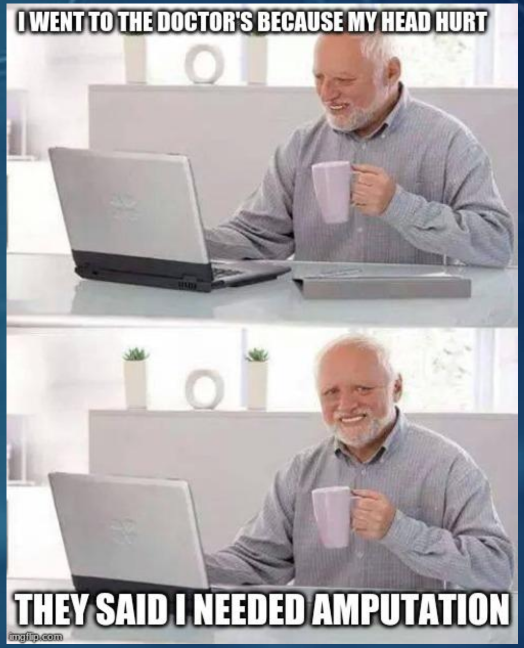
Journey Down Rabbit Holes

Why my head hurts

DAVE VE3OOI

DEC 2021 – FEB 2022



Danger Will Robinson…

Members of the Accelerator Laboratory. Drs. Cameron, Kuehner and Waddington were teaching classes when this photo was taken.

Preceding are the rambling of an ‘old’ Experimental Physicist.

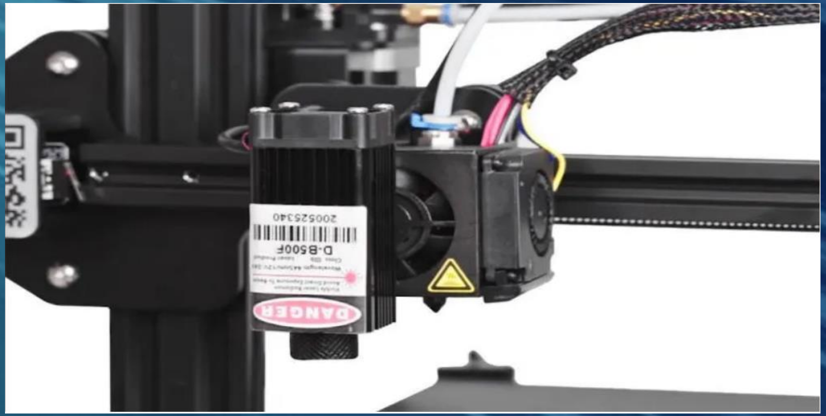
This is <u>not</u> an engineering tutorial

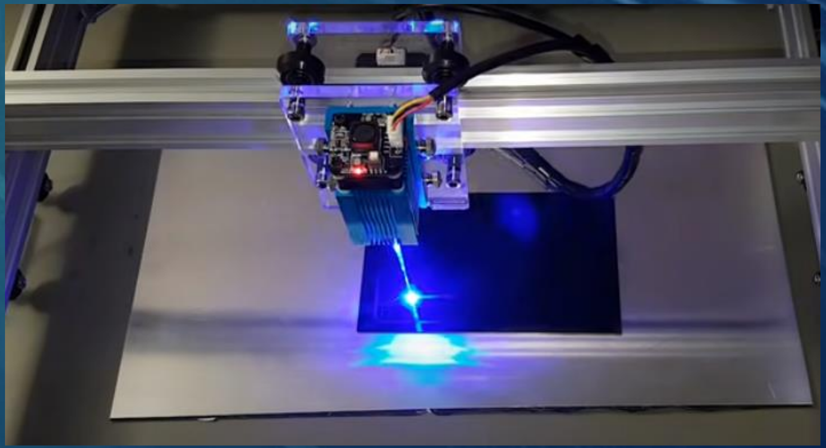
Quote Charlie Morris, ZL2CTM:
This NOT a tutorial. Its a log of my journey.

Right or wrong.

How It All Started…

- Purchased an Ender 3D Printer
- Discovered laser module for printer
  - Useful to cut parts from thin plywood
  - **Etch PCB boards!**
- Investigation of how laser modules work
  - Use laser diodes
  - Require low voltage but higher current (e.g., 3V and several amps)
- Use PWM to control voltage (Laser Power)
- Use a buck step-down converter to control voltage and higher current





The Rabbit Holes…

Laser Modules → Buck Converter

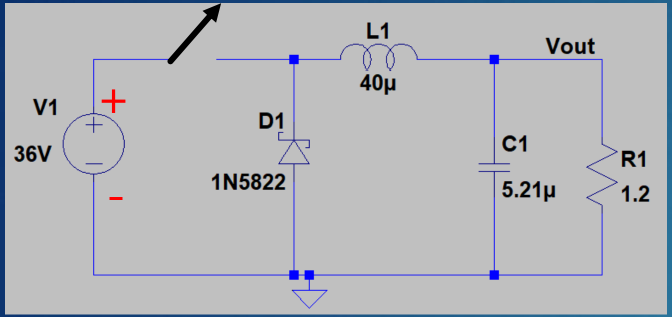
Buck Converter → Inductors

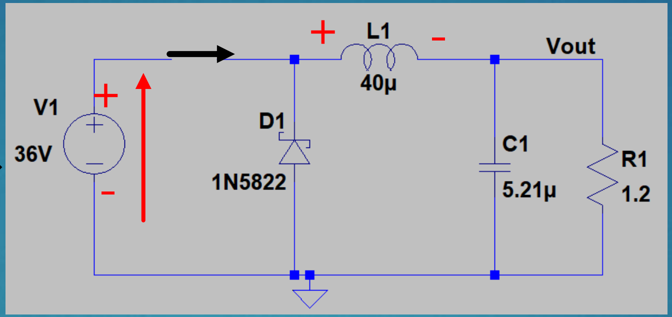
Buck Converter → Mosfets

Mosfets → Power Amp (D612)

Buck Converter: How It Works

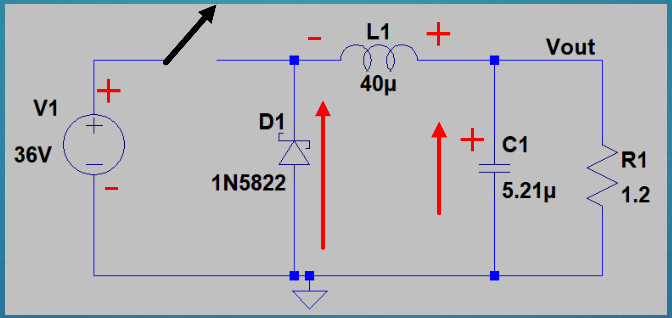
Switch



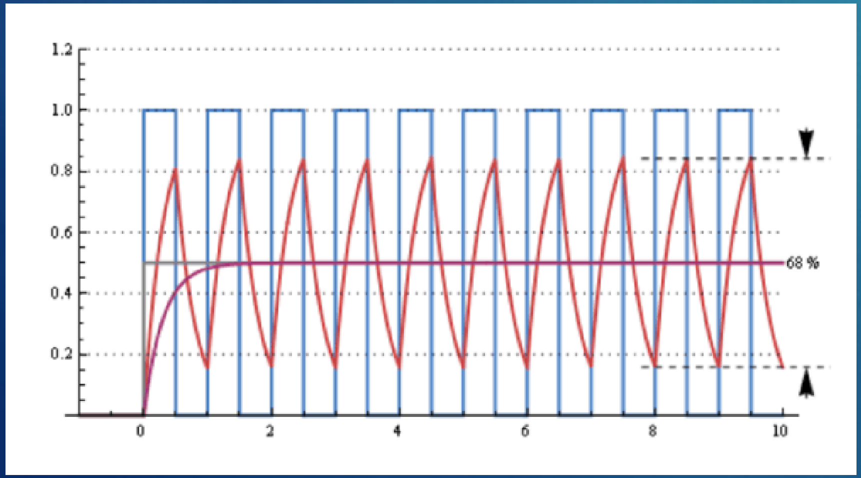


1. Switch Closed. Current slowly flows through inductor.
2. Inductor opposes current increase
3. Capacitor Charges
4. Current slowly increases through R1

Switch opens

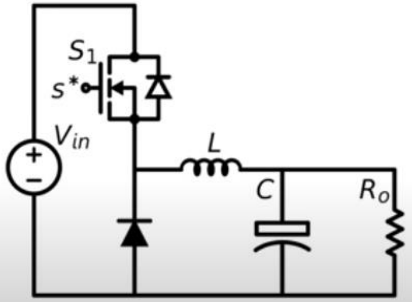


1. Current rapidly decreases through inductor.
2. Inductor opposes current decrease
3. Capacitor and inductor act as a battery
4. Current continue to flow through R1



Buck Converter: Testing

Martin Ordonez
Ph.D. - Renewable & Alternative Power Conversion



$$V_{in} = 36\,\text{V}$$

$$V_o = 12\,\text{V}$$

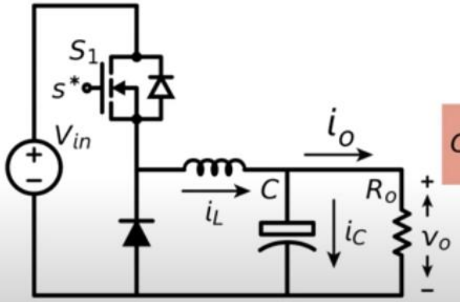
$$f_{sw} = 100\,\text{kHz}$$

$$R_{o,\text{min}} = 1.2\,\Omega$$

$$\Delta i_L = 20\,\%$$

$$\Delta v_o = \pm 2\,\%$$

Martin Ordonez
Ph.D. - Renewable & Alternative Power Conversion



$$D = \frac{12\,\text{V}}{36\,\text{V}} = 0.33 \qquad (4)$$

$$I_{L,\text{max}} = \frac{12\,\text{V}}{1.2\,\Omega} = 10\,\text{A} \qquad (5)$$

$$L = \frac{(36\,\text{V})(1-0.33)(0.33)}{(2\,\text{A})(100\,\text{kHz})} = 40\,\mu\text{H} \qquad (6)$$

$$C = \frac{(36\,\text{V})(1-0.33)(0.33)}{8\,(40\,\mu\text{H})(0.48\,\text{V})(100\,\text{kHz})^2} = 5.21\,\mu\text{F} \qquad (7)$$

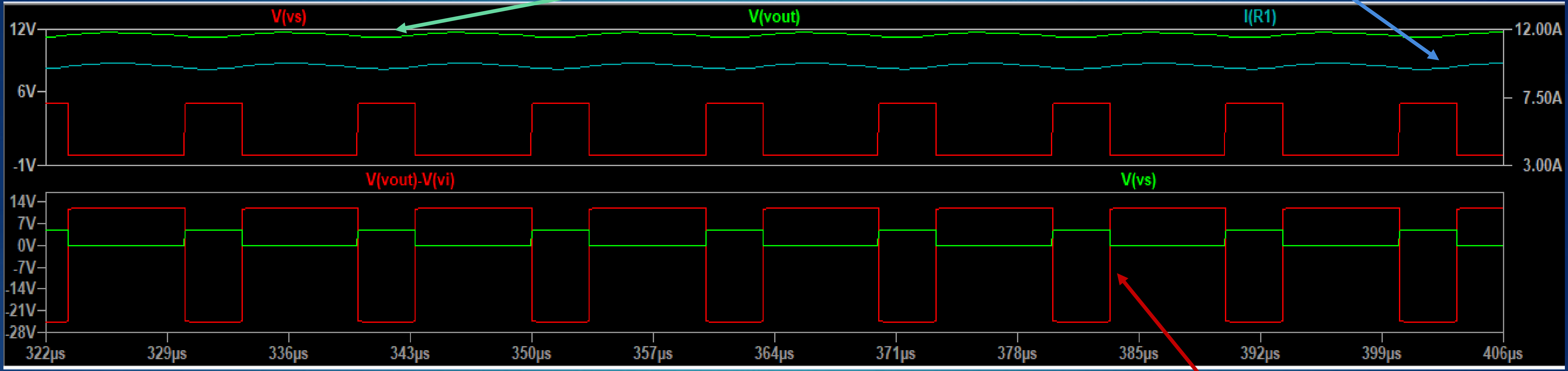
$$I_{LB} = I_{oB} = \frac{\Delta i_L}{2} = 1\,\text{A}$$

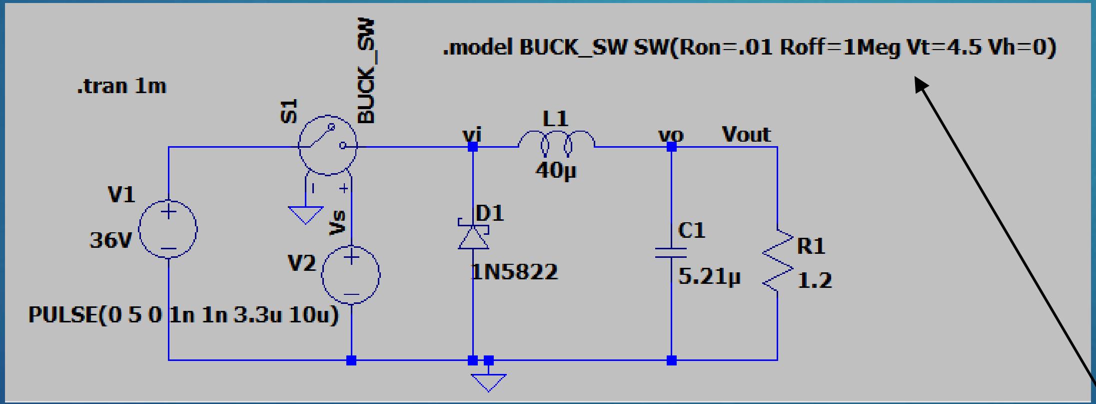
$$R_{oB} = \frac{V_o}{I_{oB}} = \frac{12\,\text{V}}{1\,\text{A}} = 12\,\Omega$$

Buck Converter: Simulation

Voltage is about 12V

Current is about 10A



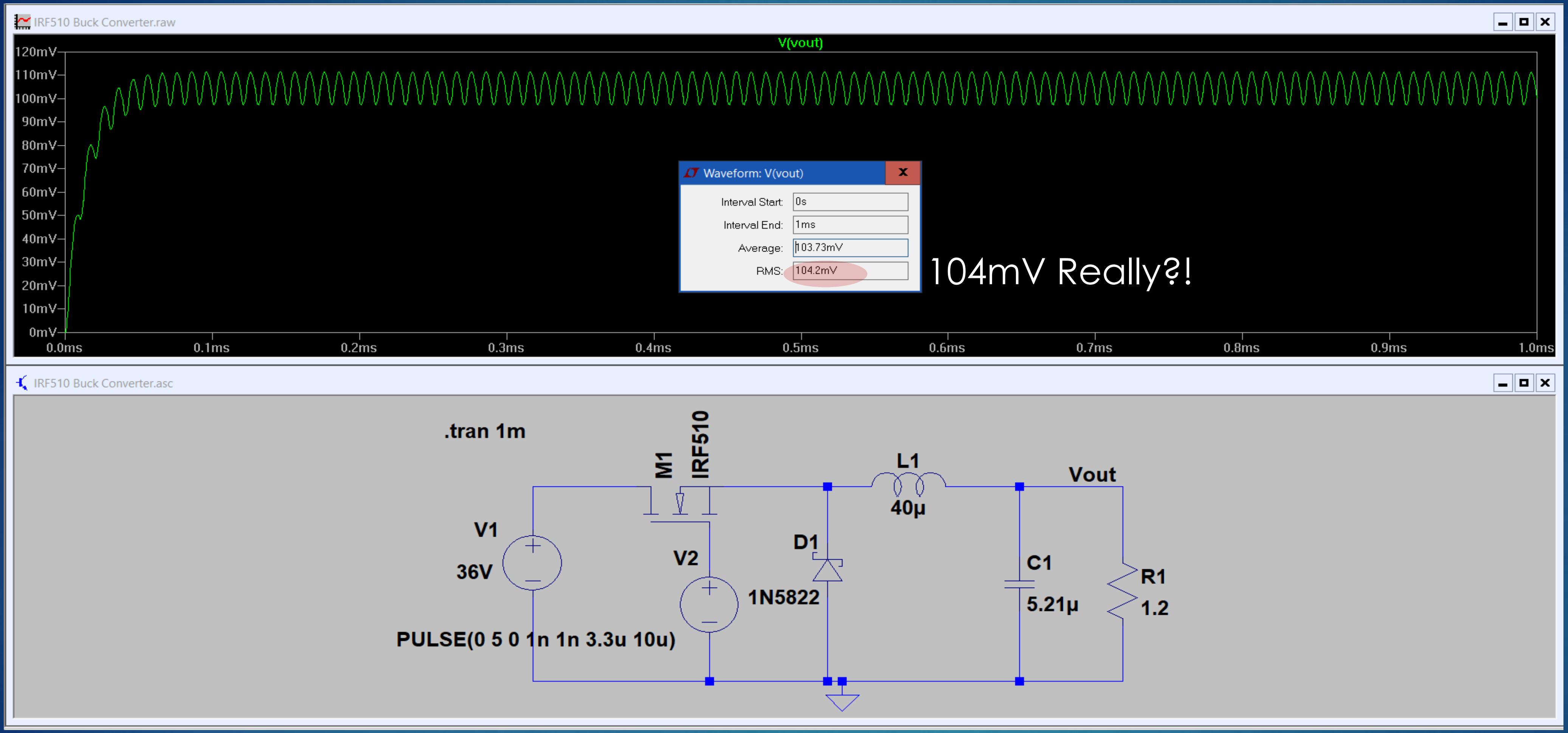


1. This is voltage across inductor (Vo-Vi)
2. Switch closed:
   - Inductor voltage is negative.
   - i.e. Vi > Vo (i.e. + to -)
3. Switch open:
   - Inductor voltage is positive.
   - i.e. Vo > Vi (i.e. - to +)

LTSpice Trick:
- ✓ right clk Select "Add Plot Plane"

http://ltwiki.org/index.php?title=S_Voltage_Controlled_Switch

WTF?!



LTSpice Trick:
- ✓ ctl + left clk for RMS

WTF!

After Rabbit Hole #3: Its actually "Vgs" Threshold. Gate voltage must be (at least) 4V higher that source voltage to turn on.

Rabbit Hole #1: Inductors

This is something you probably already understood but may have forgotten or misunderstood….

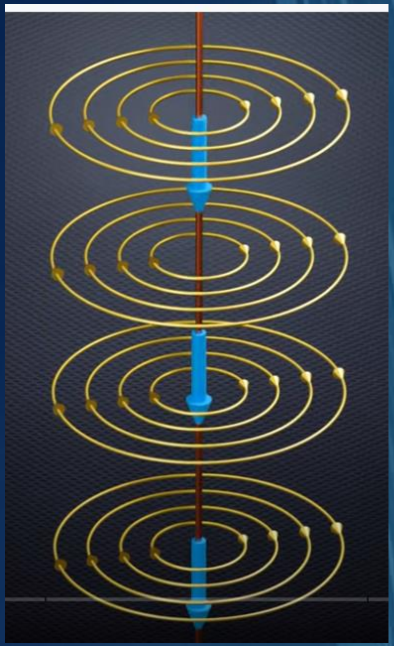
Agenda

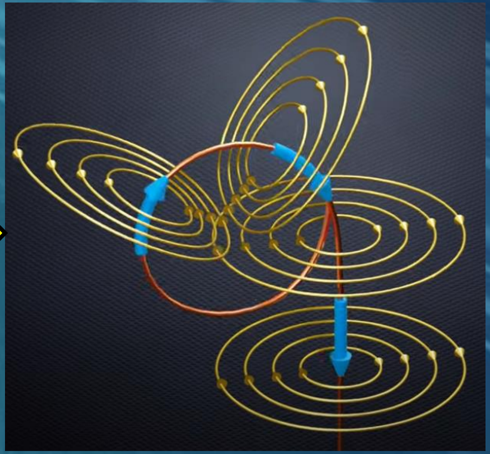
1. Magnetic Fields around a Wire

2. Faraday’s Law of Induction

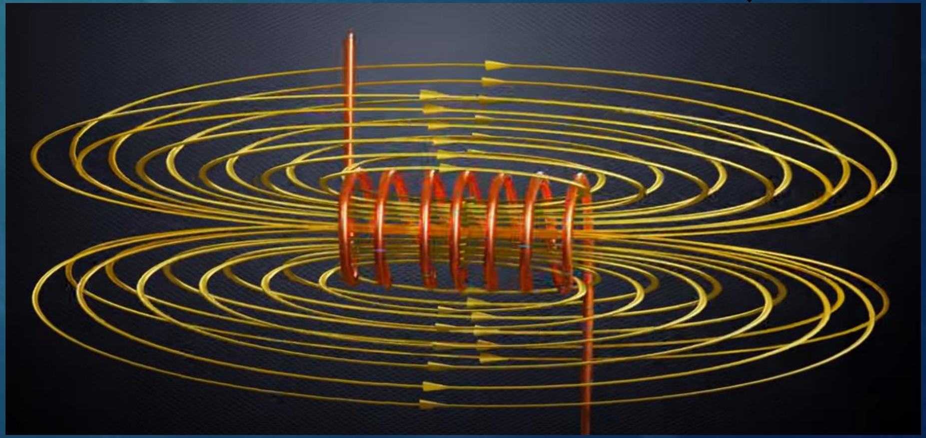
3. Lenz’s Law of Induced Magnetic Fields

