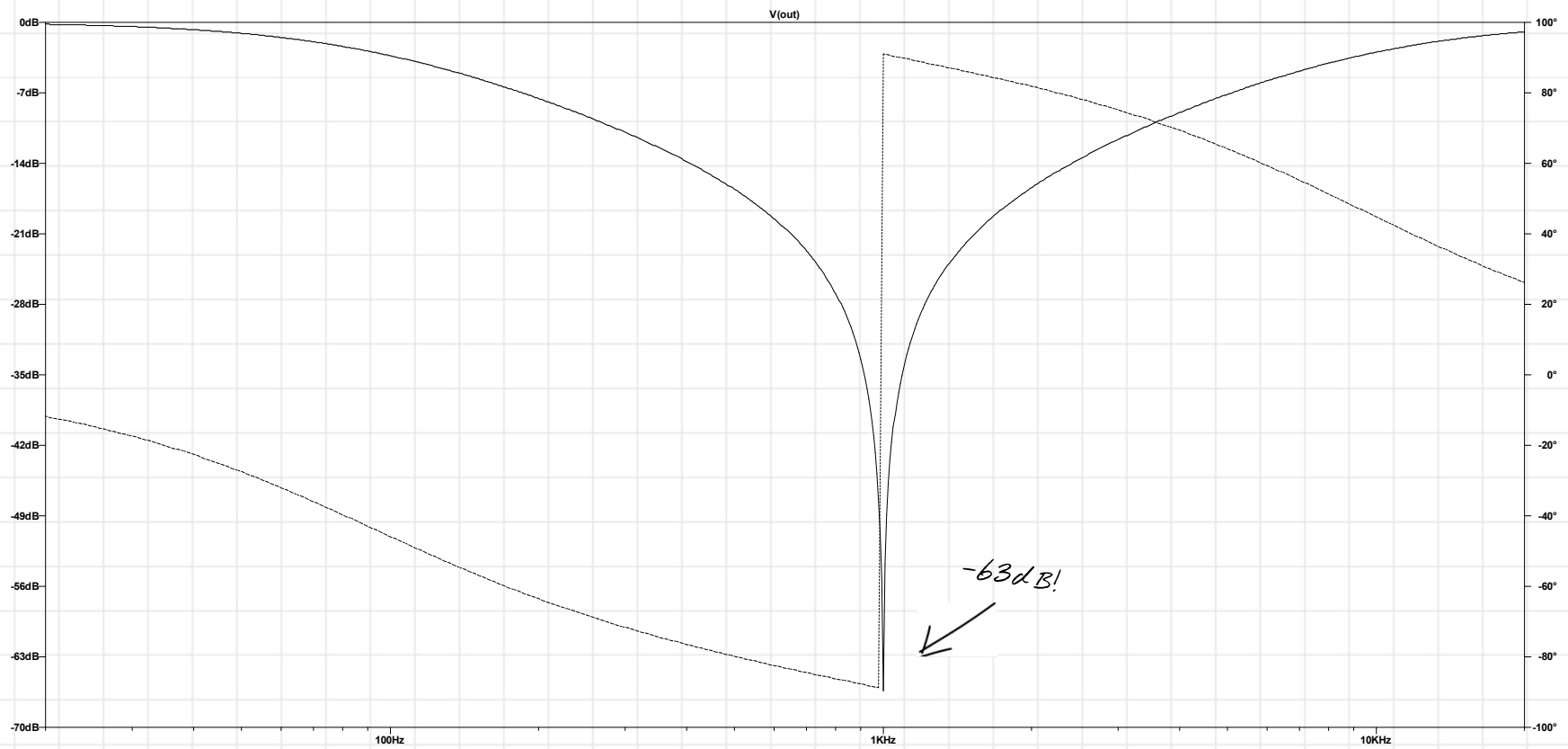


$$R1 = 6 * (R2 + R3)$$

$$C = 1 / (2 * \pi * F * \sqrt{3 * R2 * R3})$$

$$F = 1 / (2 * \pi * \sqrt{3 * R2 * R3} * C)$$

Hall Notch Filter Response