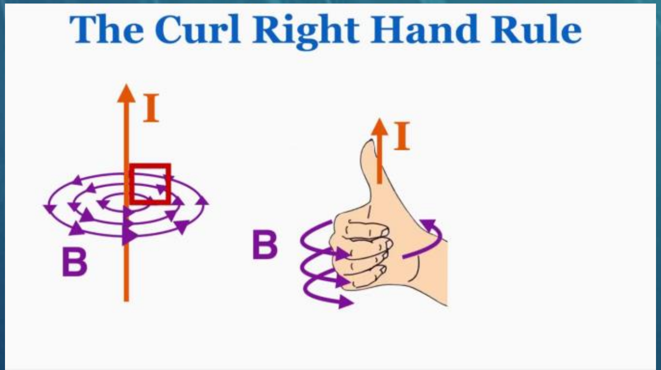
Magnetic Fields Around A Wire



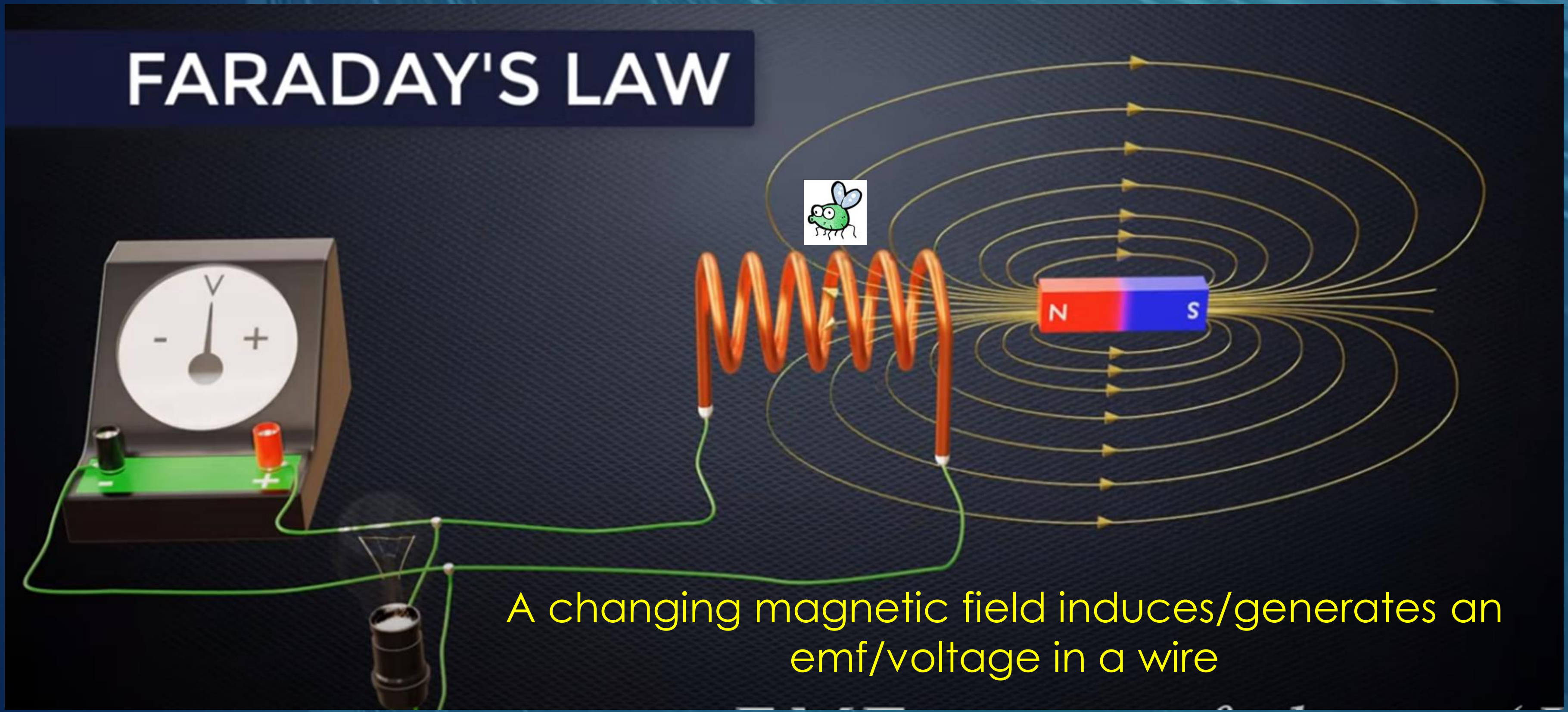


STEADY STATE: STATIC FIELD CREATED





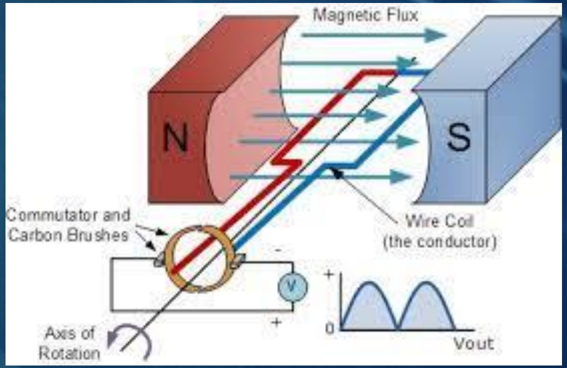
Faraday's Law



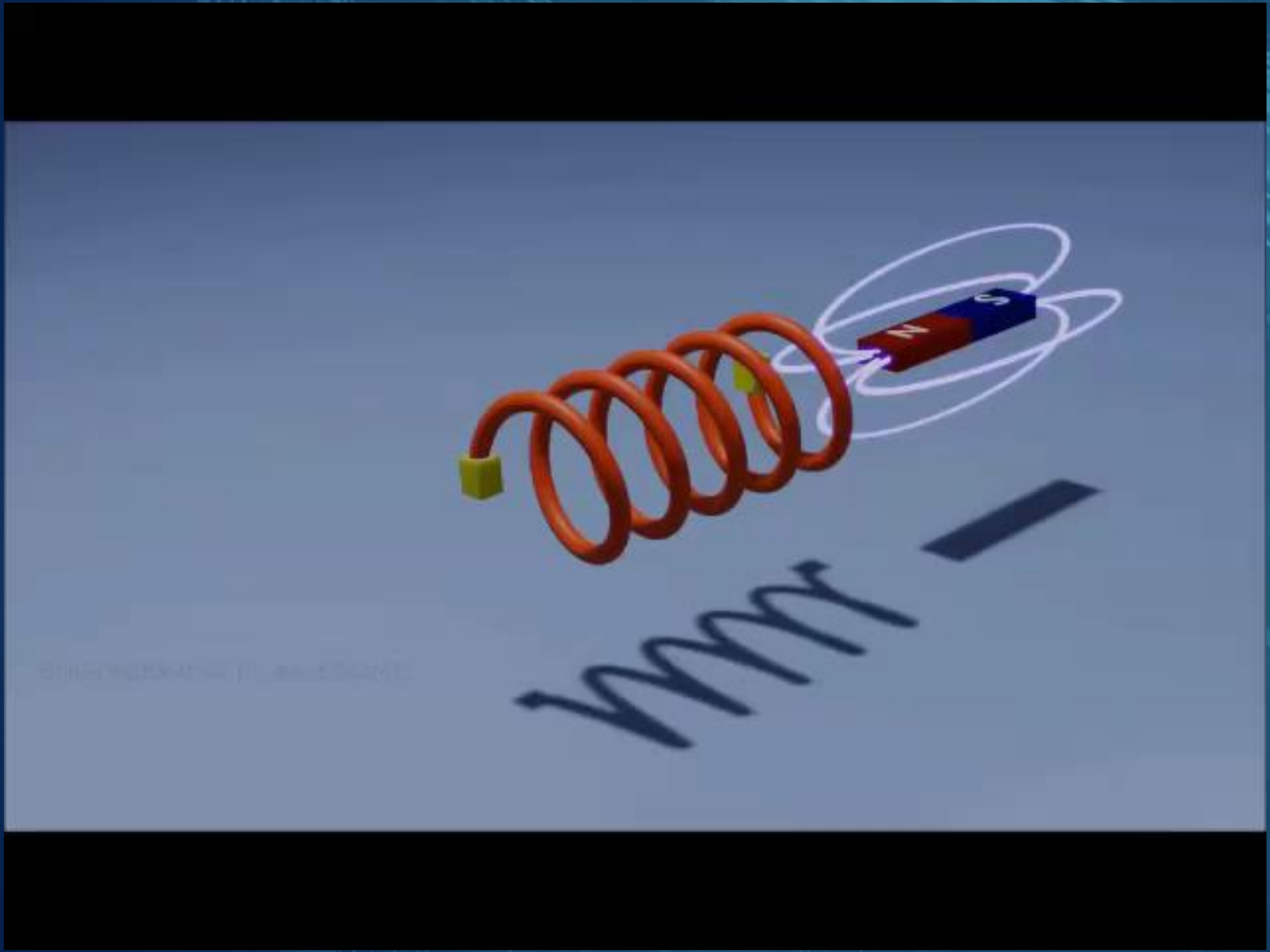
A changing magnetic field induces/generates an emf/voltage in a wire

Motion of magnet creates a changing magnetic field

Generator and Alternators generate voltages by spinning wire amateur inside a magnetic field



Faraday's Law

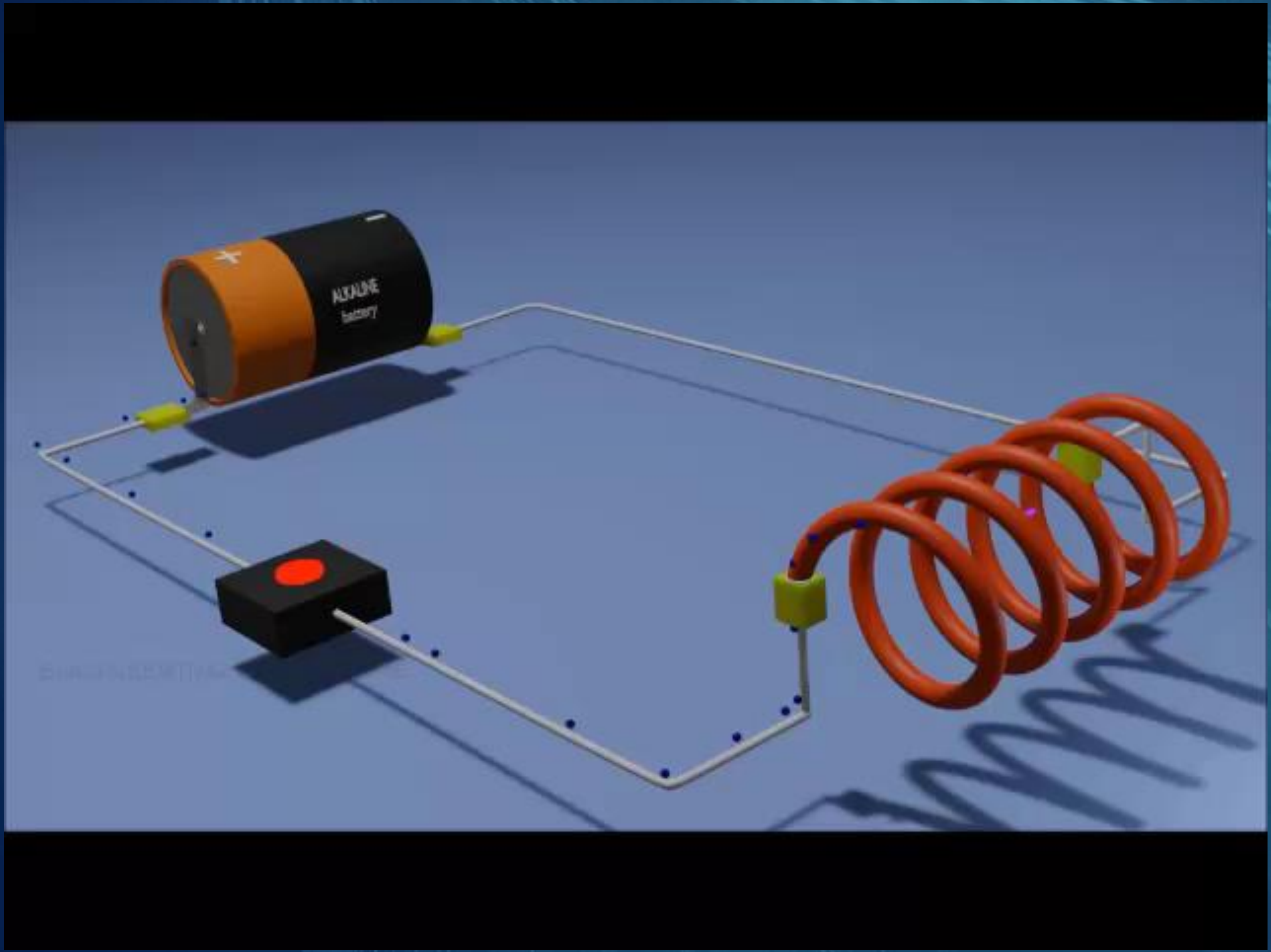


1. As magnetic field around permanent magnet moves near the coil, the coil "sees" a changing magnetic field.

2. An EMF and current is "induced" in the coil

i.e., a changing magnetic field induces an EMF in a conductor (e.g., coil)

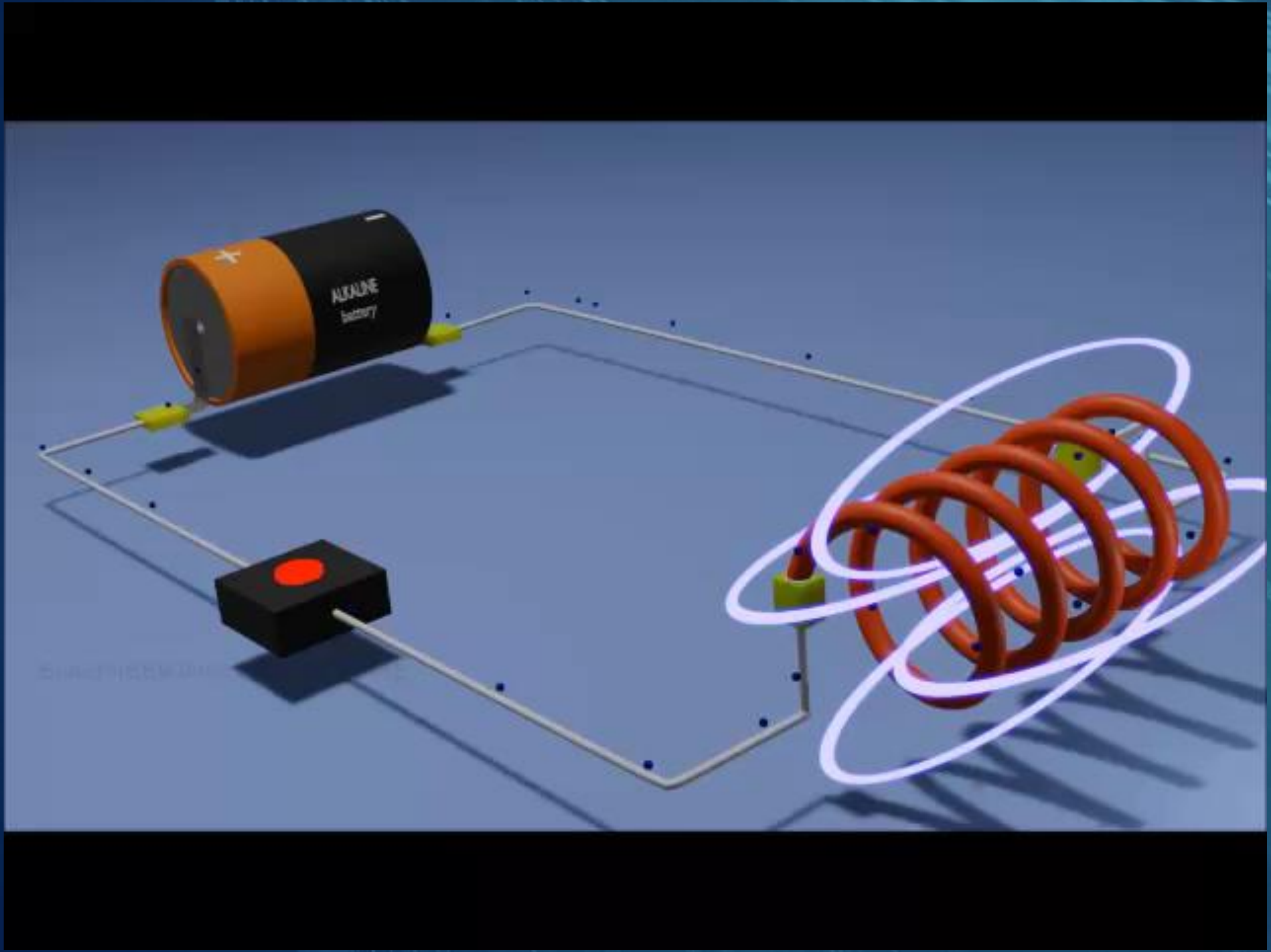
Lenz’s Law: Increasing Fields



1. As current flows through the coil, a magnetic field builds.
   - ✓ Magnetic field not created instantly
2. The magnetic field changes and therefore induces an EMF and current based on Faraday’s Law
   - ✓ This is called self induction.
3. Does the induced current field enhance or oppose the current from the battery?
4. Lenz’s Law: The induced current imposes the original current.
   - ✓ Actually, the induced current generates a magnetic field that opposed the original magnetic field.

   - ✓ This is why we are told, “An inductor opposes a change in current”
5. With a DC source, the magnetic field eventually becomes constant. When constant, there is no induced current.

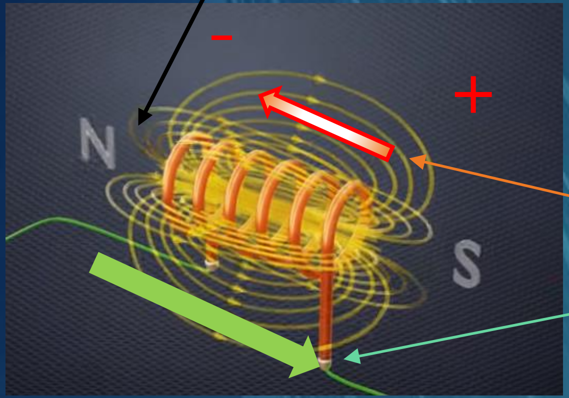
Lenz's Law: Decreasing Fields



1. When current to inductor is turned off, the established statis magnetic field reduces
2. The magnetic field changes and therefore induces an EMF and current based on Faraday's Law
   - ✓ This is called self induction.
3. Lenz's Law: The induced current imposes the original current.
4. If there is now path for the induced current to flow, the voltage can grow very large
   - ✓ This is why you need a diode across a relay coil.

Increasing VS Decreasing Current

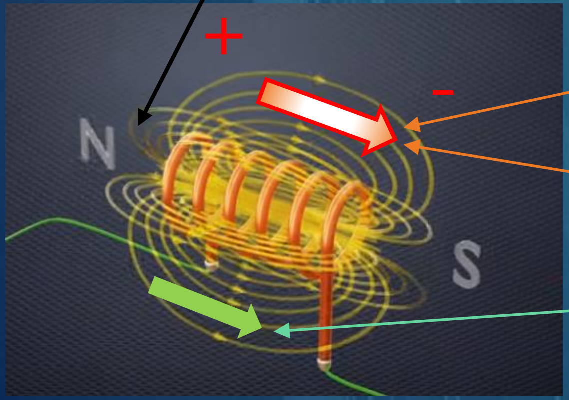
Increasing Field/Increasing Current



Induced current generates a field that opposes original changing field

Original current increasing

Decreasing Field/Decreasing Current



Induced current generates a field that opposes original changing field. In this case, the generated current tries to keep the field from changing

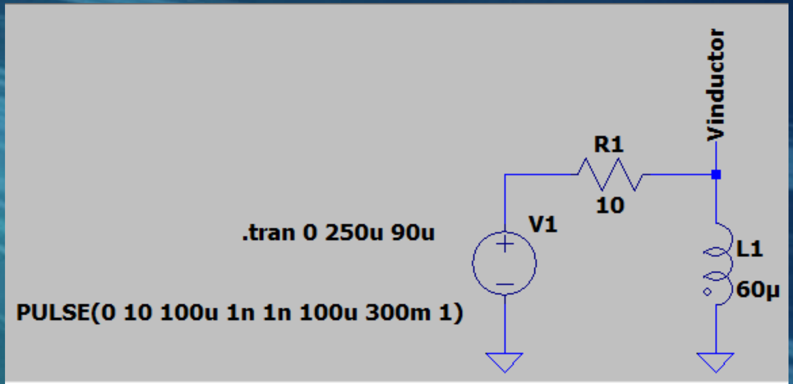
Original current decreasing

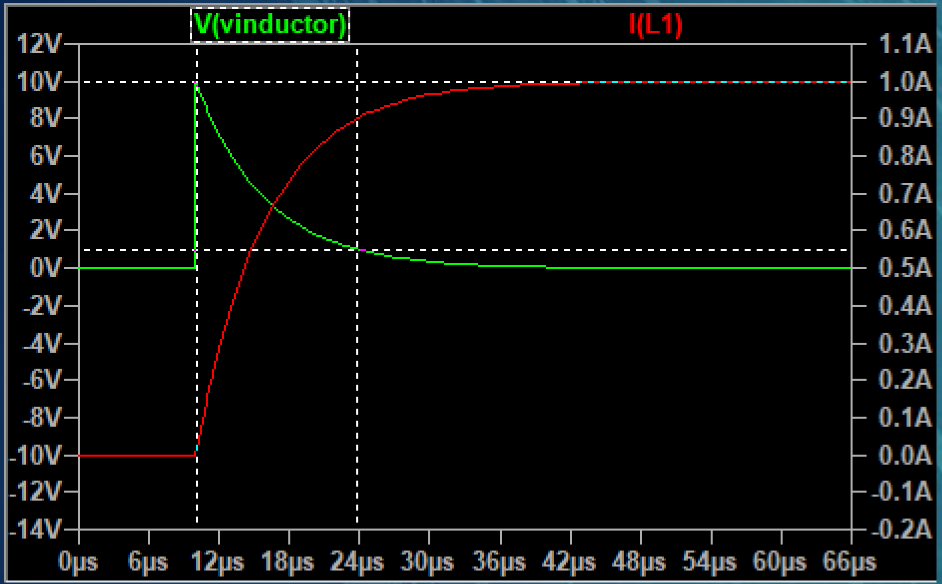
Lenz's Law: The induced current imposes the change in original current.

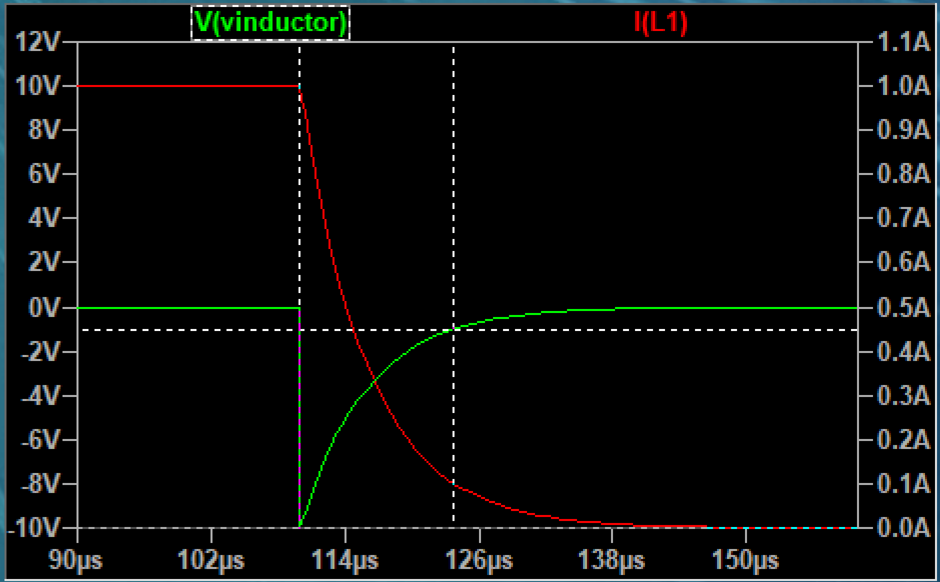
- The induced current generates a magnetic field that opposes the original magnetic field.

Note: If this current has no where to flow very large EMF results (large voltage)

Charge & Discharge



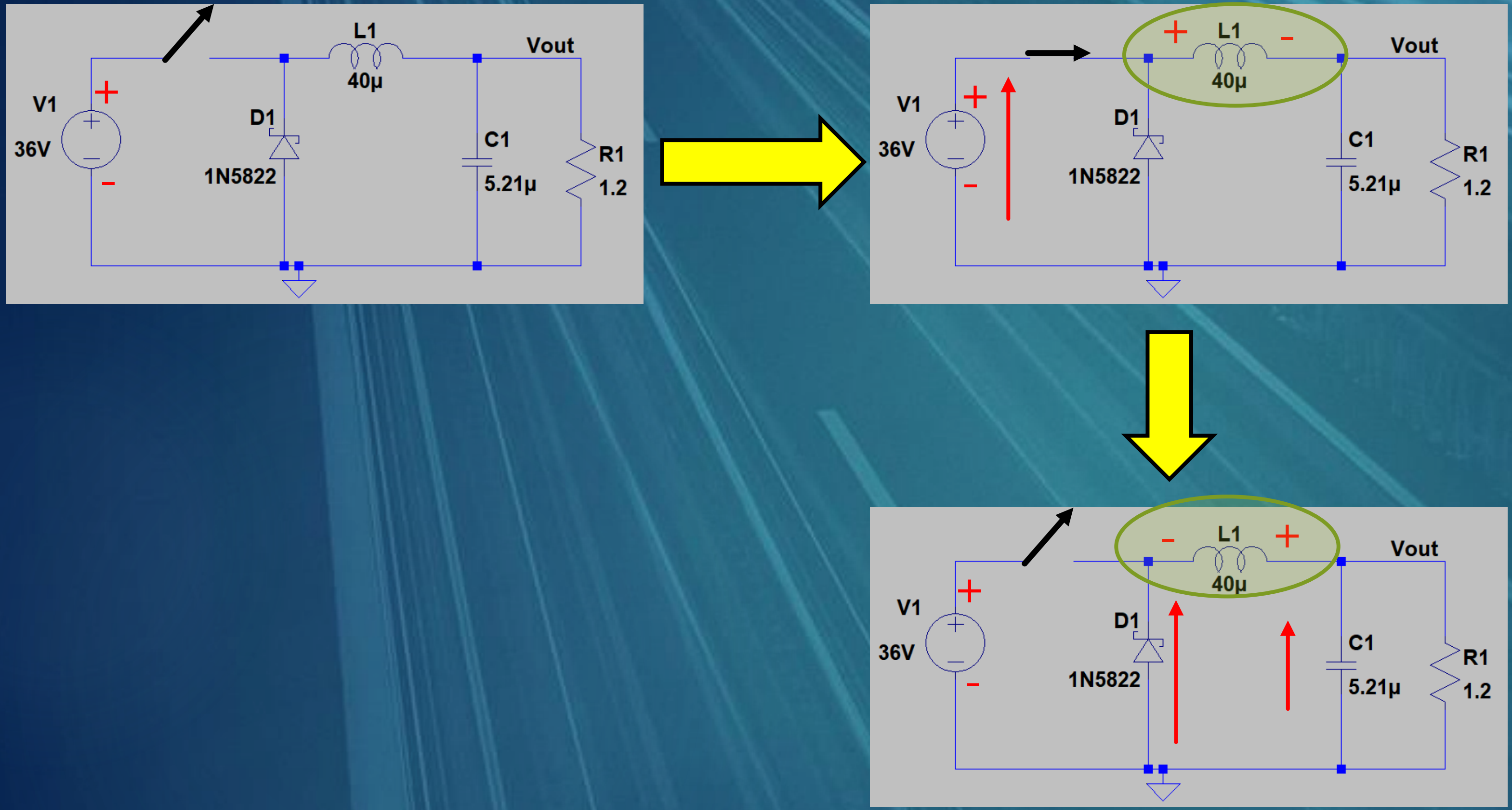




Cursor 1	V(vinductor)		
Horz:	10.015848µs	Vert:	9.9744621V
Cursor 2	V(vinductor)		
Horz:	23.81876µs	Vert:	1.0021487V
Diff (Cursor2 - Cursor1)			
Horz:	13.802912µs	Vert:	-8.9723134V
Freq:	72.44848KHz	Slope:	-650030

Cursor 1	V(vinductor)		
Horz:	110.002µs	Vert:	-9.9981623V
Cursor 2	V(vinductor)		
Horz:	123.74359µs	Vert:	-1.0138262V
Diff (Cursor2 - Cursor1)			
Horz:	13.74159µs	Vert:	8.9843361V
Freq:	72.771784KHz	Slope:	653806

Summary:



1. Switch Closed. Current slowly flows through inductor.
2. Inductor opposes current increase
3. Capacitor Charges
4. Current slowly increases through R1

1. Current rapidly decreases through inductor.
2. Inductor opposes current decrease
3. Capacitor and inductor act as a battery
4. Current continue to flow through R1

Rabbit Hole #2: Mosfets

Agenda

1. Mosfet Parameters and Buck Converter

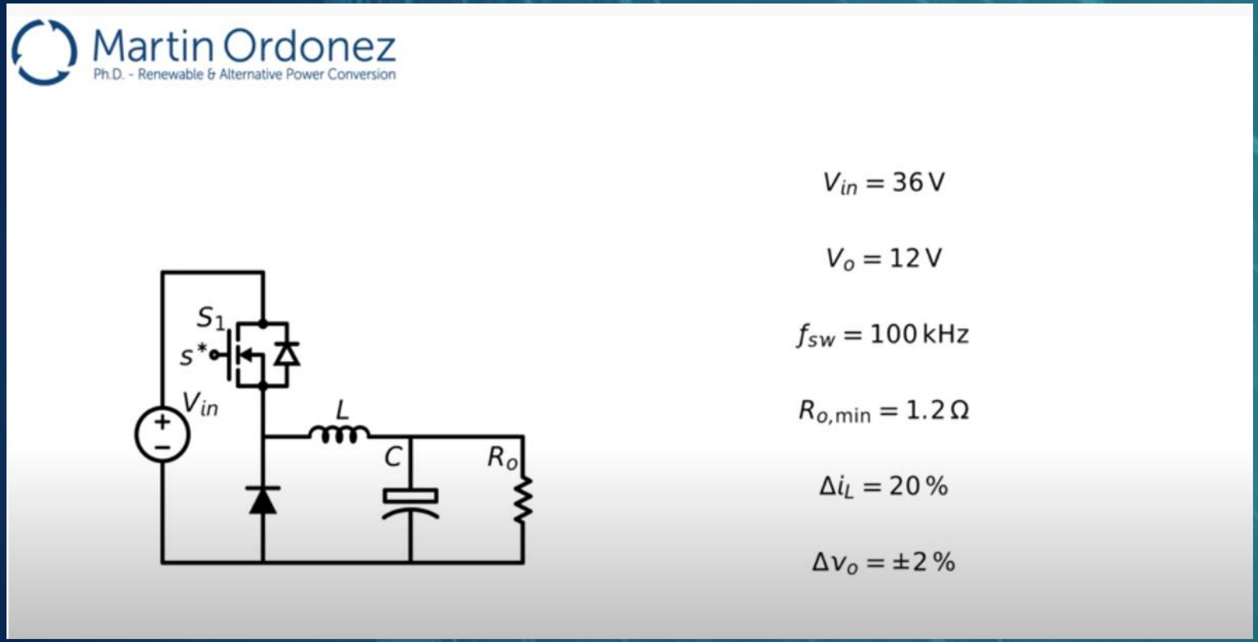
2. High Side & Low Side Switching

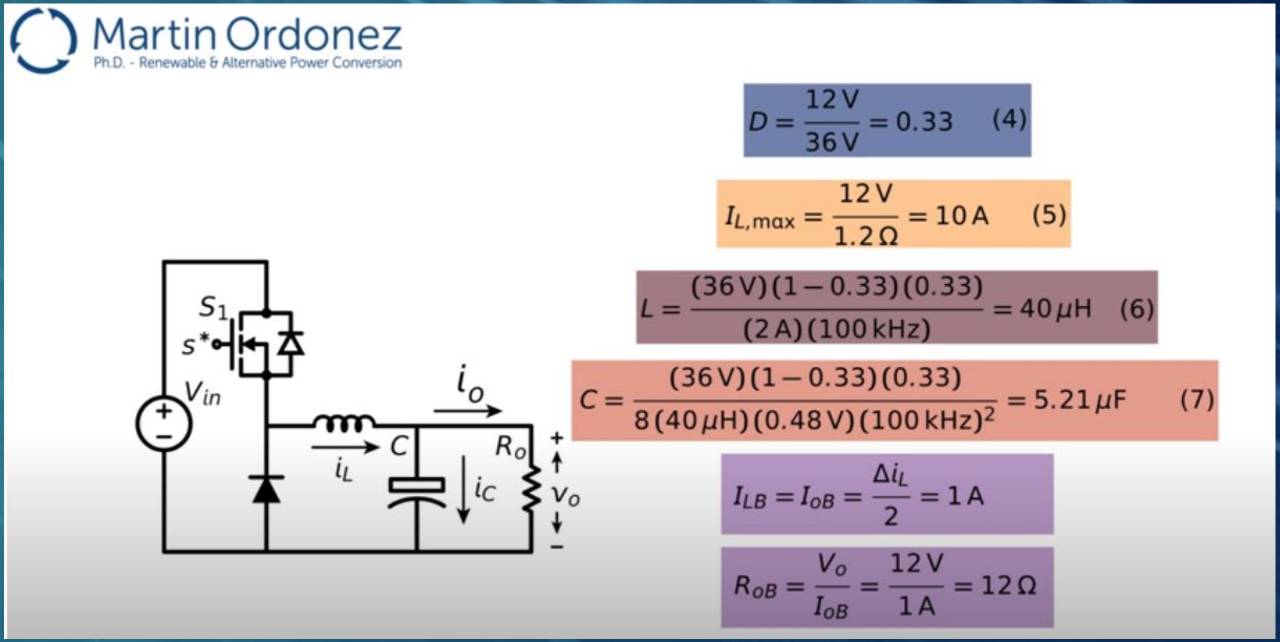
3. Mosfet Construction

4. Capacitance

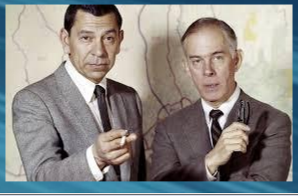
5. Mosfet Model in LTSpice

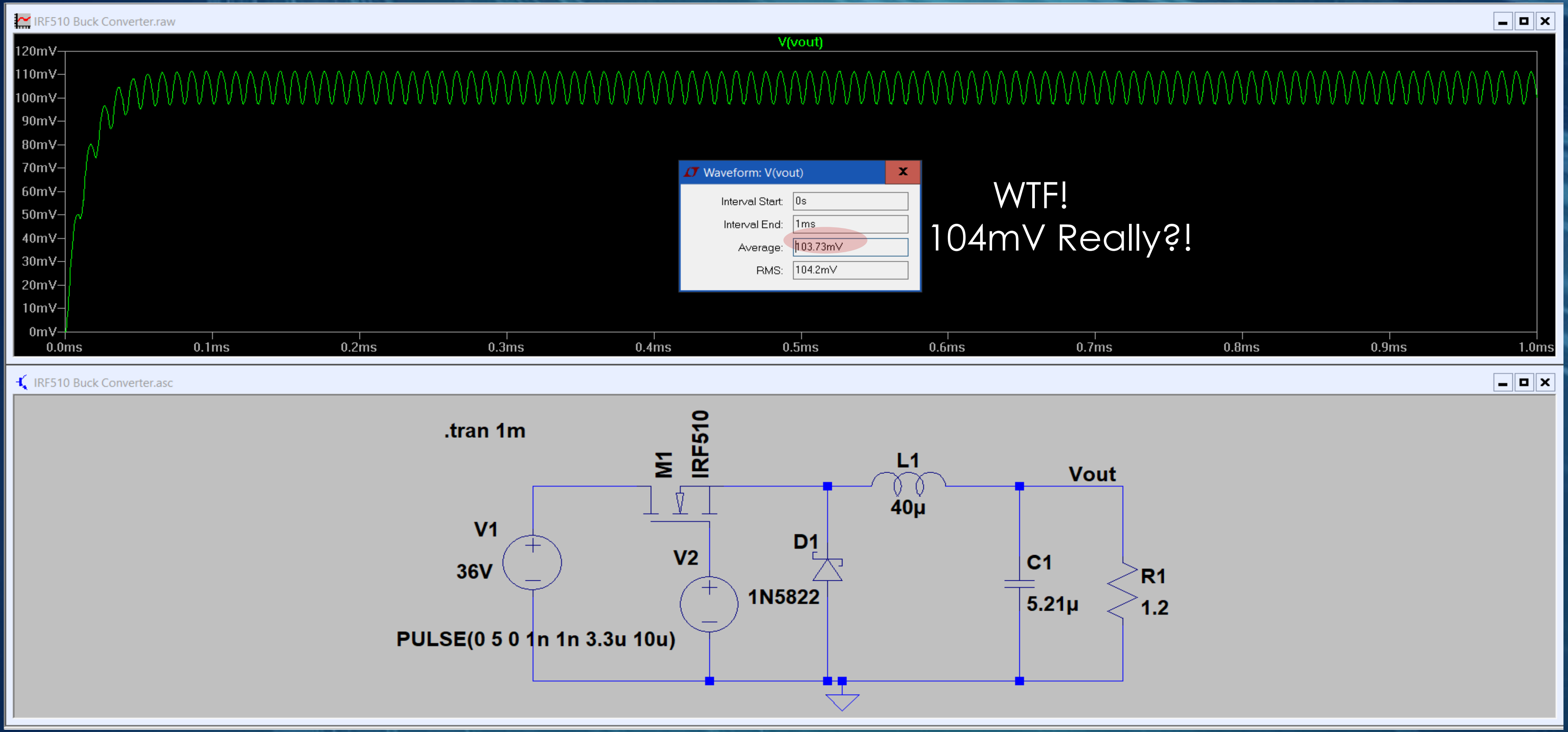
Recall: Buck Converter Design





In our last episode…





WTF!
104mV Really?!

Its actually “Vgs” Threshold.

Gate voltage must be (at least) 4V higher that source voltage to turn on.

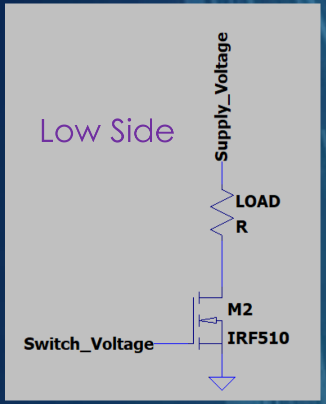
Key Parameters for Buck Converter

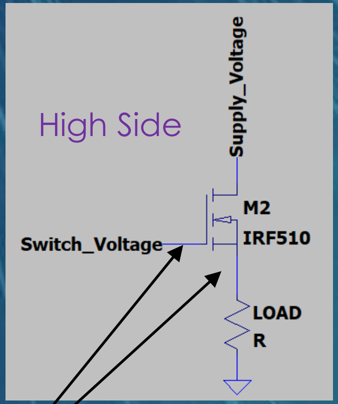
SPECIFICATIONS (T_J = 25 °C, unless otherwise noted)						
PARAMETER	**SYMBOL**	**TEST CONDITIONS**	**MIN.**	**TYP.**	**MAX.**	**UNIT**
Static						
Drain-source breakdown voltage	V_{DS}	V_{GS} = 0 V, I_D = 250 µA	100	-	-	V
V_{DS} temperature coefficient	$\Delta V_{DS}/T_J$	Reference to 25 °C, I_D = 1 mA	-	0.12	-	V/°C
Gate-source threshold voltage	$V_{GS(th)}$	V_{DS} = V_{GS}, I_D = 250 µA	2.0	-	4.0	V
Gate-source leakage	I_{GSS}	V_{GS} = ± 20 V	-	-	± 100	nA
Zero gate voltage drain current	I_{DSS}	V_{DS} = 100 V, V_{GS} = 0 V	-	-	25	µA
		V_{DS} = 80 V, V_{GS} = 0 V, T_J = 150 °C	-	-	250	
Drain-source on-state resistance	$R_{DS(on)}$	V_{GS} = 10 V, I_D =3.4 A [b]	-	-	0.54	Ω
Forward transconductance	g_{fs}	V_{DS} = 50 V, I_D = 3.4 A [b]	1.3	-	-	S

1. Gate threshold (Vgs) is relative to source.
   - ✓ E.g. If Source Grounded, Gate needs to be between 2 to 4 Volts
   - ✓ E.g. If Source is at 5V, Gate needs to be between 7 to 9 Volts

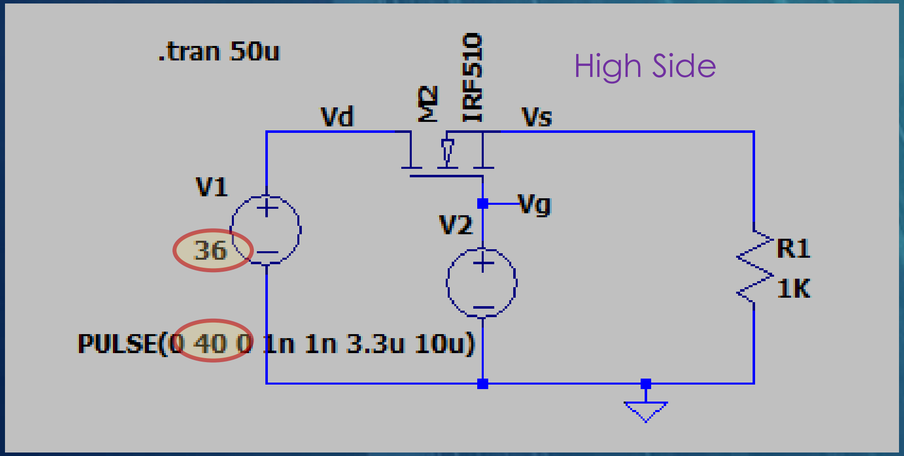
2. If Vgs is 10V, and Id is 3.4A, Ron is 0.54 ohms

High Side vs Low Side Mosfet Switch

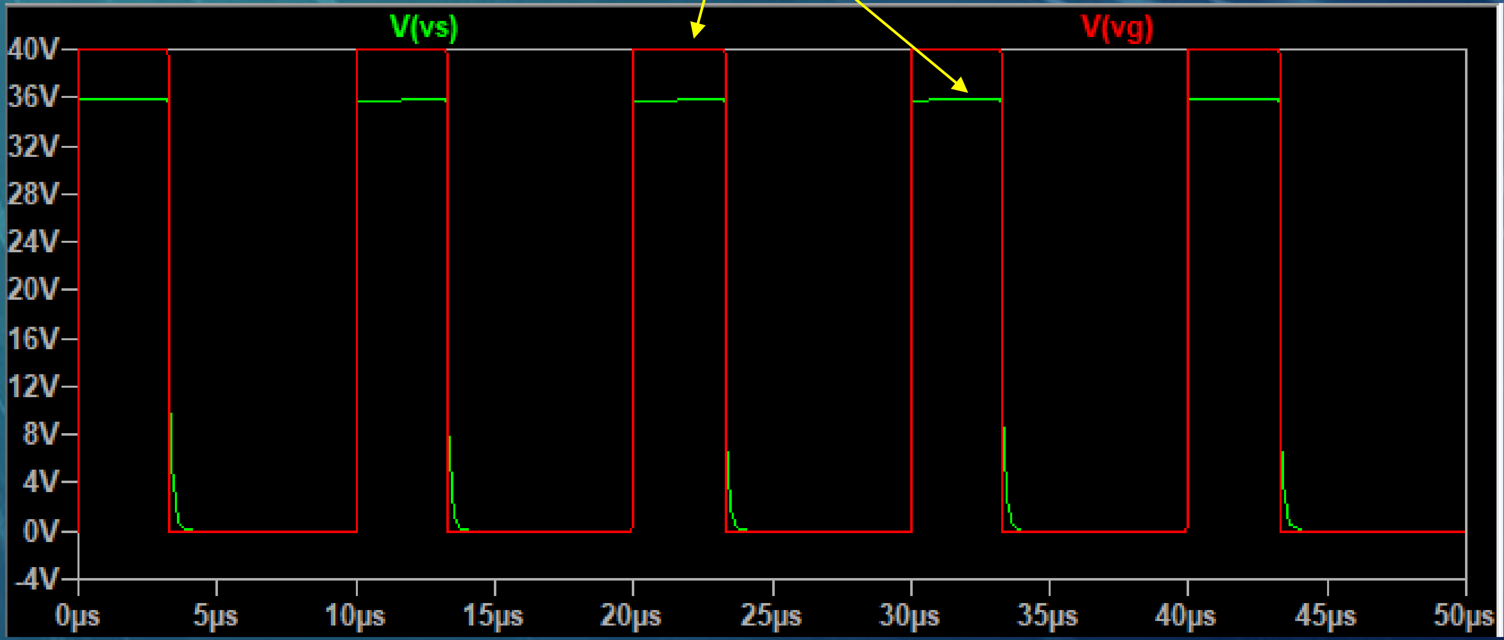




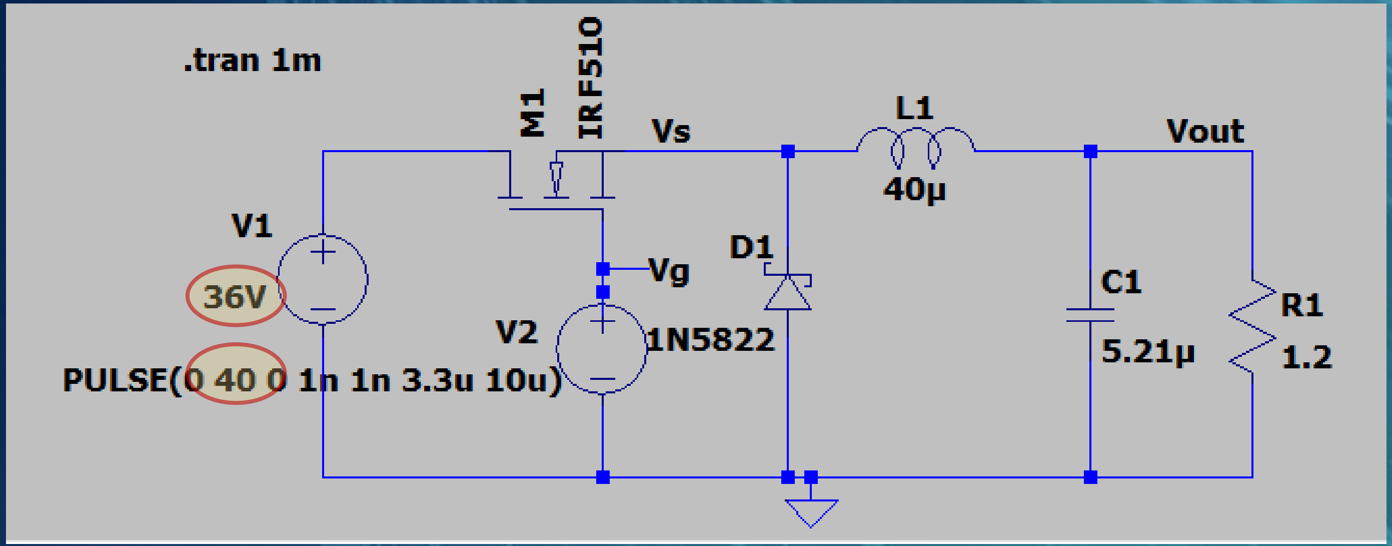
Vg >> Vs by Vgs



Vg >> Vs by Vgs=4V

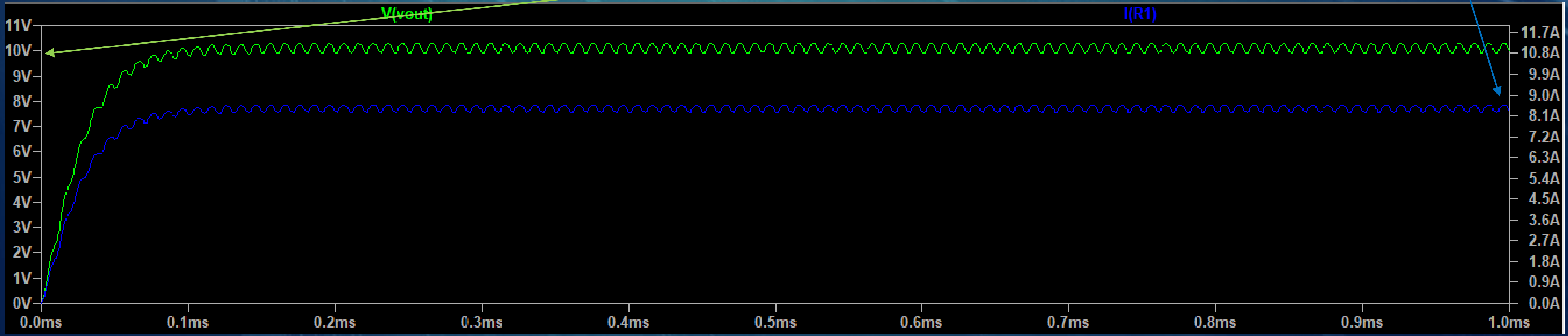


Back to the Buck…



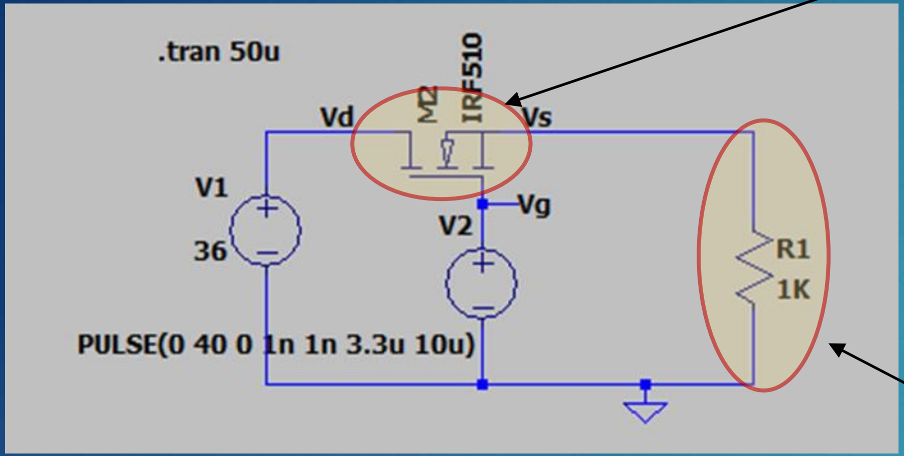
Huh? 8ish A?
Should be 10A

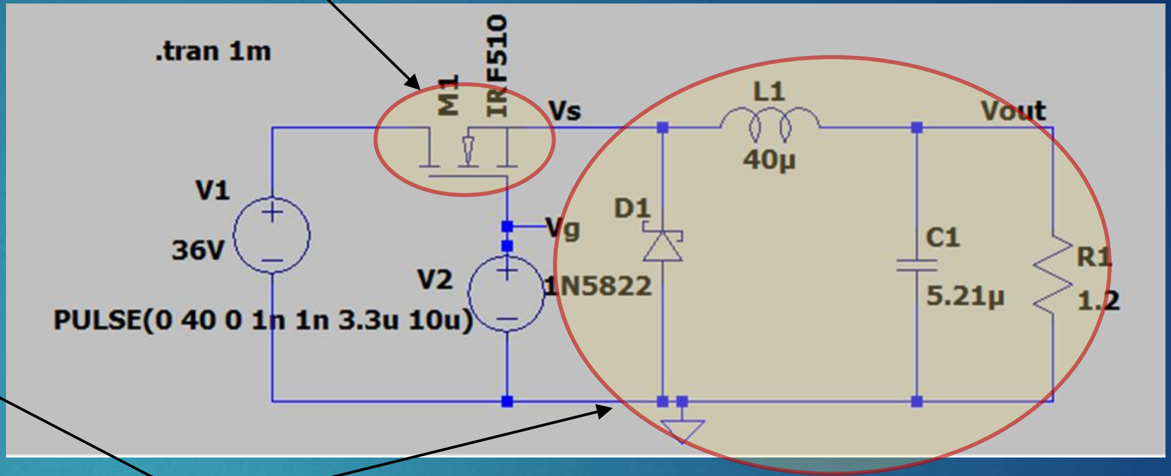
Huh? 10V?
Should be 12V



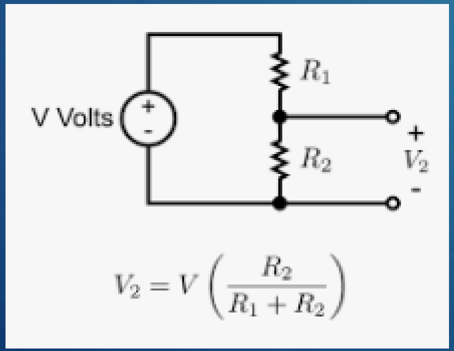
Doh....