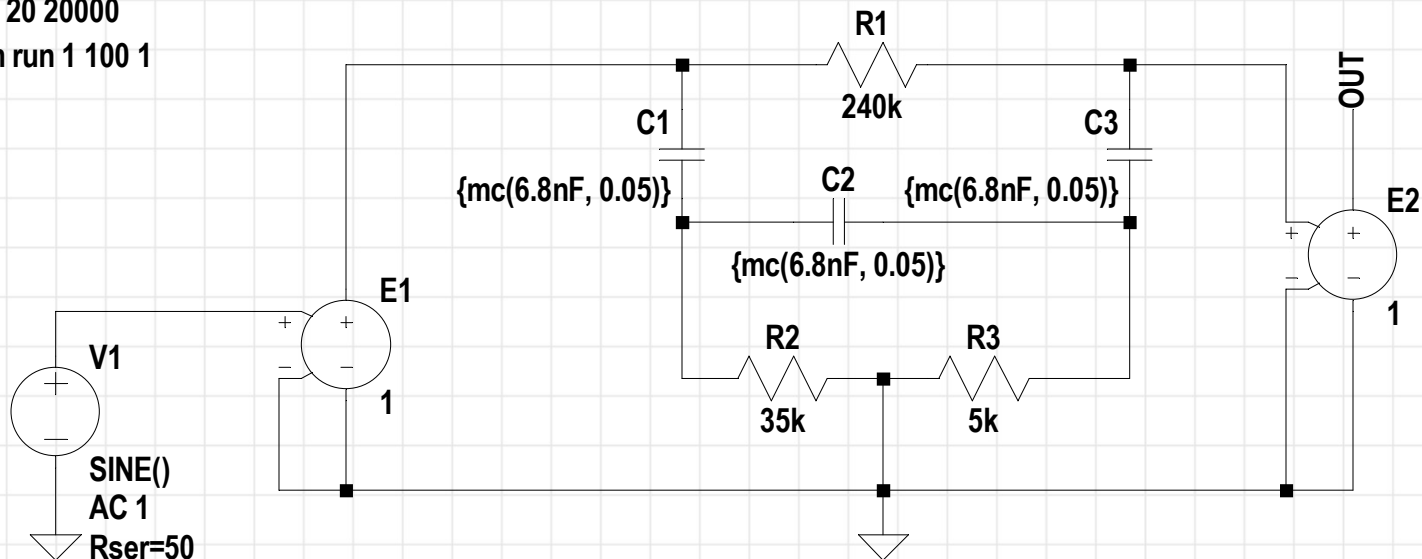


24

LESSON 24: MONTE CARLO

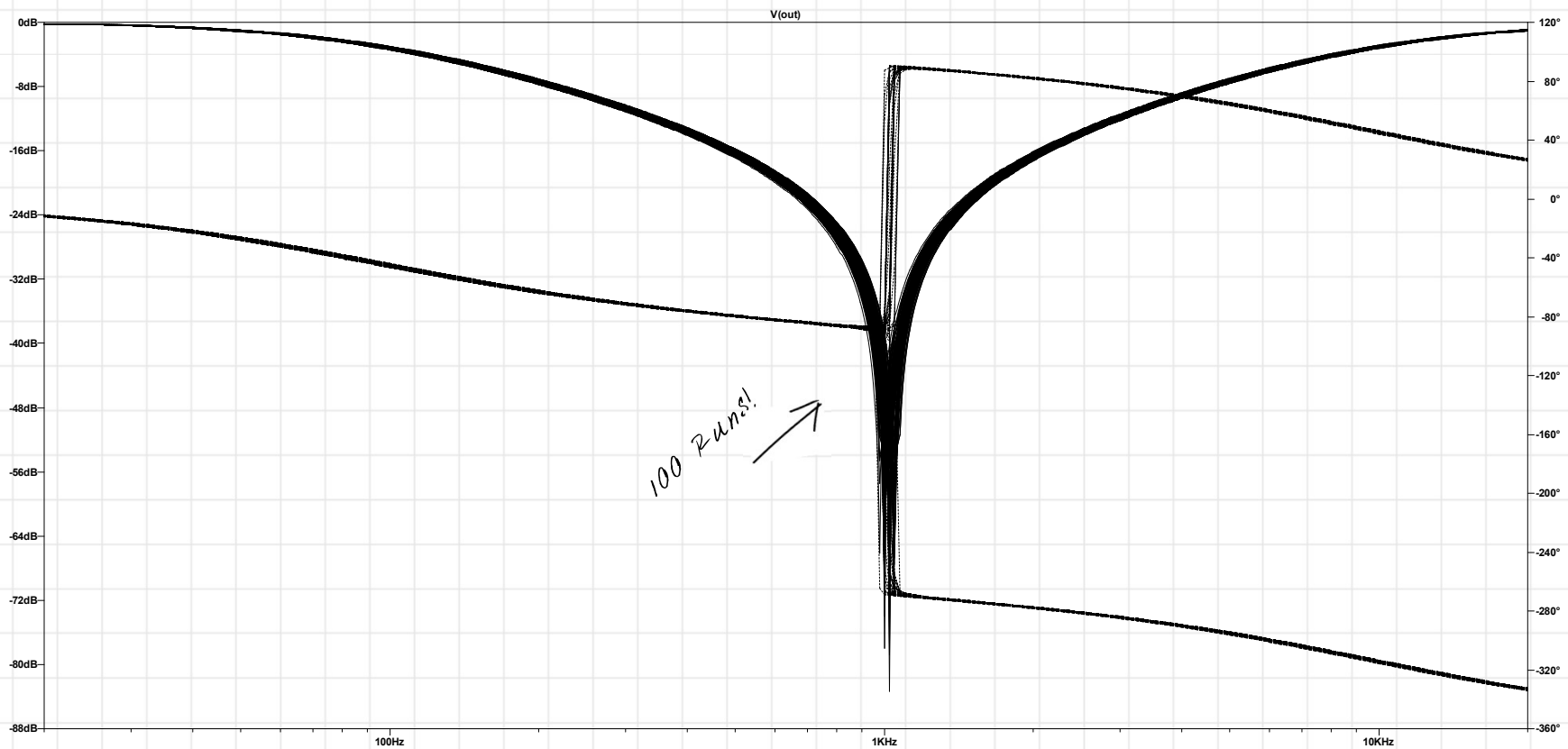
HALL NOTCH

```
.ac dec 100 20 20000
.step param run 1 100 1
```