R1





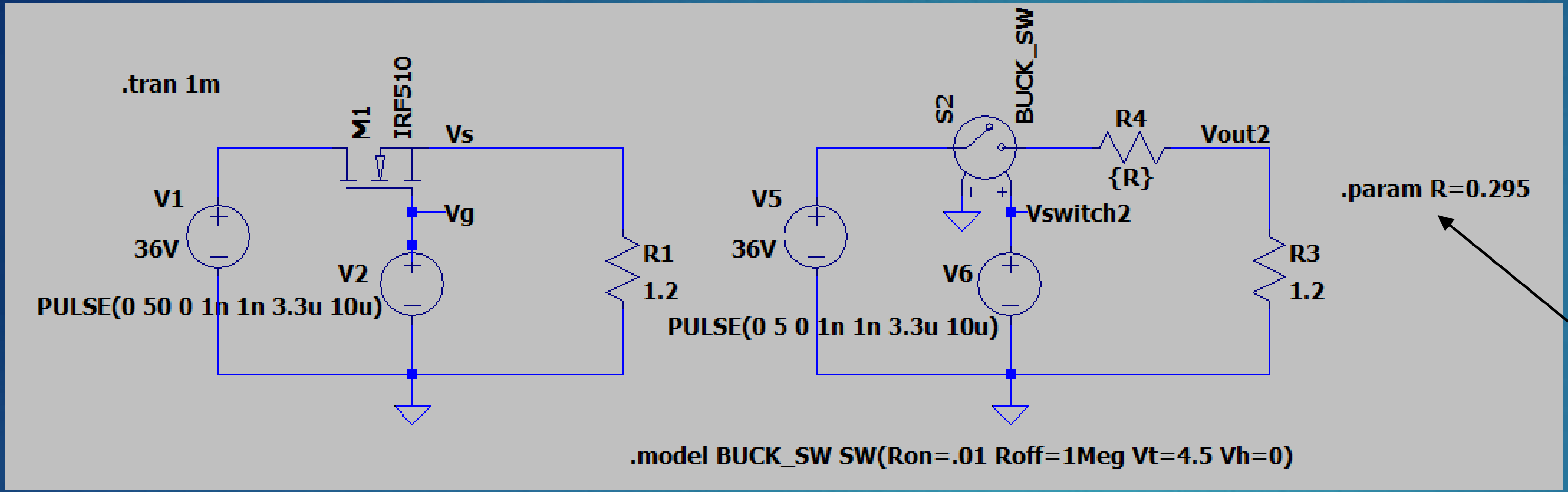
R2

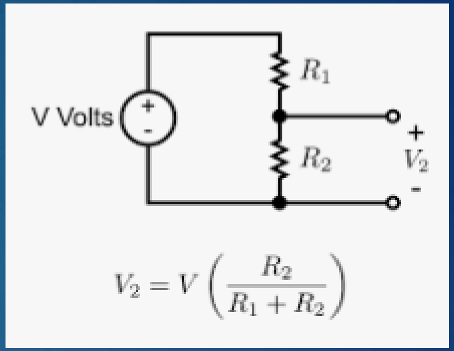


R1

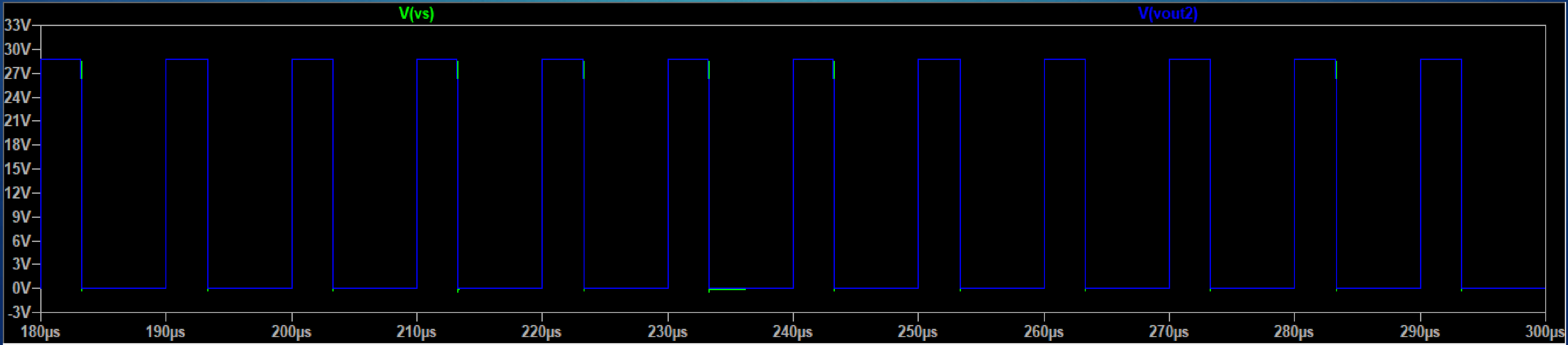
Drain-source on-state resistance	$R_{DS(on)}$	V_{GS} = 10 V	I_D =3.4 A [b]	-	-	0.54	Ω

SUCCESS!!!!!!!

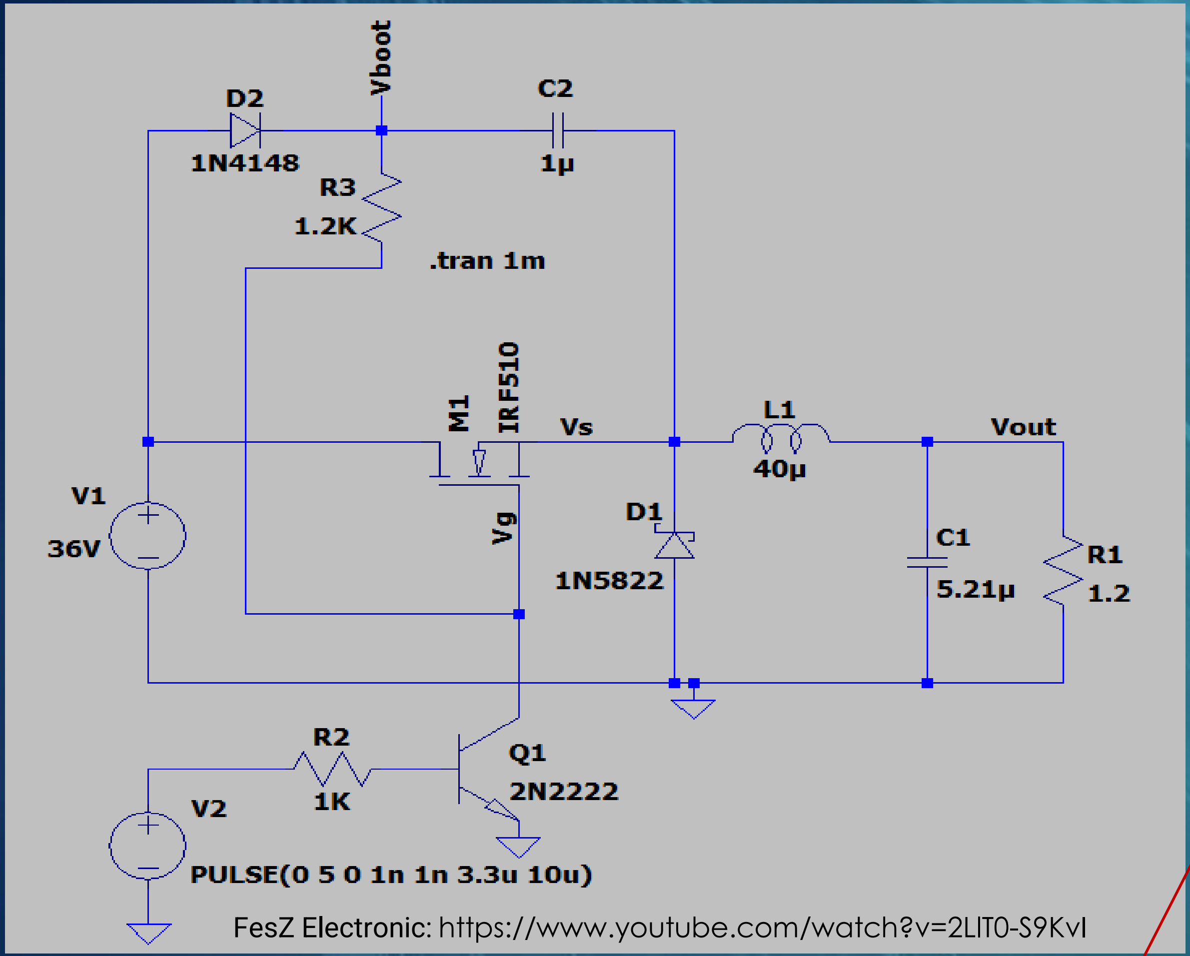


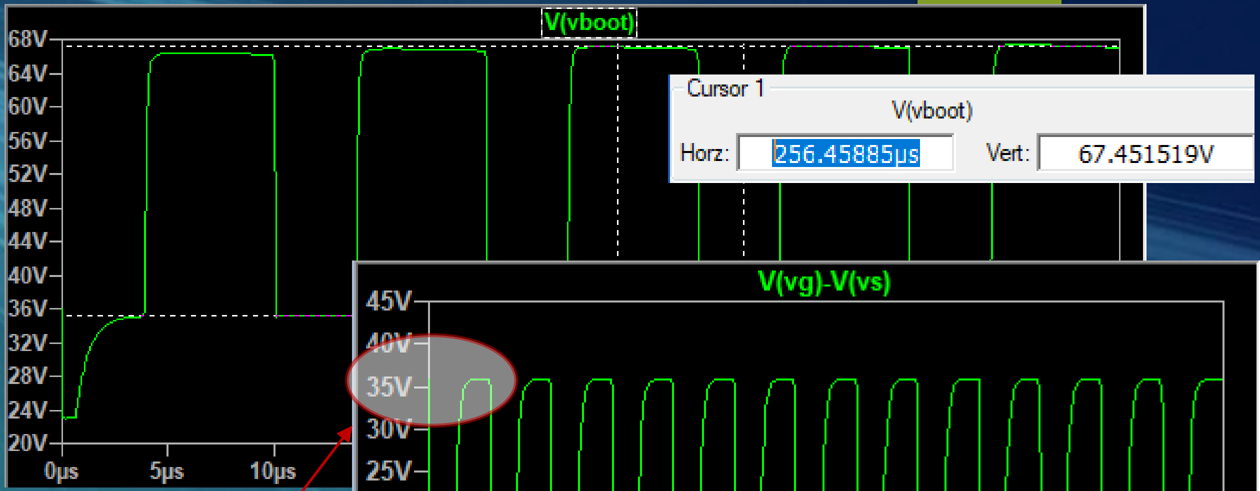


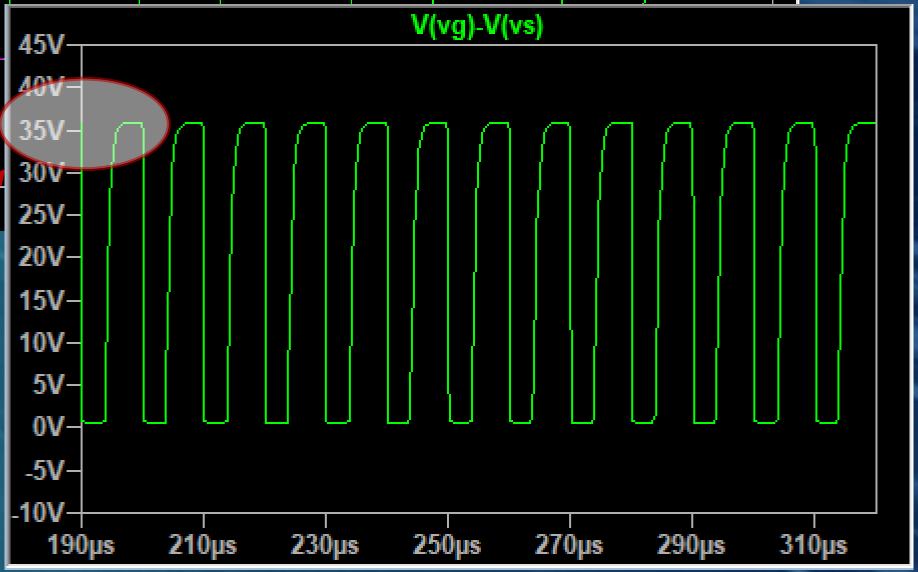
With some math…Ron is 0.3 ohms

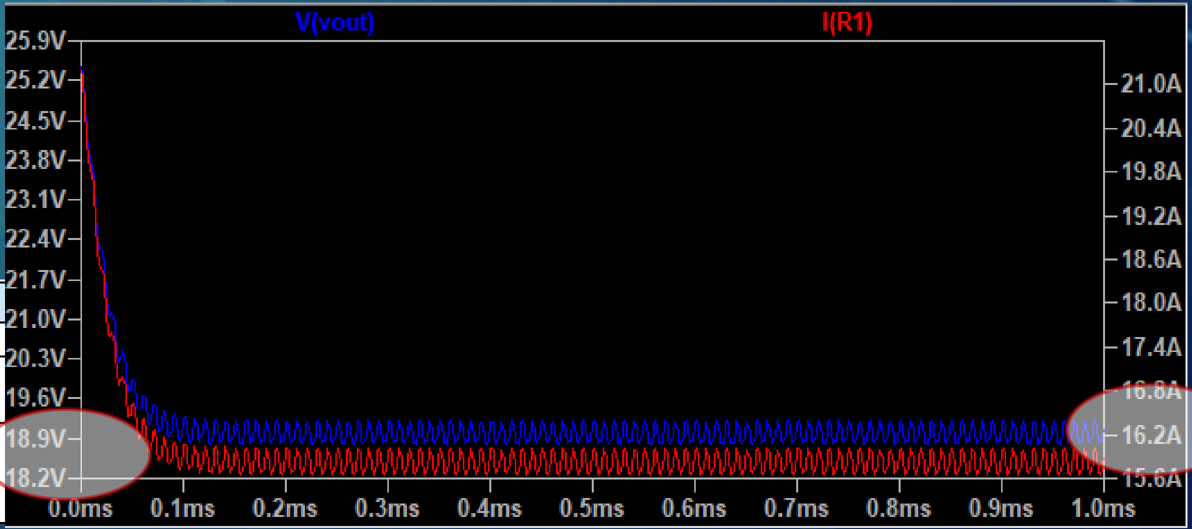


High Side Bootstrap









ABSOLUTE MAXIMUM RATINGS (T_C = 25 °C, unless otherwise noted)

PARAMETER			SYMBOL	LIMIT	UNIT
Drain-source voltage			V_{DS}	100	V
Gate-source voltage			V_{GS}	± 20	V
Continuous drain current	V_{GS} at 10 V	T_C = 25 °C	I_D	5.6	A
		T_C = 100 °C		4.0	
Pulsed drain current [a]			I_{DM}	20	

Proper Buck Converter

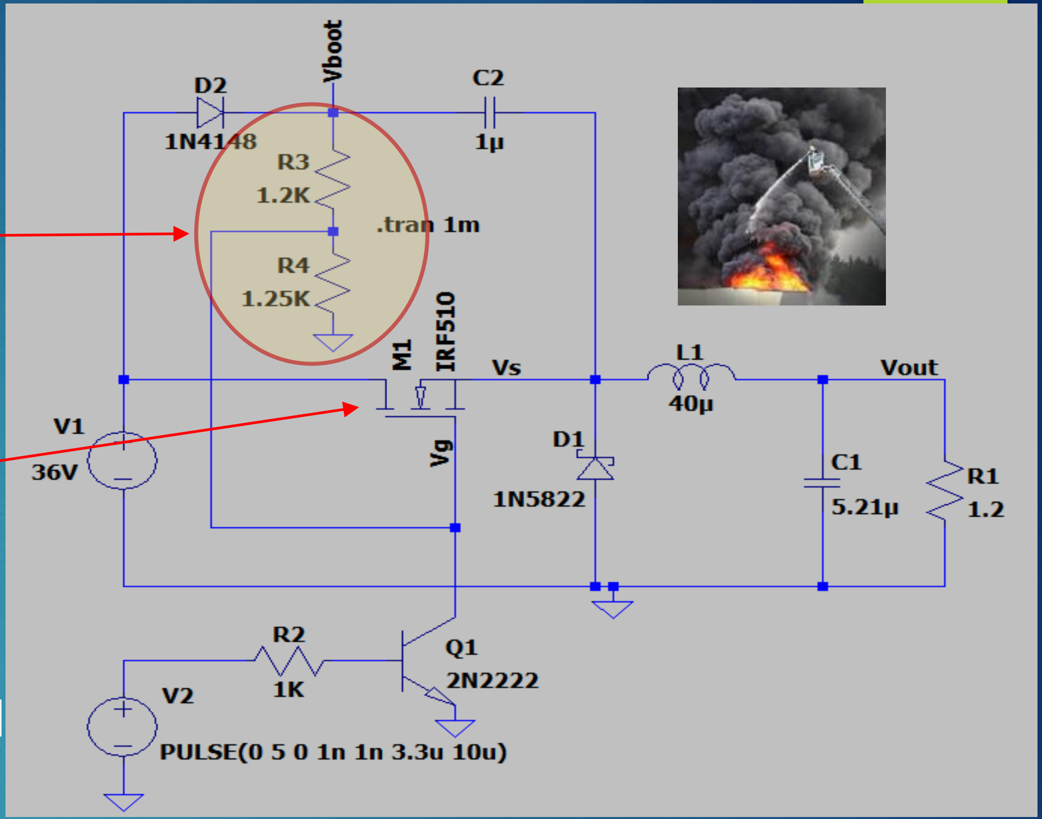
Voltage Divider
to produce Vg
so that Vs is 36V

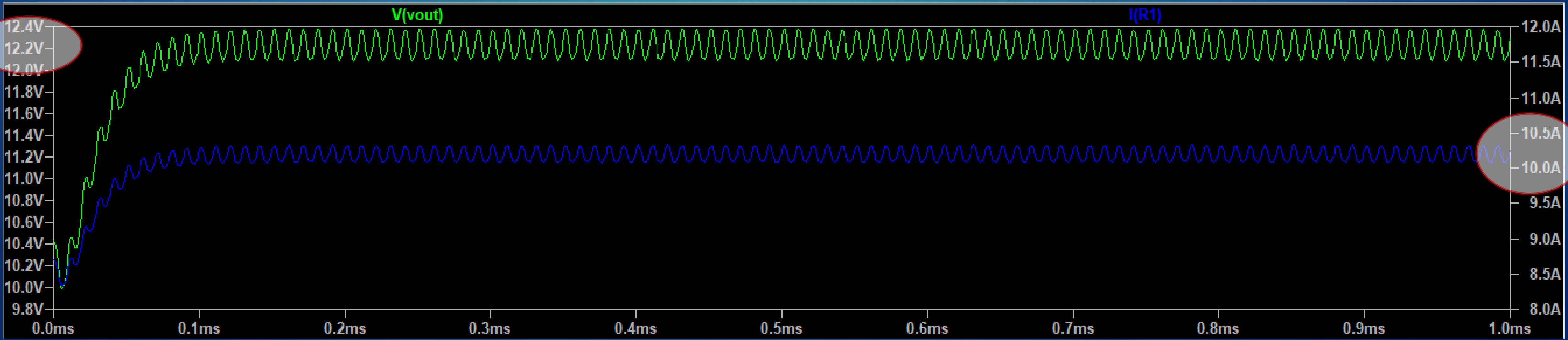
LTSpice Trick:

- ✓ Press ALT Key + Click component (pwr plot)
- ✓ Press CTL Key + Click on trace (integrate/rms)

Interval Start:	0s
Interval End:	1ms
Average:	99.044W
Integral:	99.044mJ

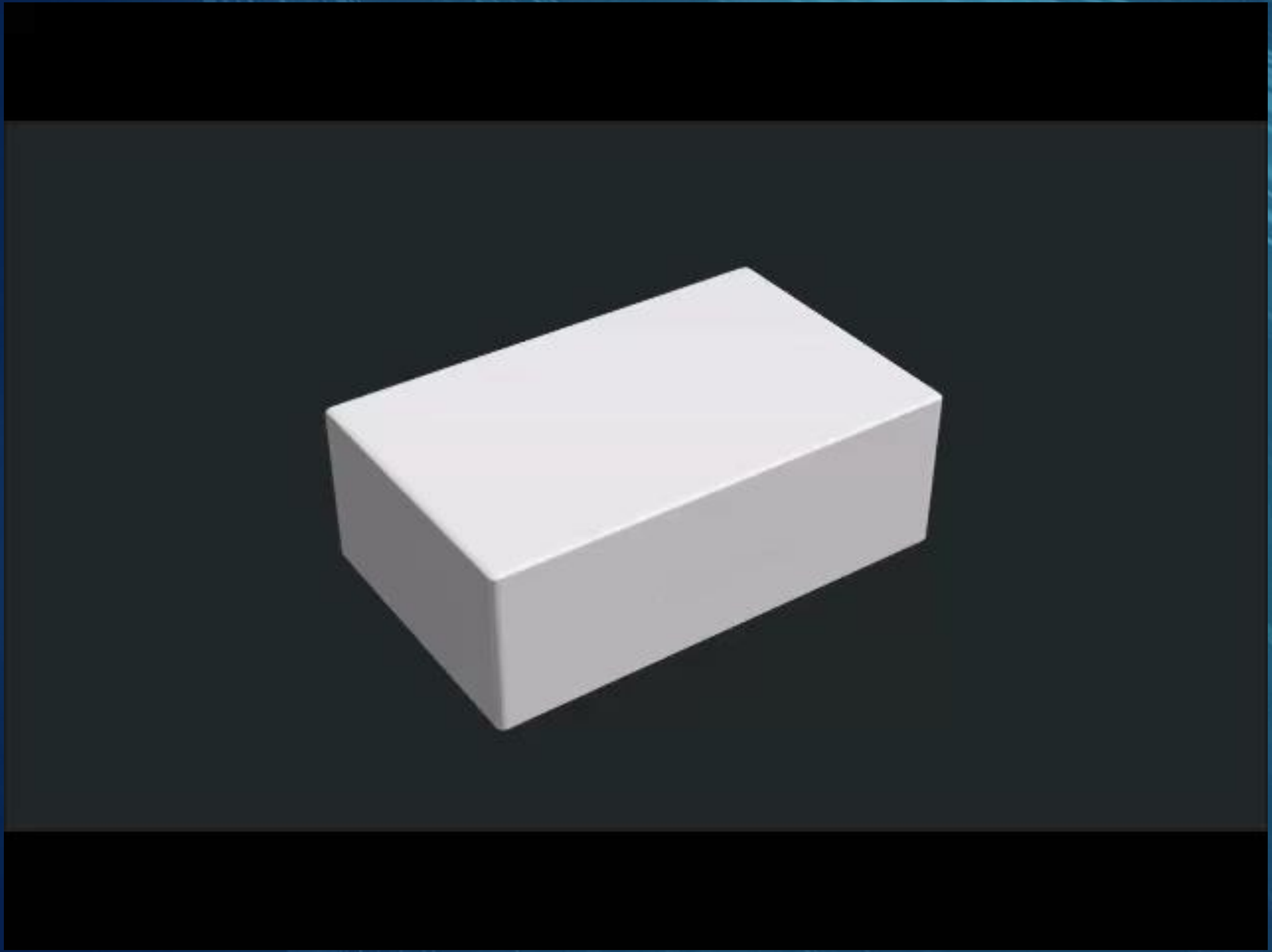
Maximum power dissipation	T_C = 25 °C	P_D	43	W





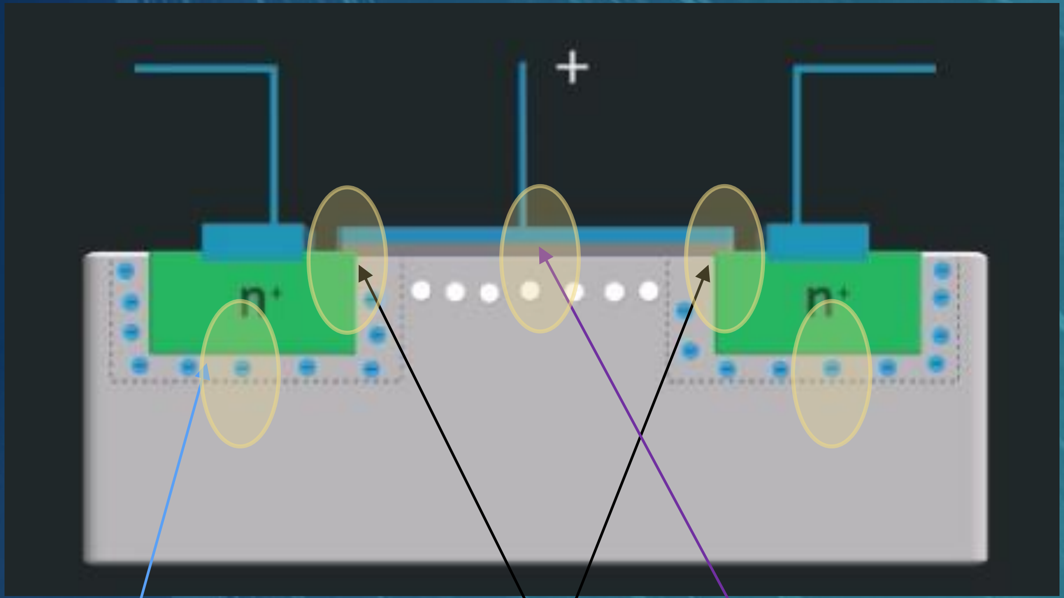
MOSFET CONSTRUCTION

N Channel
Enhancement Mode



1. Created by applying two "N" doped semiconductors to a based on "P" doped semiconductor
2. N-Doped has impurity added with excess electrons and P-Doped has impurity added with more holes (missing electrons)
3. The N doped semiconductors are source and drain (Collector/Emitter)
4. A metal plate with an insulator is added to the P-doped base to create a capacitor.
5. When a voltage is applied to the gate with **respect to the source**, elections are attracted to the gate, and a channel is formed.
6. Once a threshold gate voltage is applied, current flows between drain and source

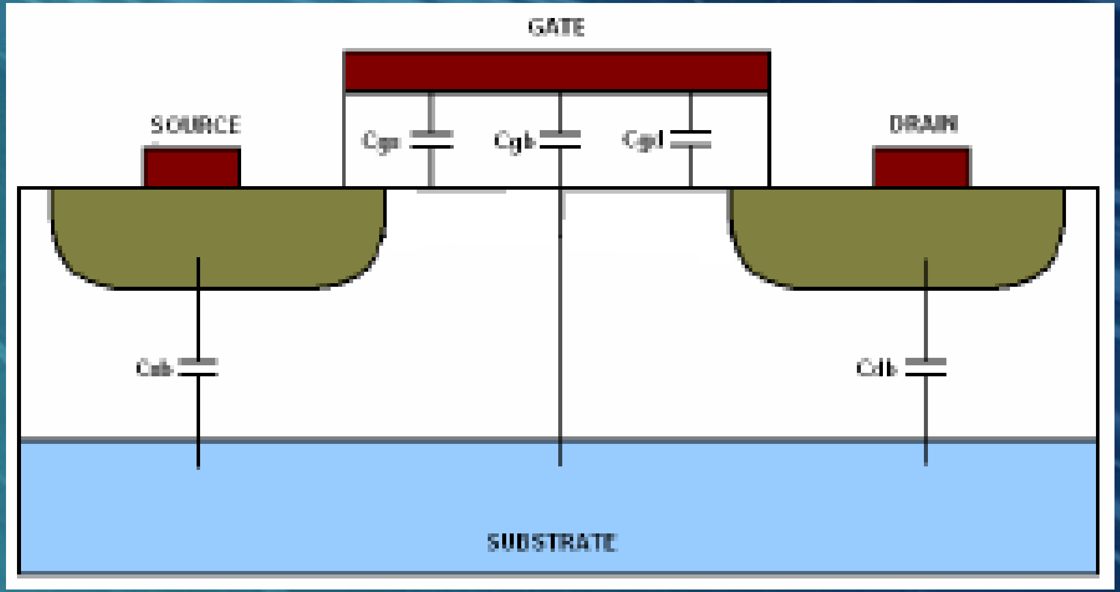
Capacitors

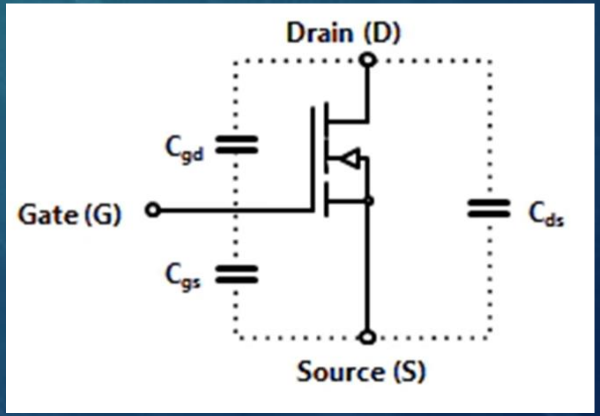


Depletion region

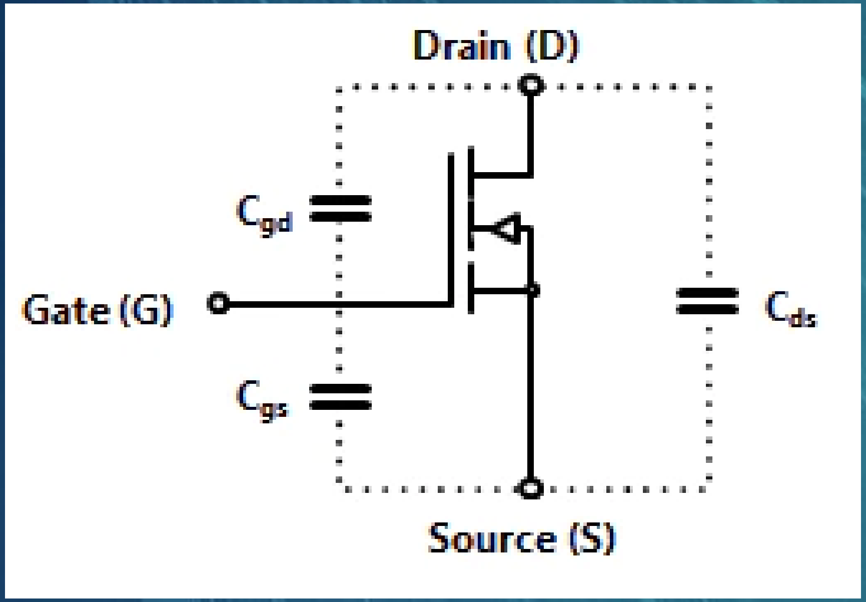
Overlap

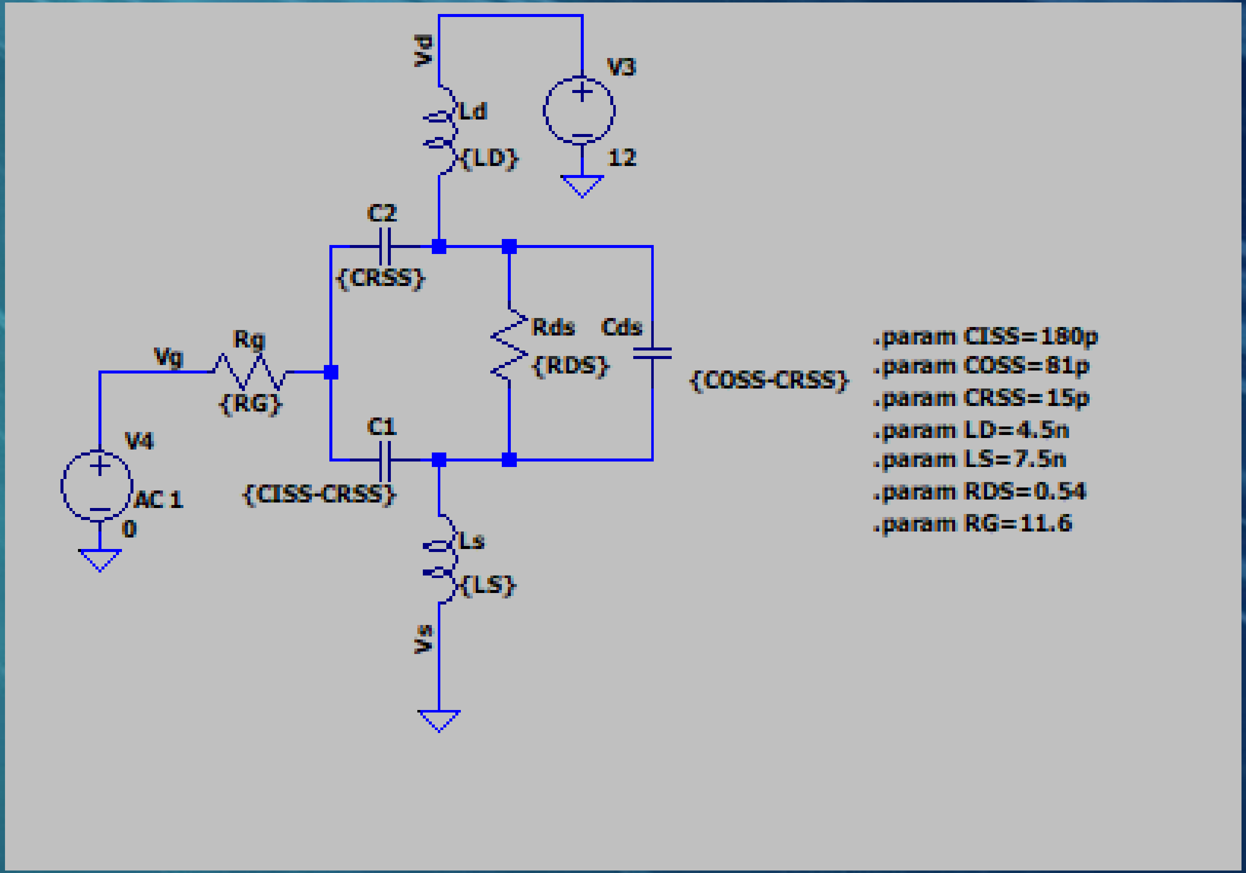
Oxide/dielectric





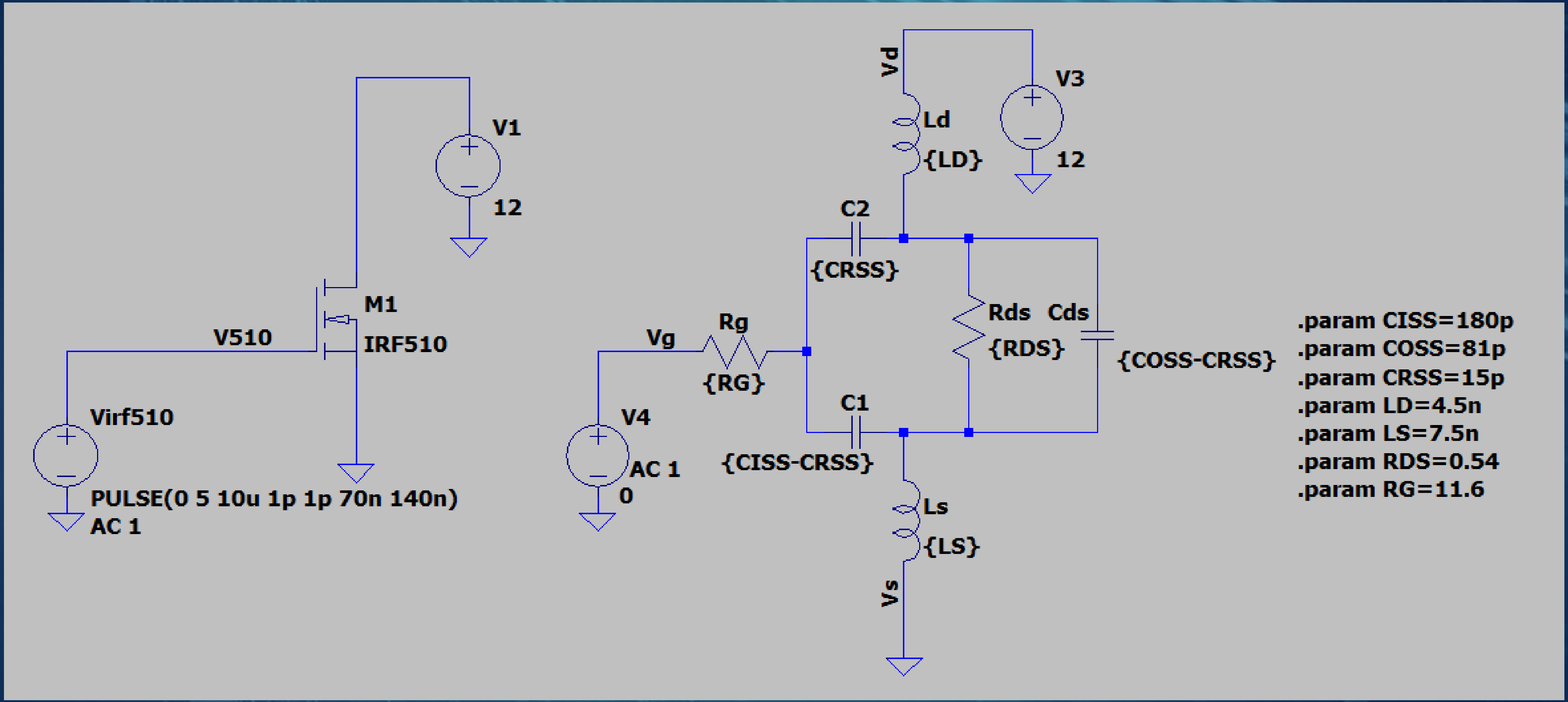
MOSFET CAPACITANCE DEFINED



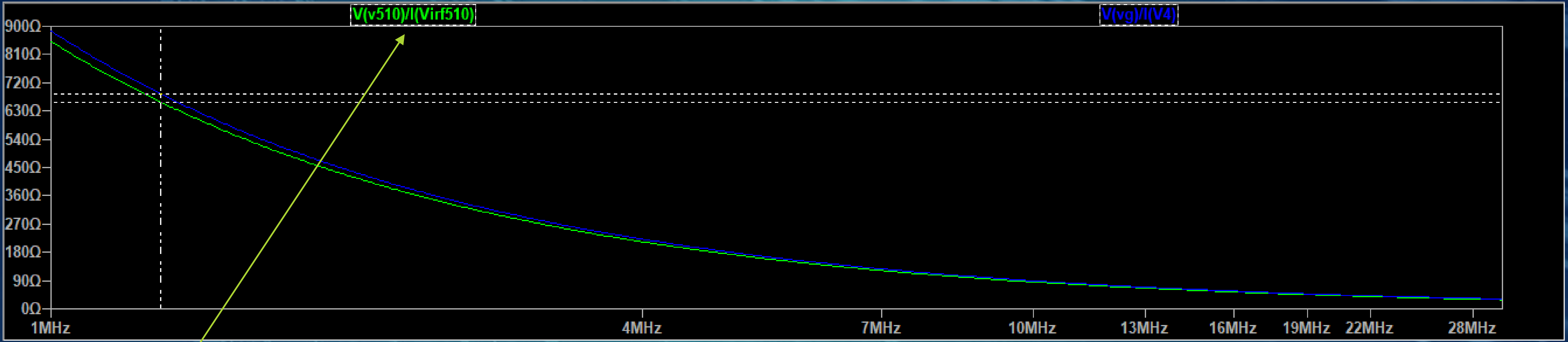


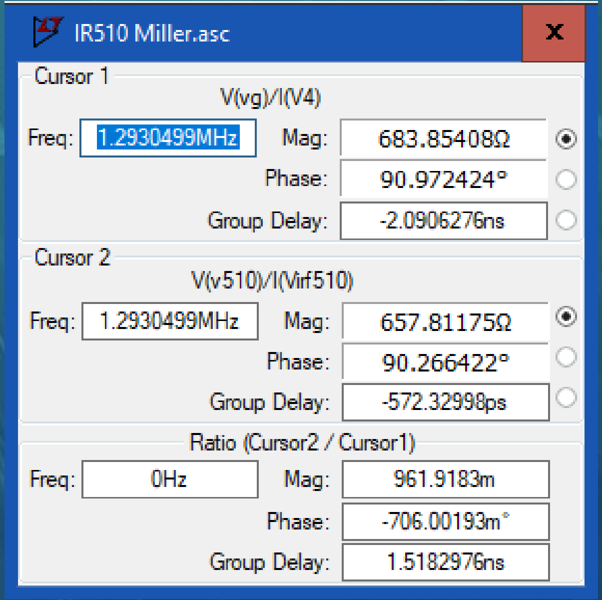
Dynamic						
Input capacitance	C_{iss}	V_{GS} = 0 V, V_{DS} = 25 V, f = 1.0 MHz, see fig. 5	-	180	-	pF
Output capacitance	C_{oss}		-	81	-	
Reverse transfer capacitance	C_{rss}		-	15	-	

Model Comparison



Winner…Winner…



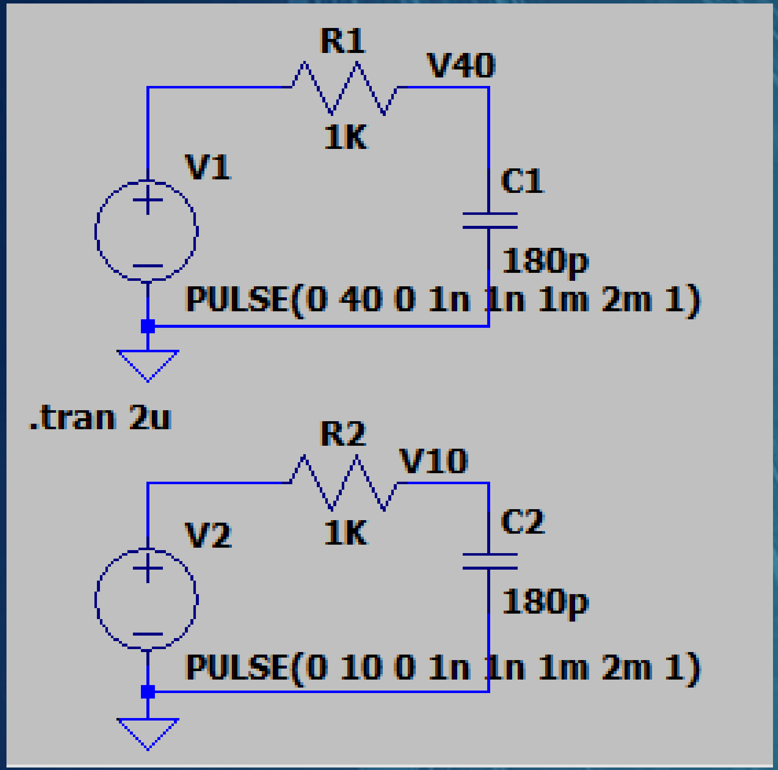


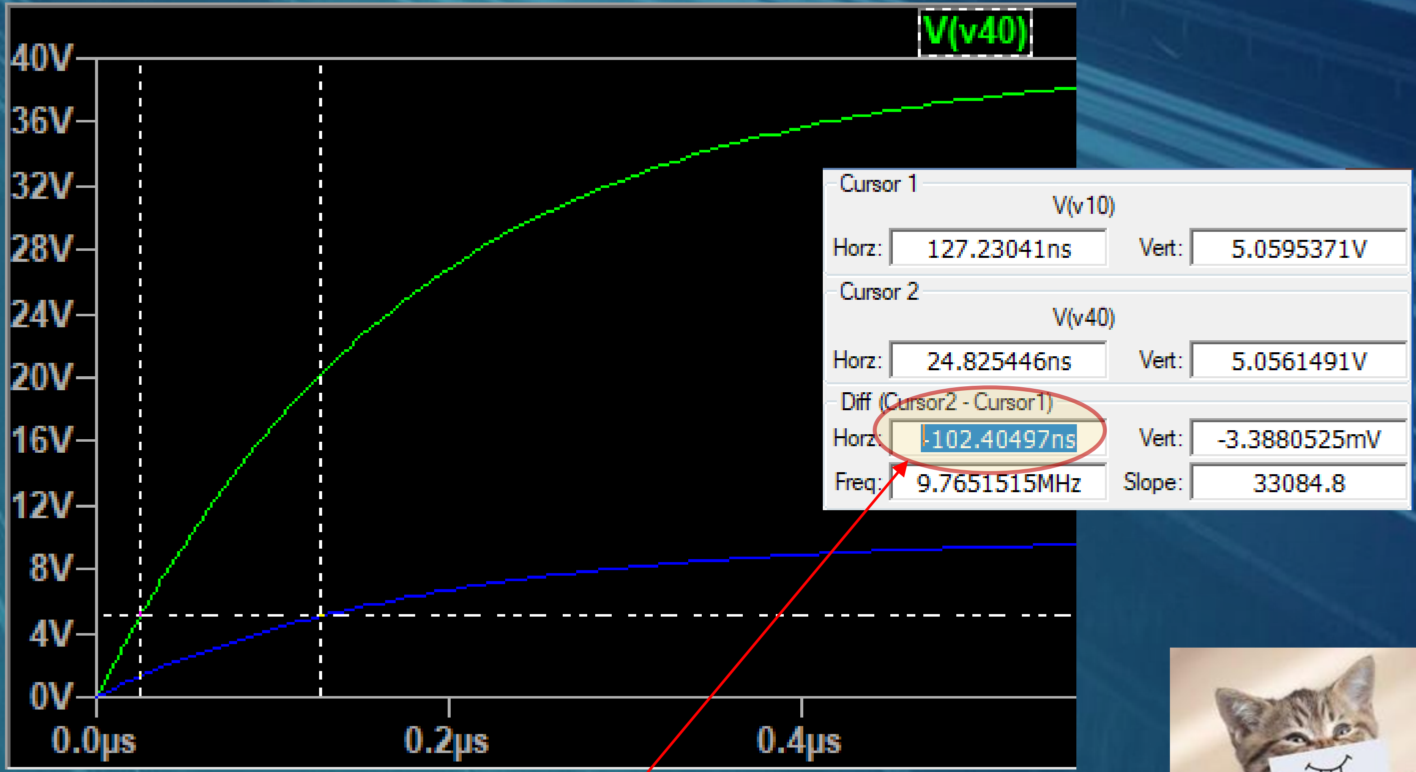
LTSpice Trick:

- ✓ right clk Select "Add Plot"
- ✓ select what you want to plot
- ✓ Can use * / + - fun()

http://ltwiki.org/index.php?title=Waveform_Arithmetic

Back to the Buck…

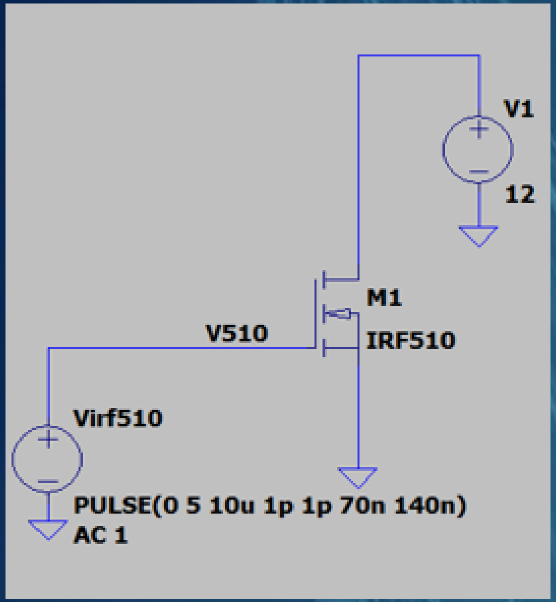


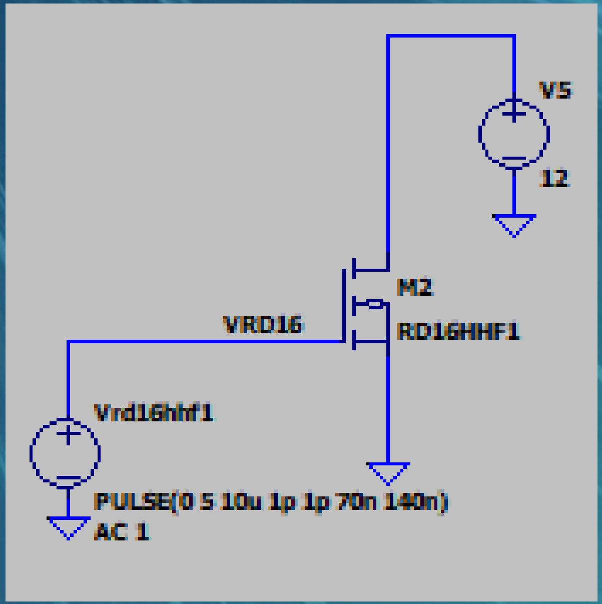


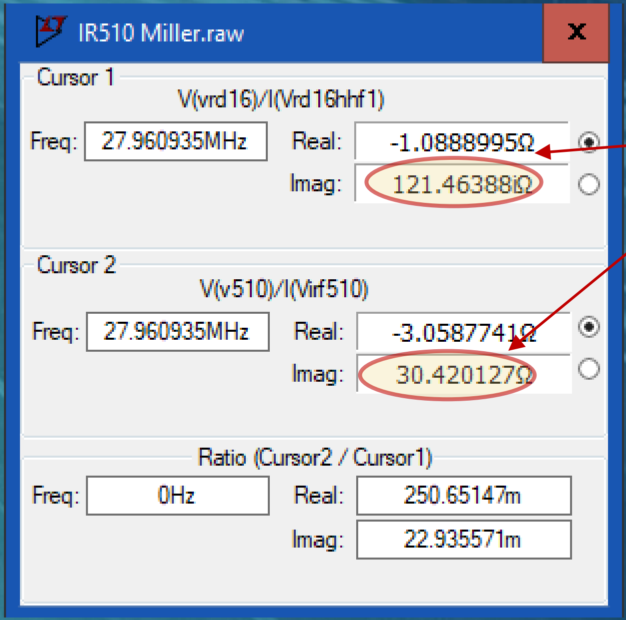
Lower voltage input takes longer to reach threshold

i.e. Higher Vgs causes Mosfet capacitor to charge faster and Mosfet to turn on faster

What Does This Mean?!