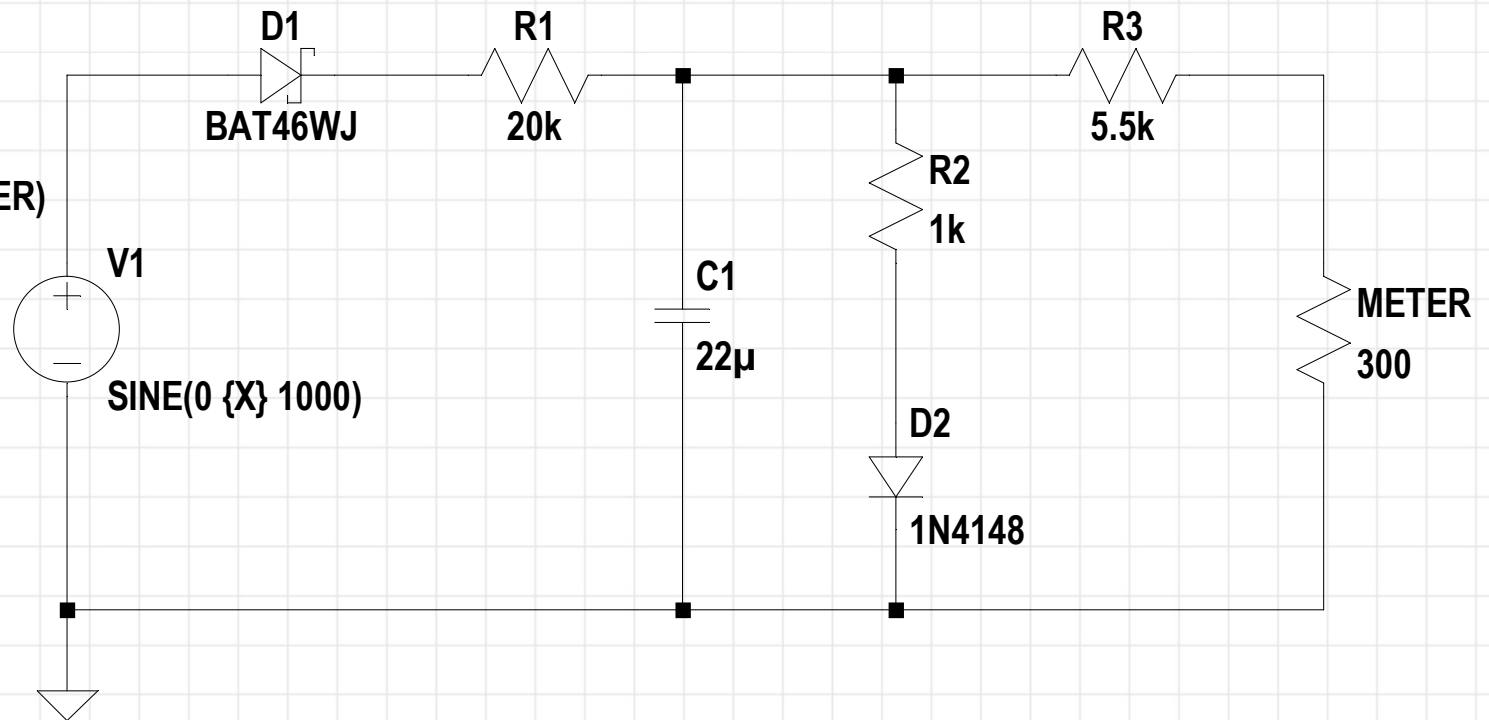
note: run is a dummy parameter here so we can step through the monte carlo runs