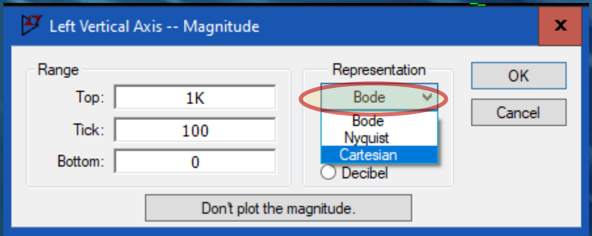


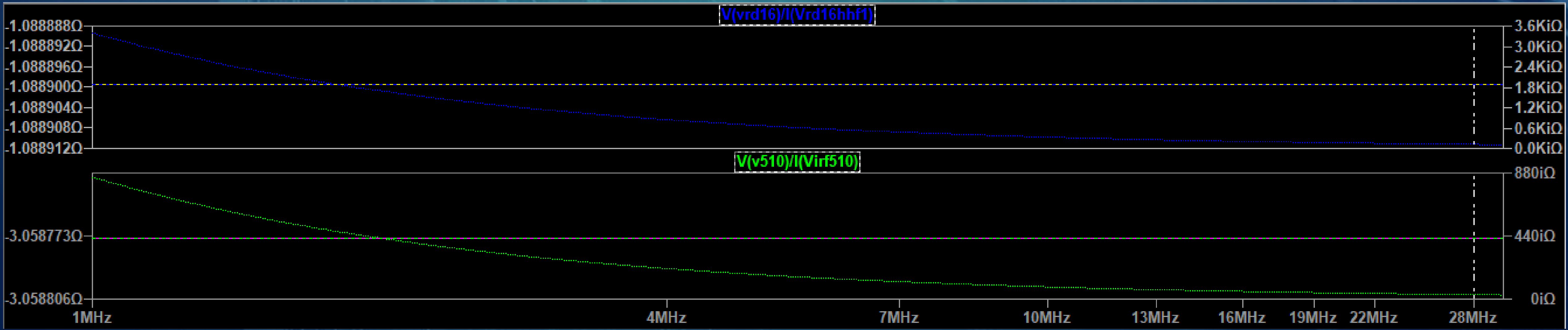




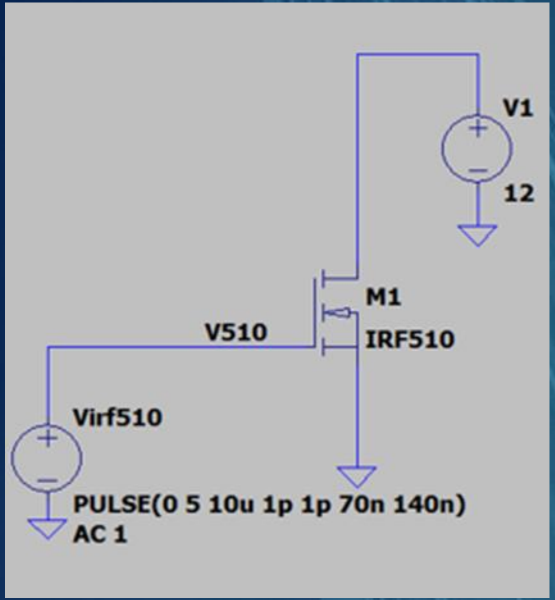
Dominated by **Imaginary** Impedance (at any frequency)

LTSpice Trick:





In English…Please

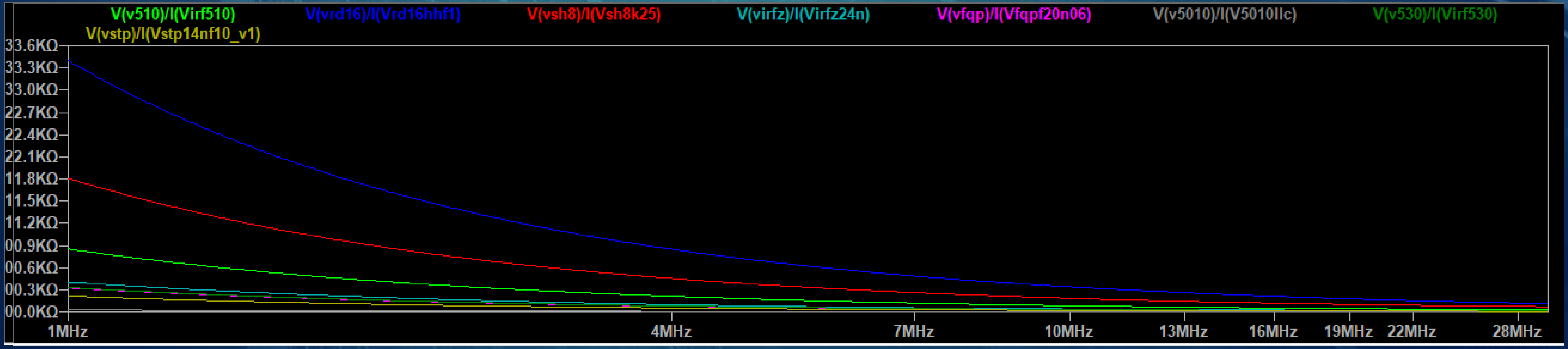


Plot the impedance for several Mosfets at (say) 1.9 & 14.1 MHz

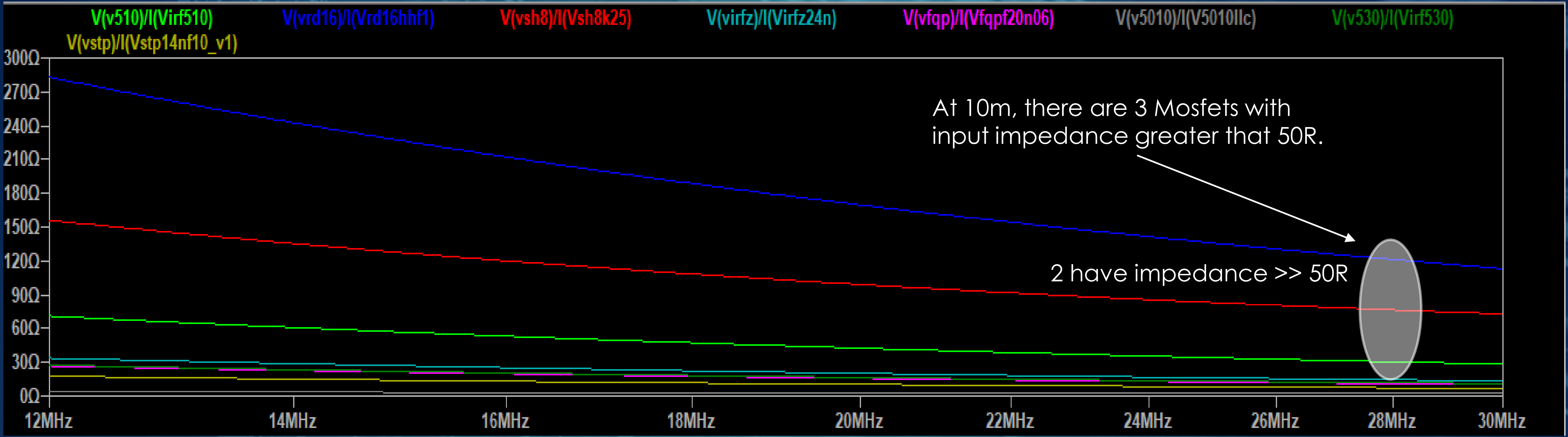
	1.9 MHz			14.1 MHz		
Mosfet	Magnitude	Real	Complex	Magnitude	Real	Complex
5010LLC	15.5	-3.2	15.2	3.5	-3.2	1.4
FQPF20N06	170.2	-1.0	170.2	22.8	-1.0	22.8
IRF530	173.0	-3.0	173.0	23.5	-3.0	23.3
IRFZ24N	212.5	-2.5	212.5	28.7	-2.5	28.6
IRF510	447.3	-3.1	447.3	60.4	-3.1	60.3
stp16nf06	113.1	-3.0	113.1	113.1	-3.0	113.1
SH8K25	950.9	-41.0	950.0	134.4	-41.0	128.0
RD16HHF1	1786.0	-1.1	1786.0	240.7	-1.1	240.7

Notes:

1. Negative real impedance is typical for Mosfets (current direction? Phase? Capacitors?)
2. These measurements were done the hard way before I figured out how to make automated measurements



Higher Frequencies….

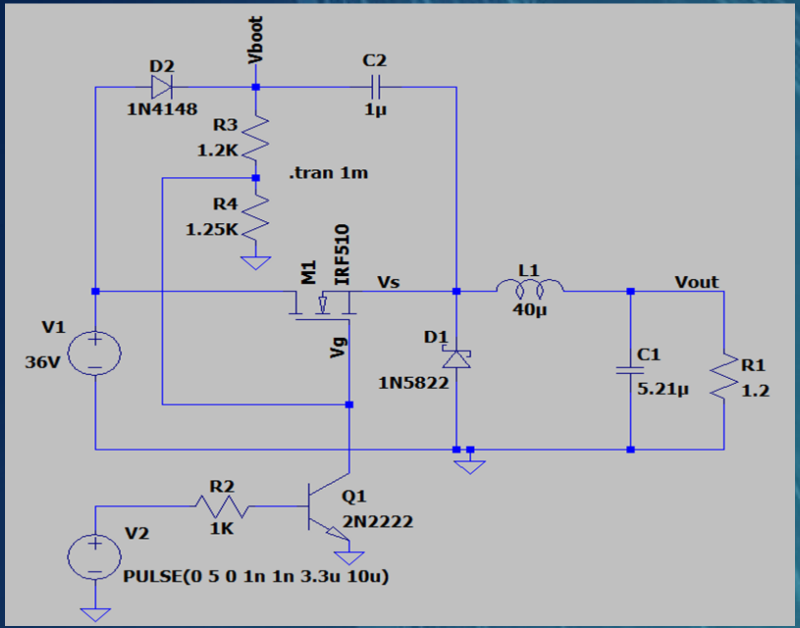


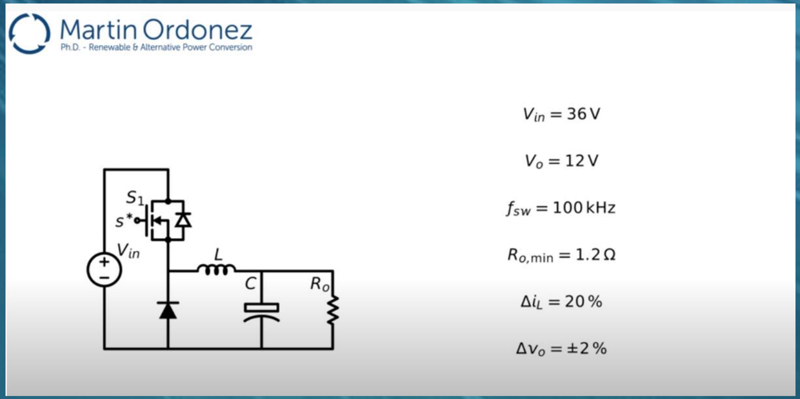
Hmmm…Maybe I can fix my D612 Power Amp.

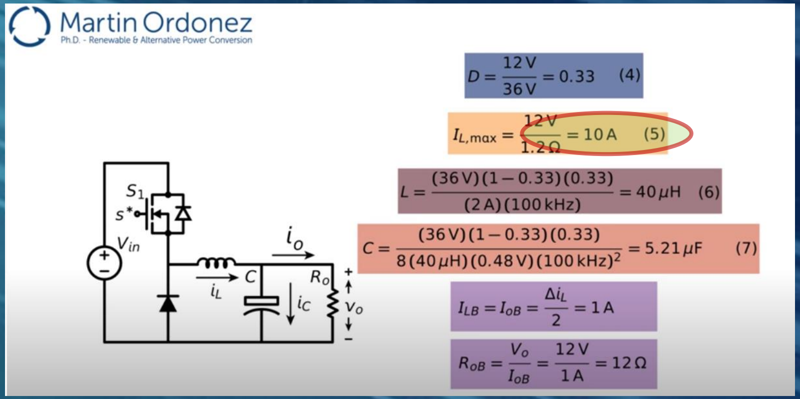
Rabbit Hole #3: Dueling SA612s MOSFET Power Amp Issues

More of a log and D612 background information

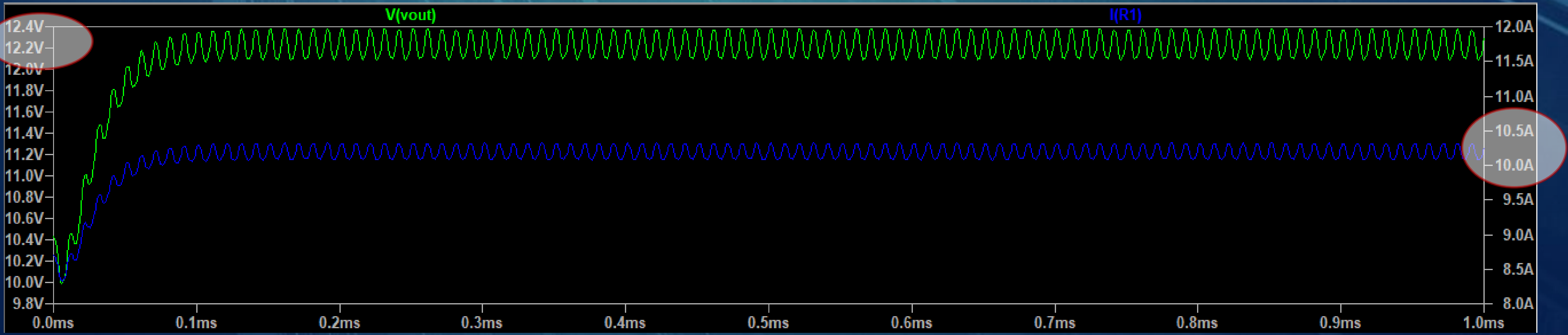
In our last episode…



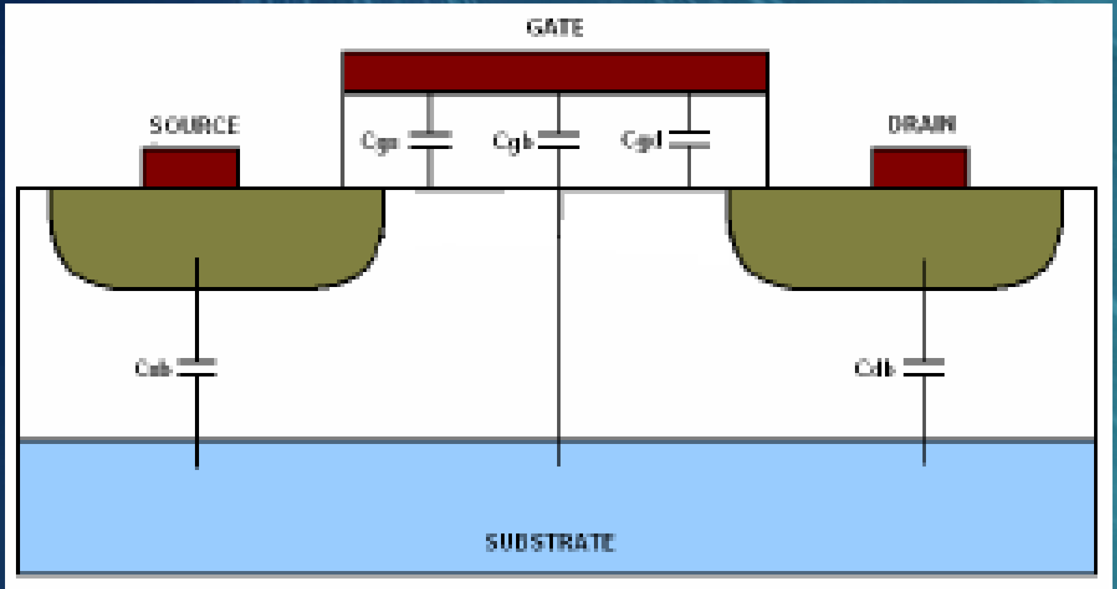


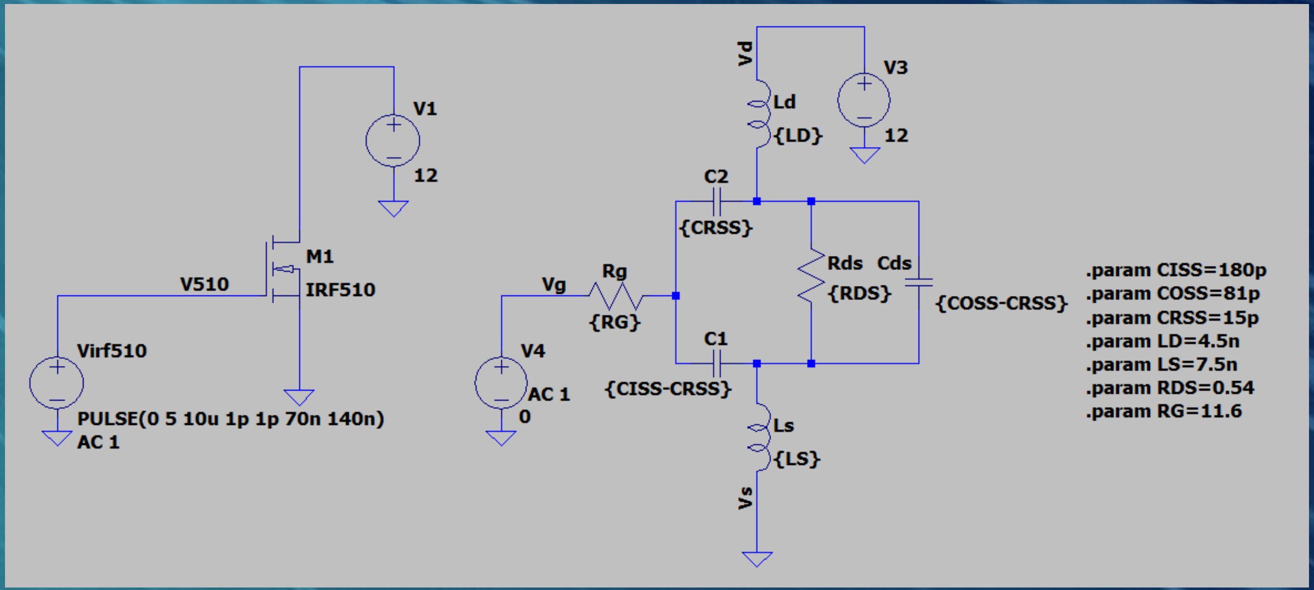


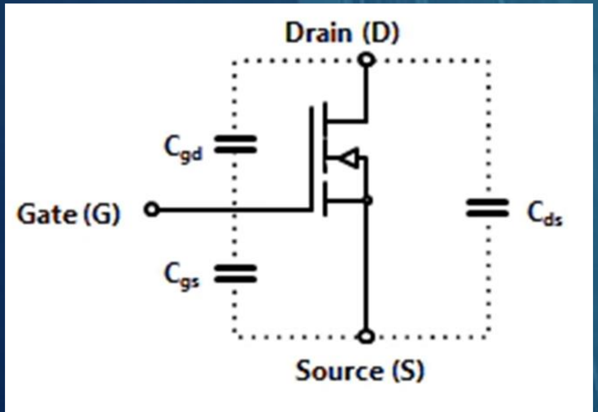
Buck converter woes solved by high side bootstrap to turn on MOSFET properly

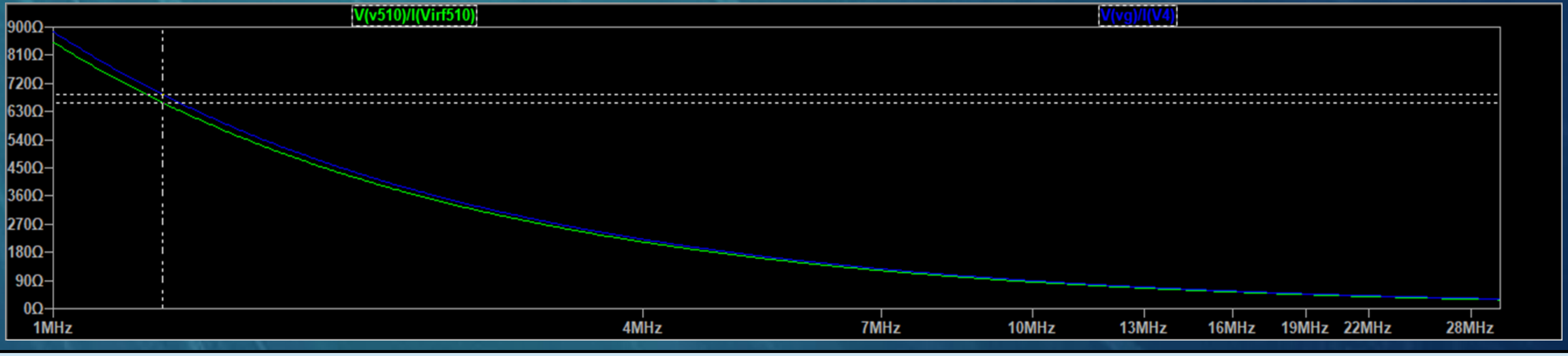


In our last episode…









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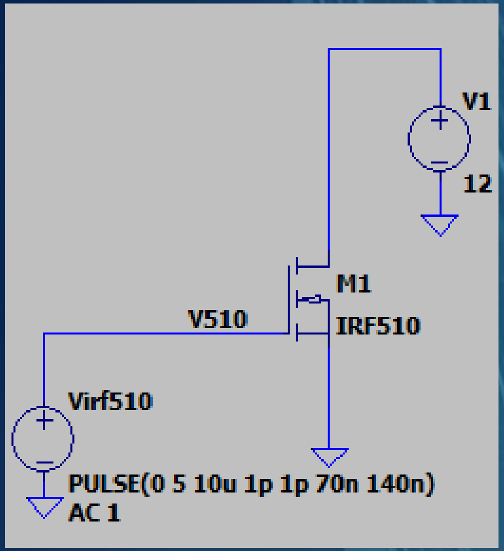
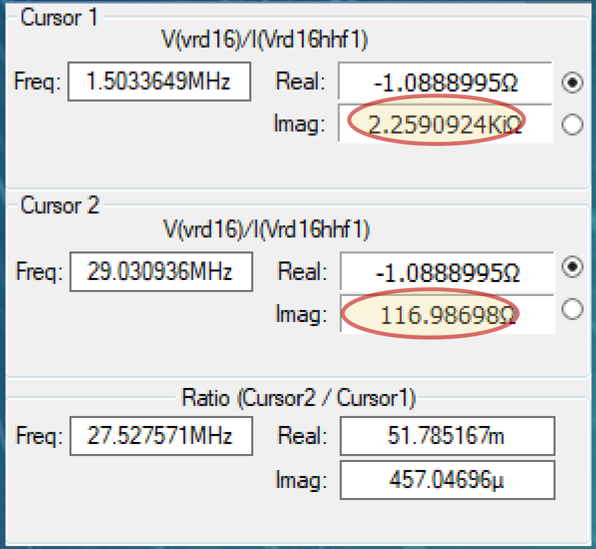
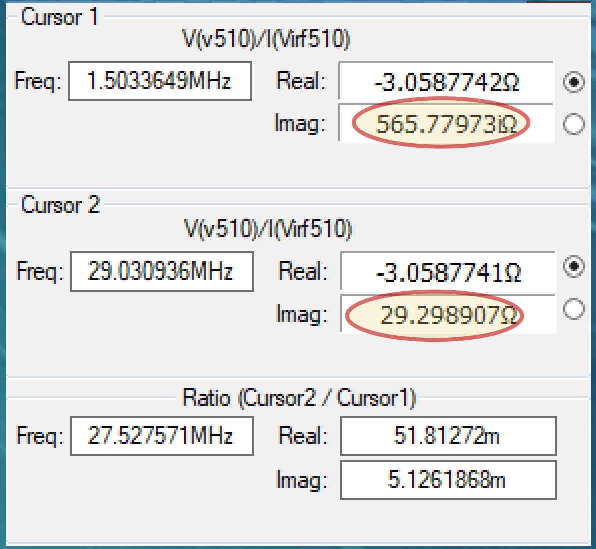
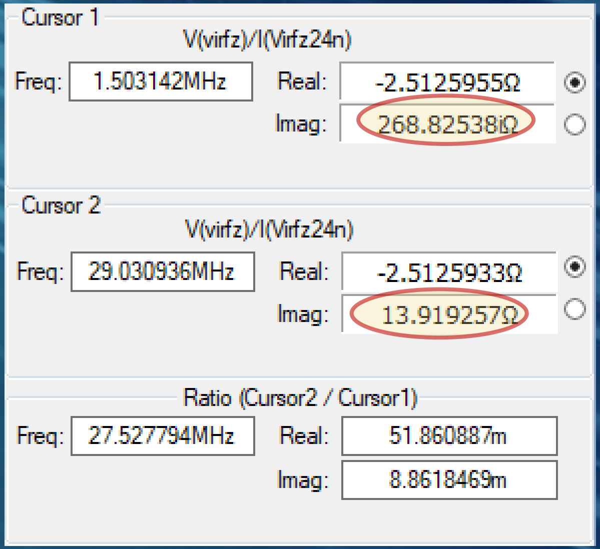
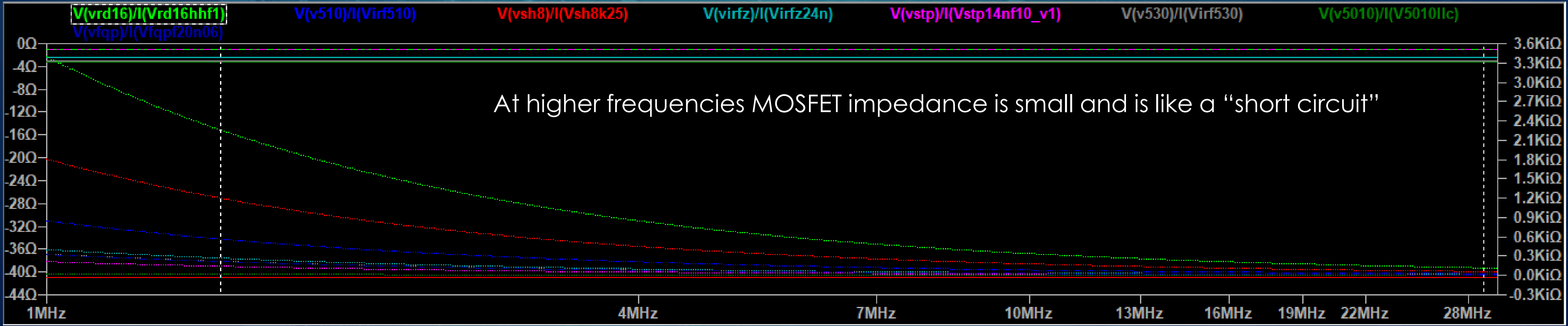
In our last episode…







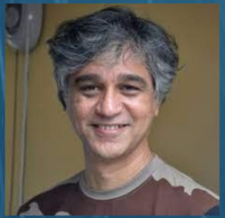




Agenda

1. Background of Dueling SA612 Transceiver and Power Amp (PA)

2. The ugly rears its head 

3. Select most popular/functional MOSFET PA for D612  

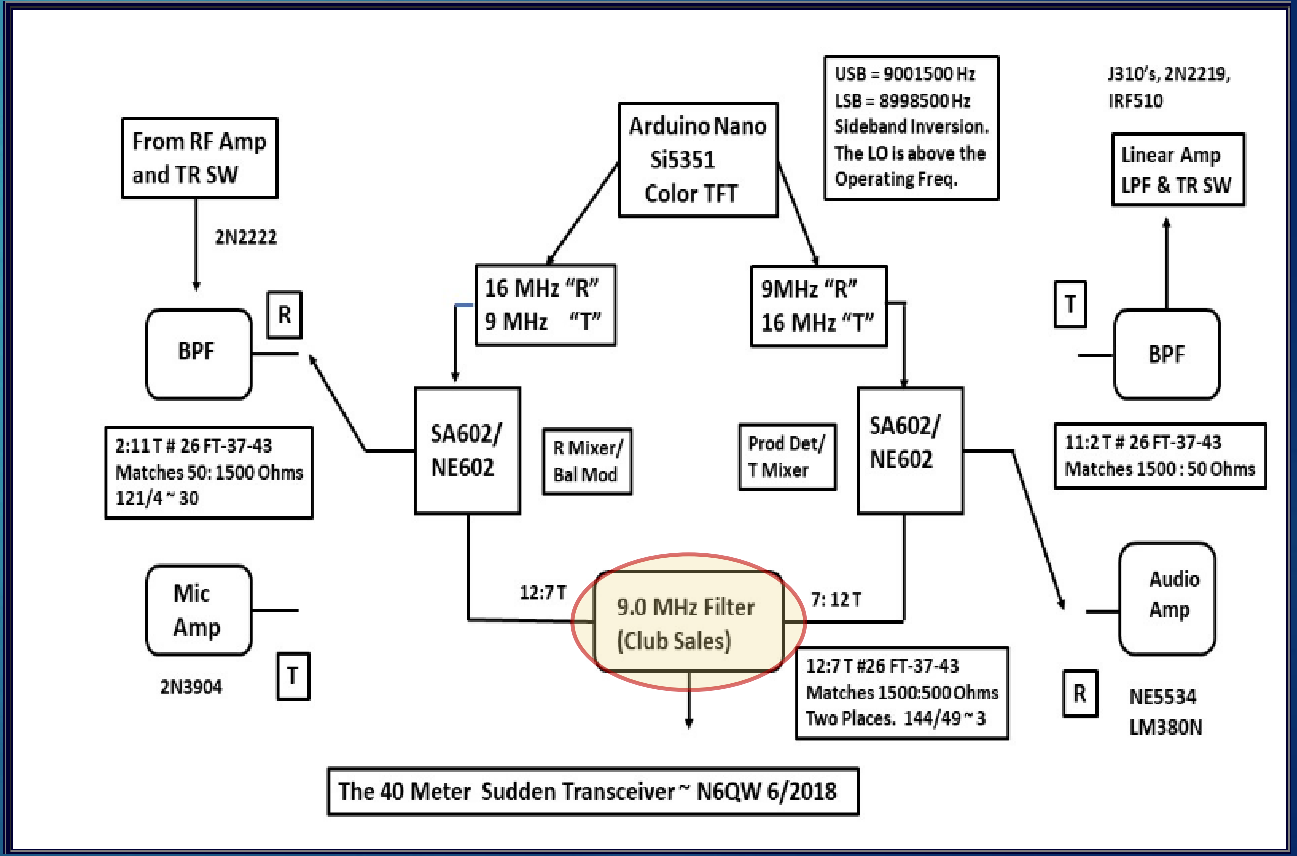
4. Analyze and select best PA with best MOSFET

Reinvent the Wheel

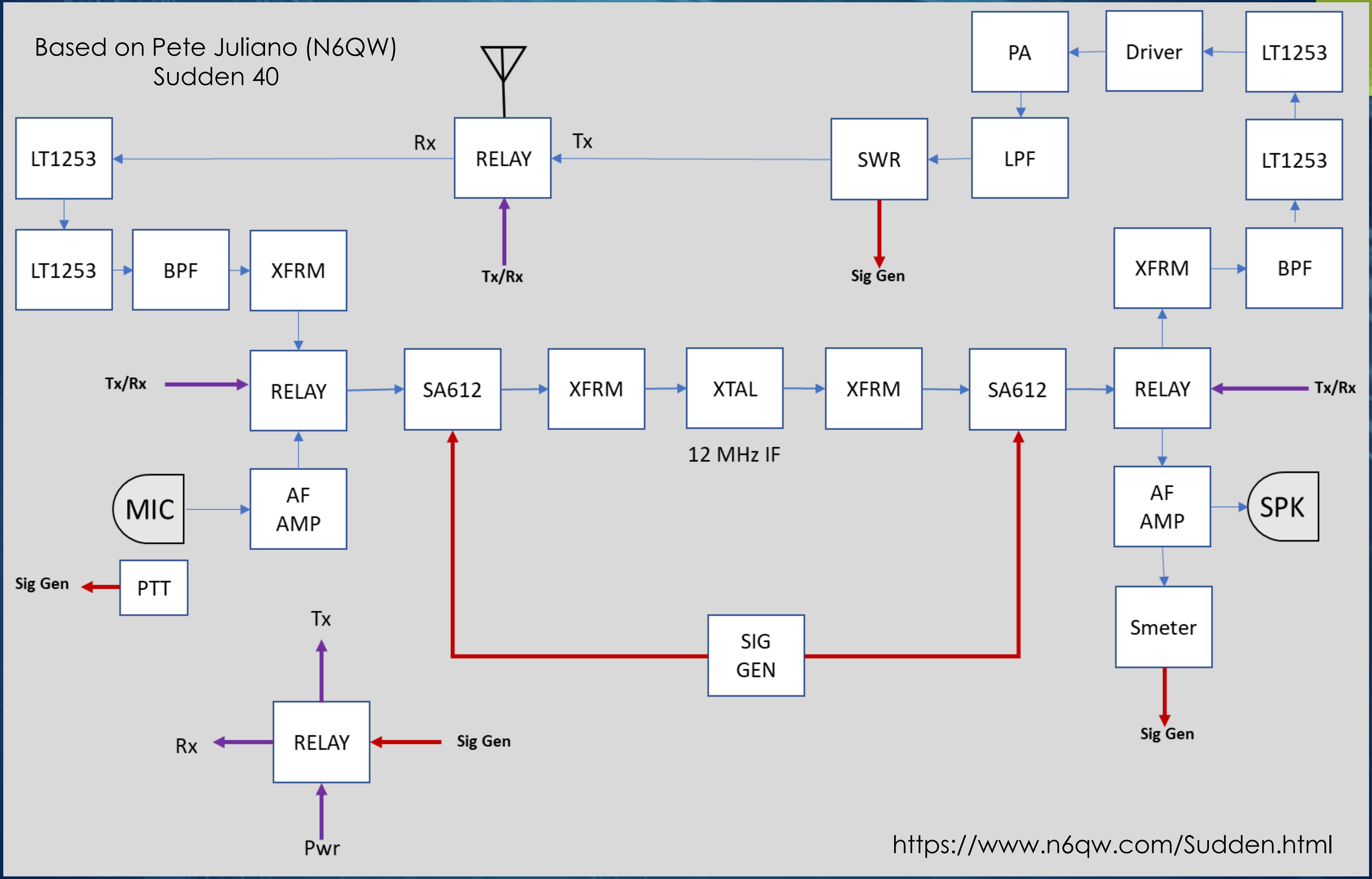
Design Goals (BUMA)

1. Based on Pete Juliano (N6QW) Sudden 40 (circa 2018)
2. Multiband – original was 40m only
   - ✓ Use 12 MHz IF instead of 9 Mhz (Bitx40)
   - ✓ Use pluggable BPF & LPF
3. Use opamps as much as possible to keep size down
   - ✓ Opamps can control gain
     - ✓ Control RF Pre Amp
     - ✓ Control Power output
   - ✓ Use LM386
4. Smeter, PWR, SWR
5. Use PARC Sig Gen
6. ~~Not use relays~~

Band	Orig Amp		New Amp (Typical)		New Amp (Max)	
	Power	Voltage Gain	Power	Voltage Gain	Power	Voltage Gain
160m	4	174	9	146	9	146
80m	5	173	8	145	10	147
40m	5	174	5	142	12	149
20m	1	165	2	129	11	149
10m	0.03	137	0.11	103	2.24	132

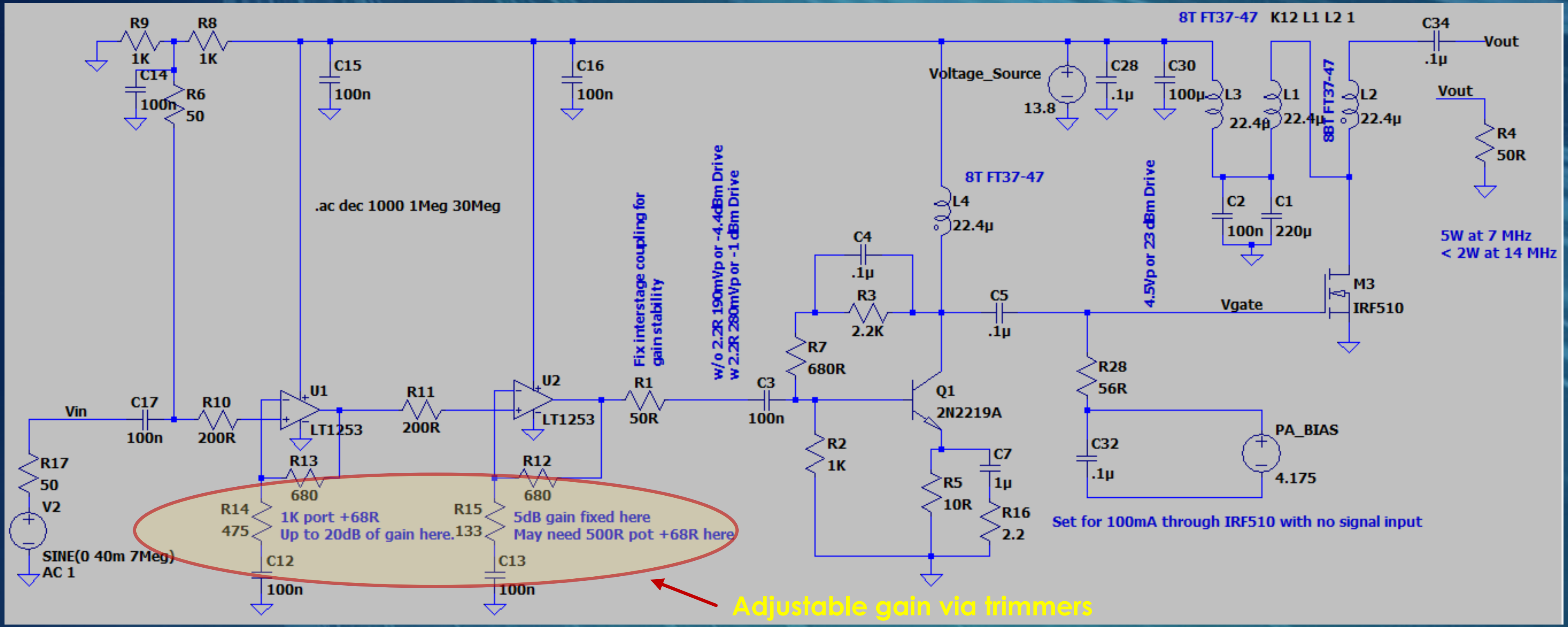


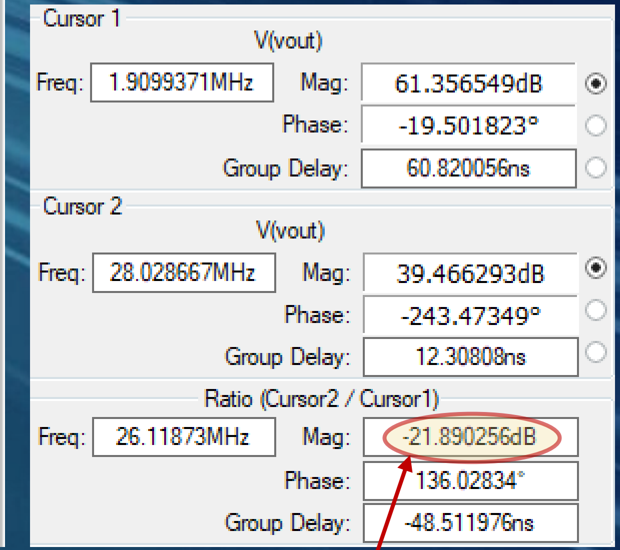
Dueling 612



Based on Pete Juliano (N6QW)
Sudden 40
LT1253
Rx
RELAY
Tx
SWR
LPF
PA
Driver
LT1253
LT1253
LT1253
BPF
XFRM
Tx/Rx
Sig Gen
XFRM
BPF
Tx/Rx
RELAY
SA612
XFRM
XTAL
XFRM
SA612
RELAY
Tx/Rx
12 MHz IF
MIC
AF AMP
AF AMP
SPK
Sig Gen
PTT
Smeter
Tx
SIG GEN
Rx
RELAY
Sig Gen
Sig Gen
Pwr
https://www.n6qw.com/Sudden.html

Modified D612 PA

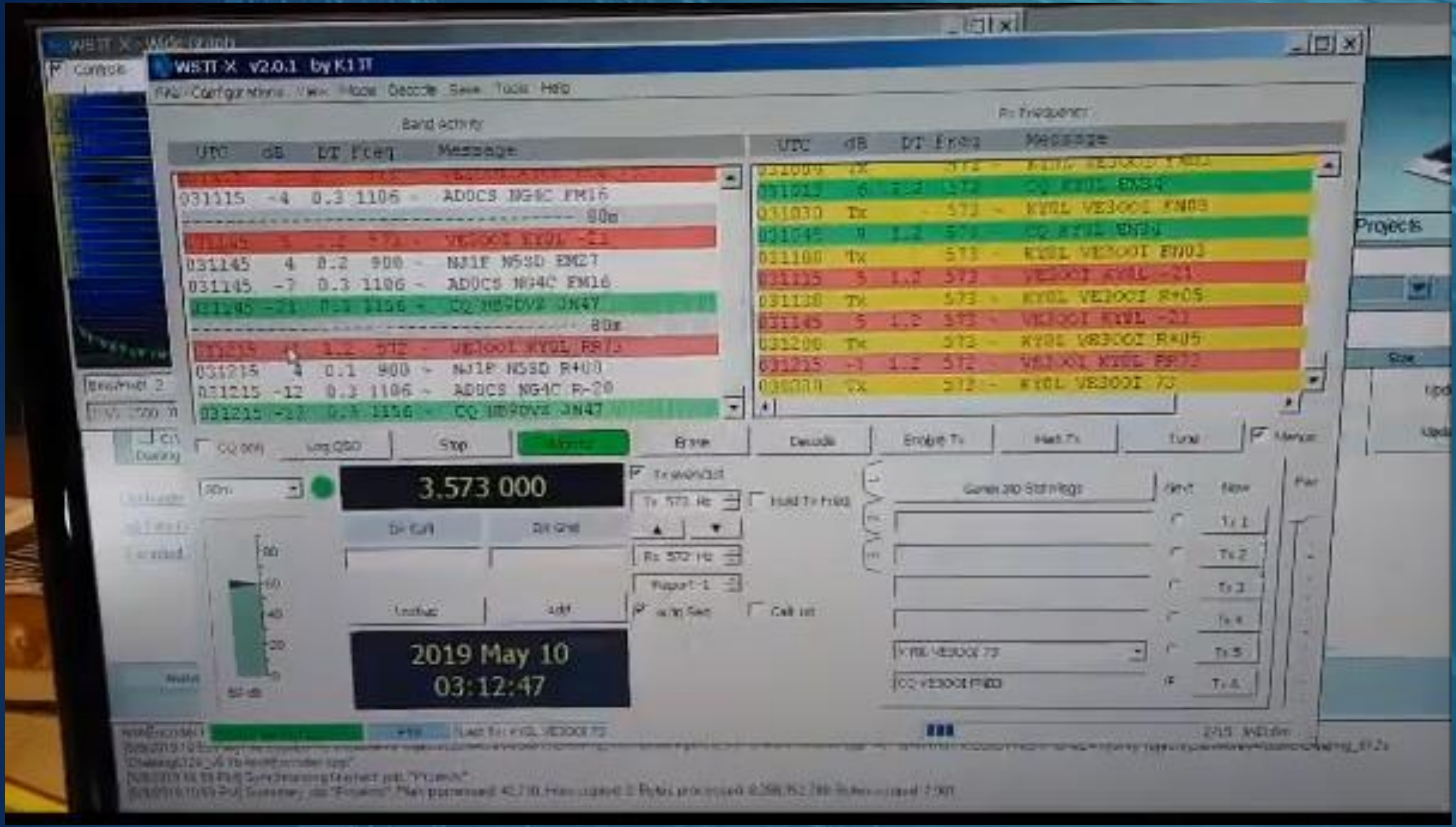




Can adjust gain

Dueling 612

80m Contact

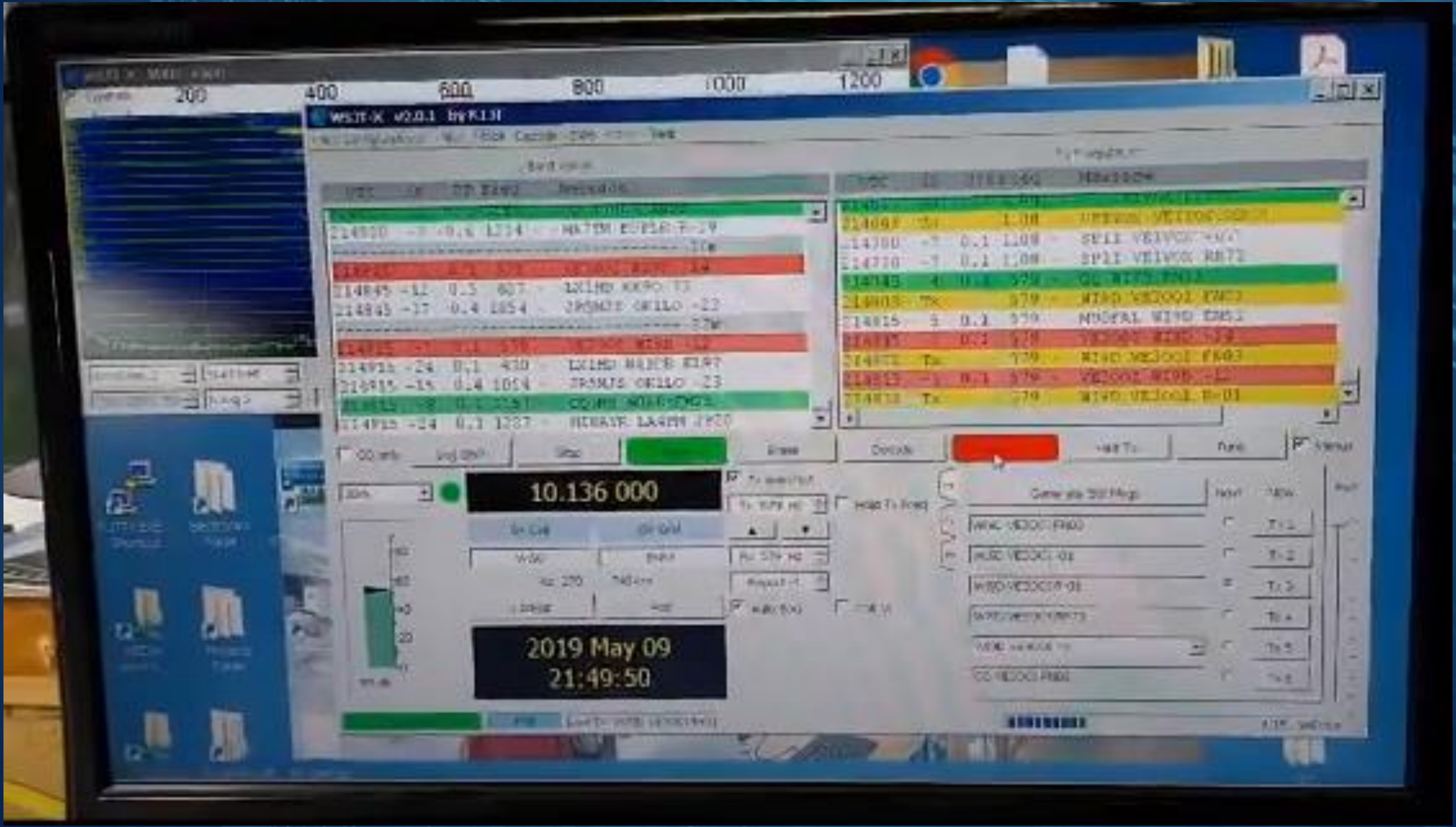

WSJT-X v2.0.1 by K1JT
Band Activity
UTC dB DT Freq Message
3.573 000
2019 May 10
03:12:47


Tx VFOA:03573000 USB
SWR:1.02
VFOB:03950000 80m
RADIO
PARC
Signal Generator

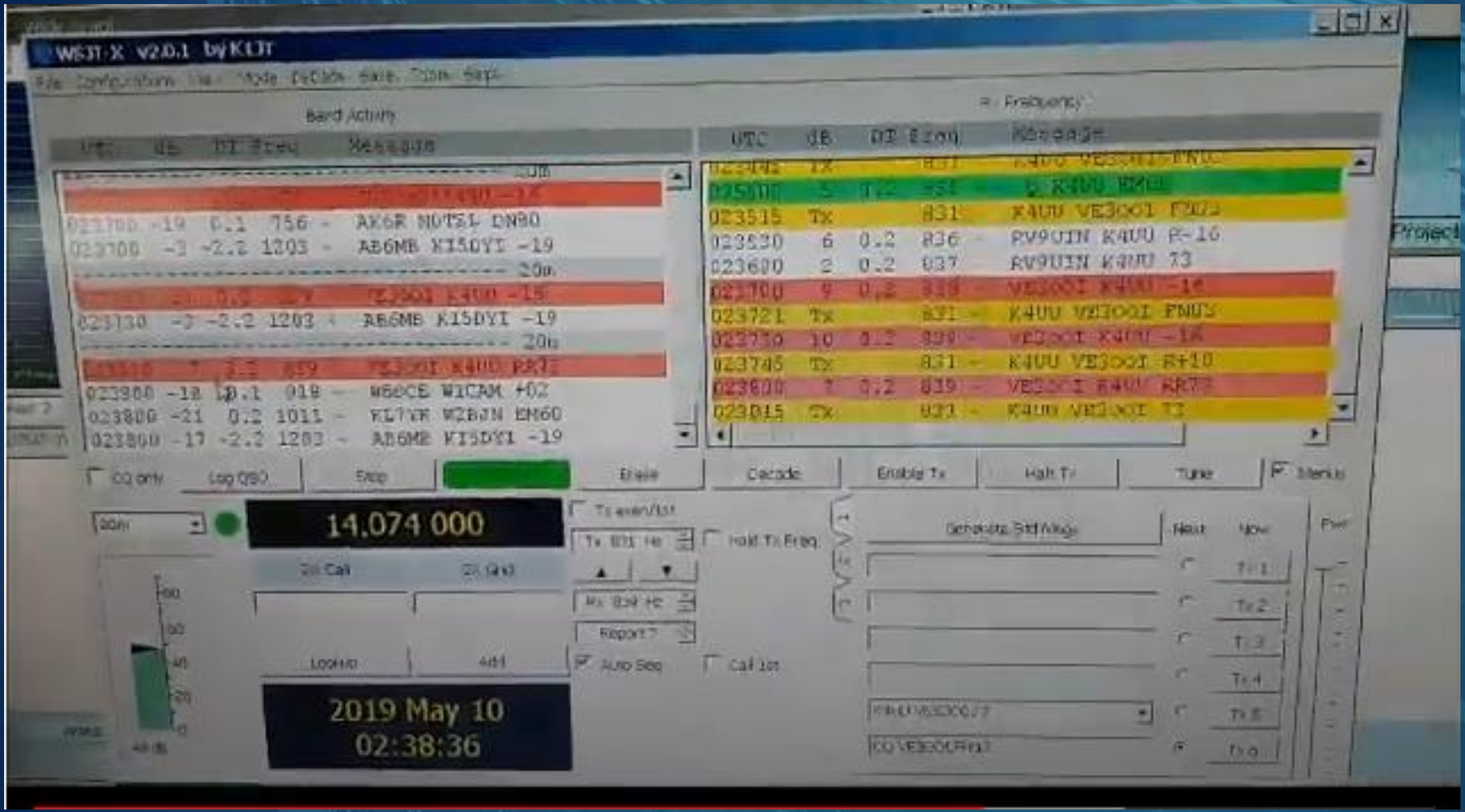
40m Contact


WSJT-X v2.0.1 by K1JT
Band Activity
Rx Frequency
UTC dB DT Freq Message
7.074 000
2019 May 09
21:24:19
GSDR calibration.p...