Hall Notch Filter Response (Monte Carlo)



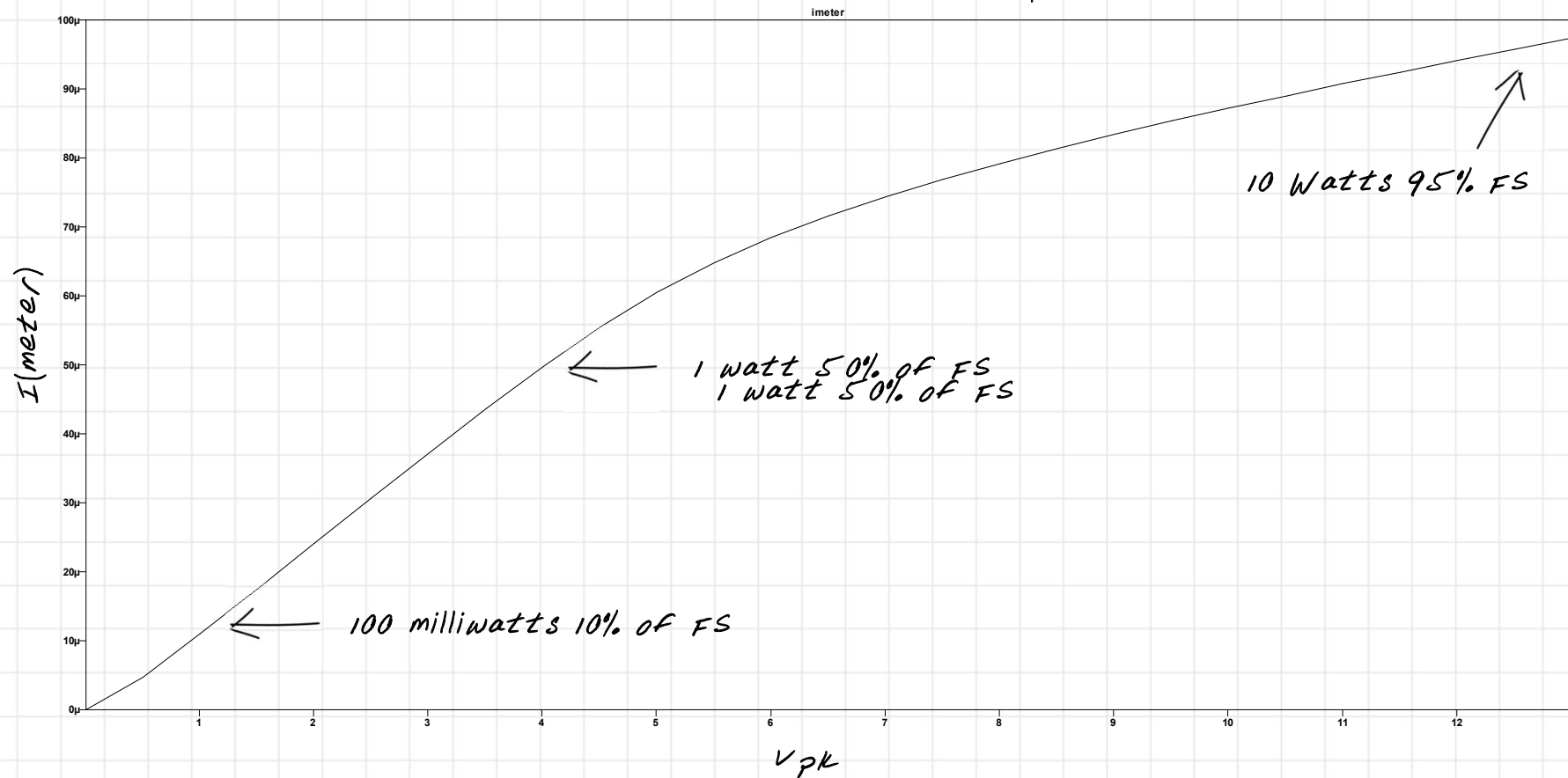
LESSON 25: THE FIRST WATTMETER

```
.tran 0 .6 .3  
.param X = 4  
.step param X 0.01 13 .5  
.measure IMETER AVG I(METER)
```



PROBE METER CURRENT THEN OPEN ERROR LOG AND PLOT MEASURED STEP DATA

First Wattmeter Response



DON'T
FORGET TO
HAVE FUN!