30m Contact



20m Contact


WSJT-X v2.0.1 by K1JT
Band Activity
Rx Frequency
UTC dB DT Freq Message
023700 -3 -2.2 1203 ~ AB6MB KI5DYI -19
023830 6 0.2 836 ~ RV9UIN K4UU R-16
023900 -17 -2.2 1203 ~ AB6MB KI5DYI -19
Log QSO
Stop
Erase
Decode
Enable Tx
Halt Tx
Tune
14.074 000
2019 May 10
02:38:36


SWR:1.45
VFOB:14343000 20m
RADIO
PARC
Signal Generator

Spurious Emission's Ugly Head

97.307 Emission standards.

(d) For transmitters installed after January 1, 2003, the mean power of any spurious emission from a station transmitter or external RF power amplifier transmitting on a frequency below 30 MHz must be at least 43 dB below the mean power of the fundamental emission.

For transmitters installed on or before January 1, 2003, the mean power of any spurious emission from a station transmitter or external RF power amplifier transmitting on a frequency below 30 MHz must not exceed 50 mW and must be at least 40 dB below the mean power of the fundamental emission. For a transmitter of mean power less than 5 W installed on or before January 1, 2003, the attenuation must be at least 30 dB. A transmitter built before April 15, 1977, or first marketed before January 1, 1978, is exempt from this requirement.

Category C	Category C limits are an example of more stringent spurious emission limits than Category A limits. They are based on limits defined and adopted in the United States of America and Canada and used by some other countries. These limits are given in § 4.4.

HF broadcasting	80 dBc

The power of unwanted emissions shall be attenuated below the transmitter's output power, P (dBW) as follows:

a. 25 dB; on any frequency removed from the channel frequency by more than 50% and up to 100% of the authorized bandwidth measured with a resolution bandwidth of 300 Hz;
b. 35 dB; on any frequency removed from the channel frequency by more than 100% up to 250% of the authorized bandwidth measured with a resolution bandwidth of 300 Hz;
c. 43 + 10*log(p) or 70 dB, whichever is less stringent; in any 30 kHz bandwidth removed from the channel frequency by more than 250% of the authorized bandwidth.

Where:

p refers to the transmitter's output power expressed in watts.

https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf01240.html

In Canada:

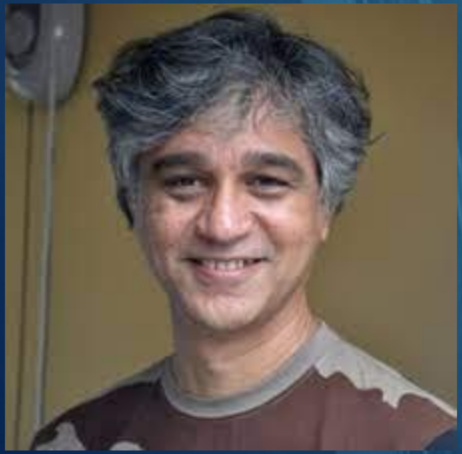
- For 5W, emission: 43.7dBc
- For 10W, emission: 44.0 dBc
- ✓ 44 dBc

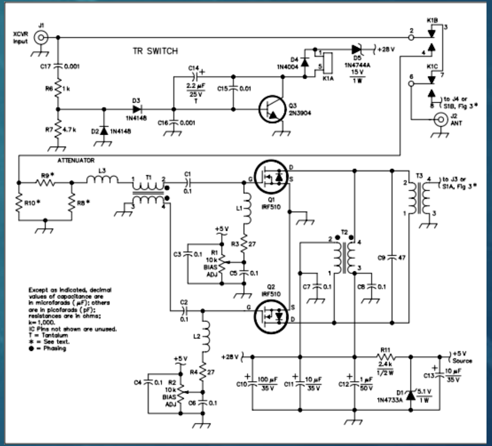
The Issue (2019)…

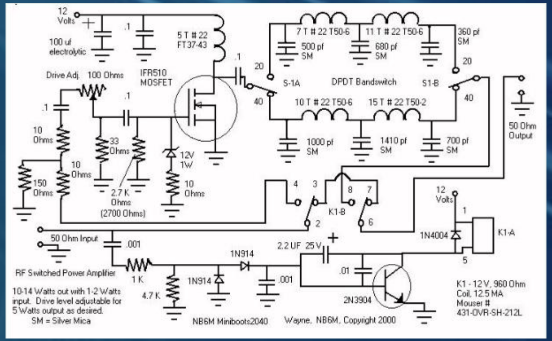
- The D612 had harmonics stronger than -44 dBc limit (mid to high -30 dBc)
- For 20m, had to adjust gain on PA pre-driver to get 4-5 Watts output. Harmonics got worst
  - With same Gain on Opamp: 5W@7MHz, 1.7W@14MHz
- Power Amp was too dirty. Hard to make contacts. Thrown against wall.

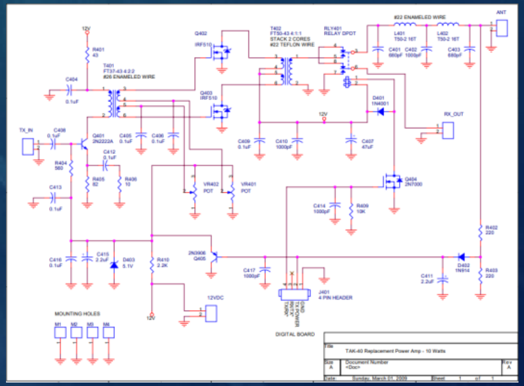
Recently (2022)…After RH#3

- Abandon D612 PA to find a better alternative
- Searched and reviewed designs. Basically, the same
- Focused on BitX and Hans Summers Push Pull (Tony Parks - SK).

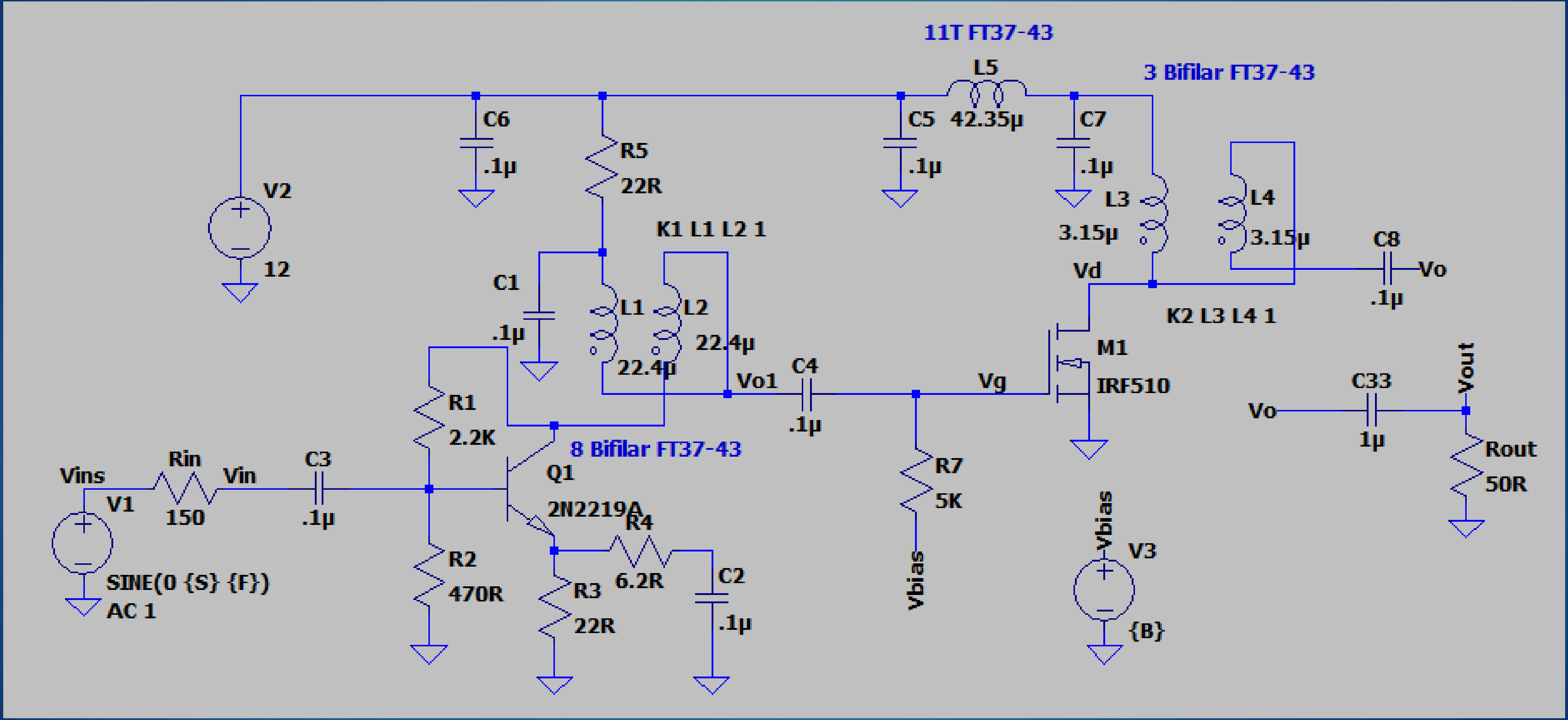




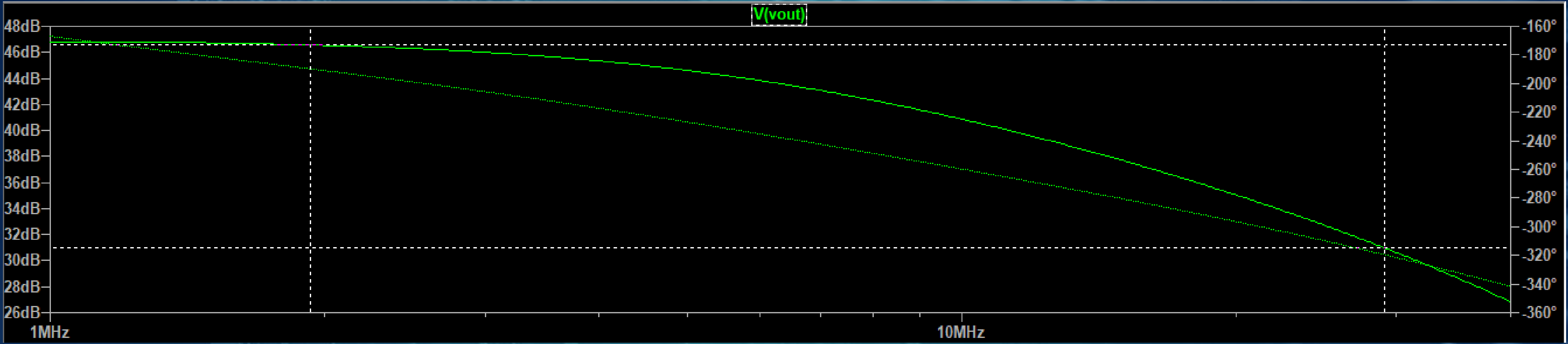


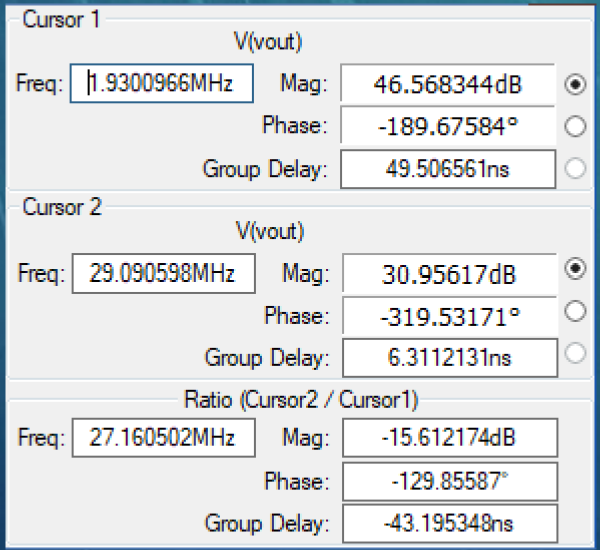


Original BitX20 PA



Sweep of BITX20 Amp

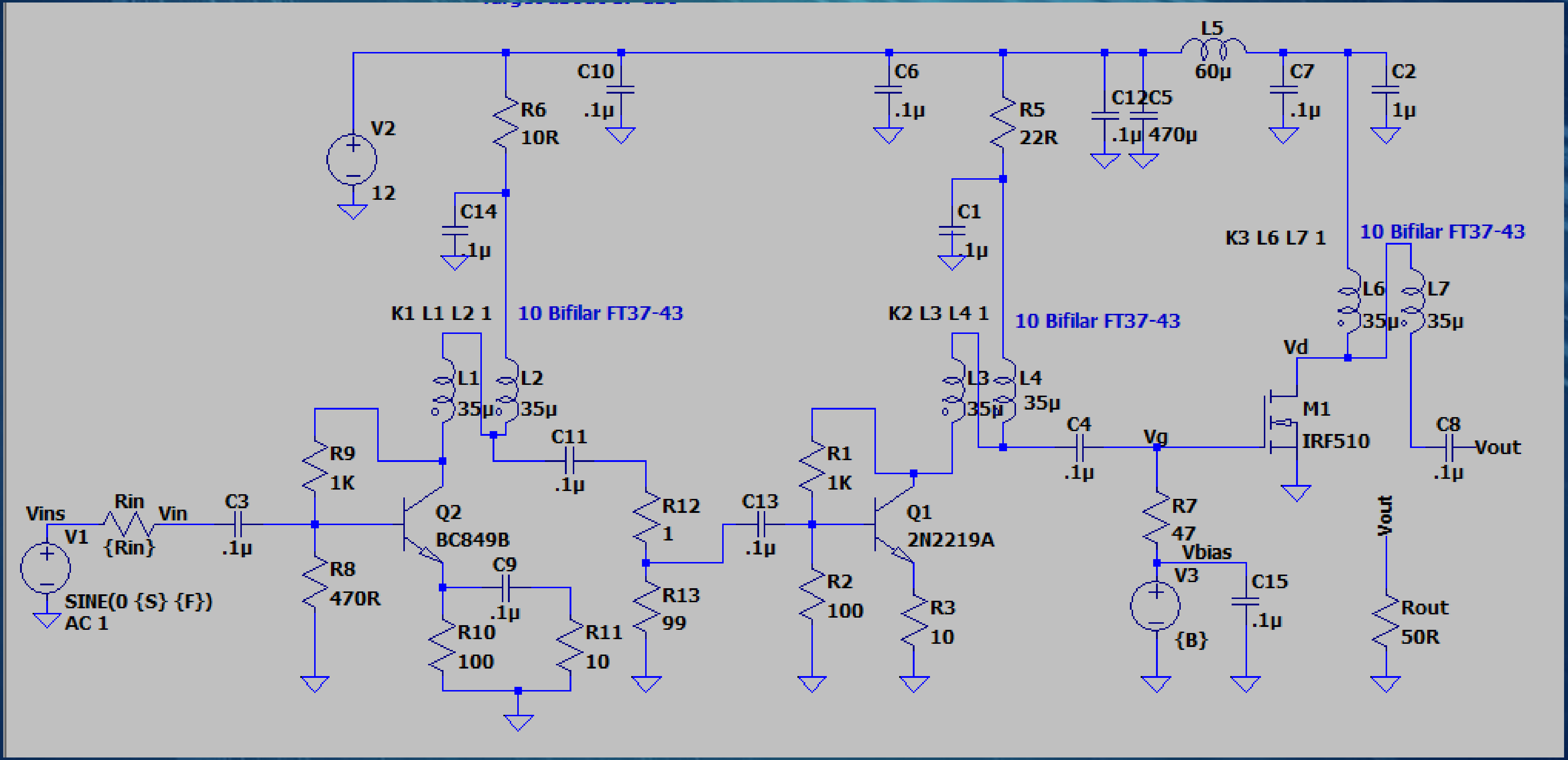




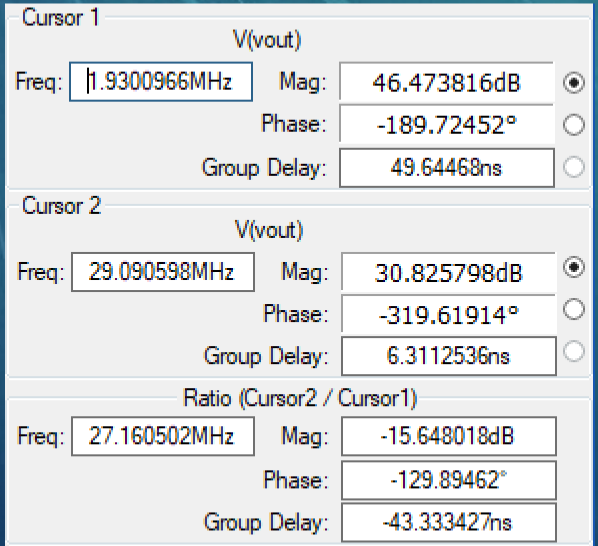
Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	28	27	26	25	25	24	23	21

7 dB Roll Off

Newer BitX40 PA



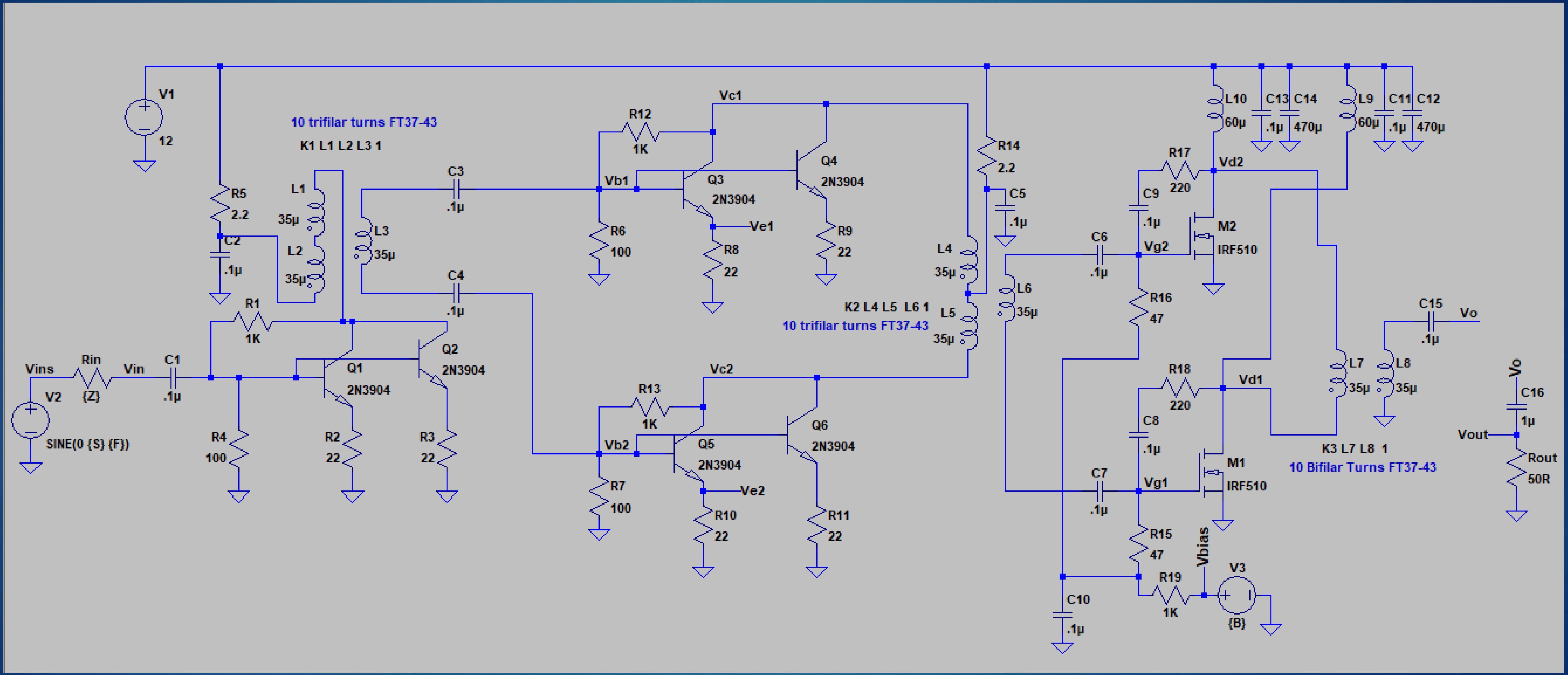
Sweep of BitX40 Amp



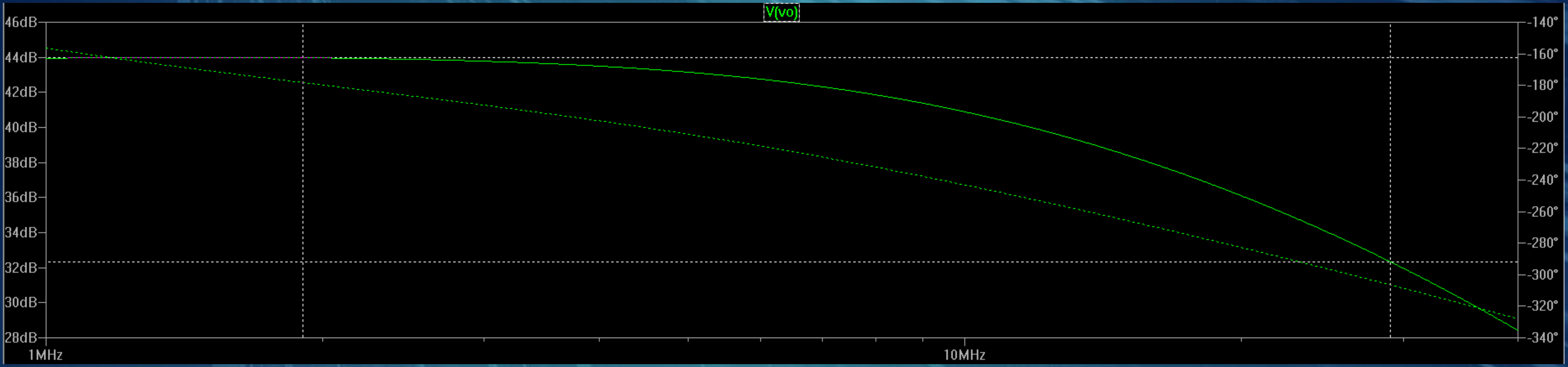
Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	27	27	27	27	27	27	26	25

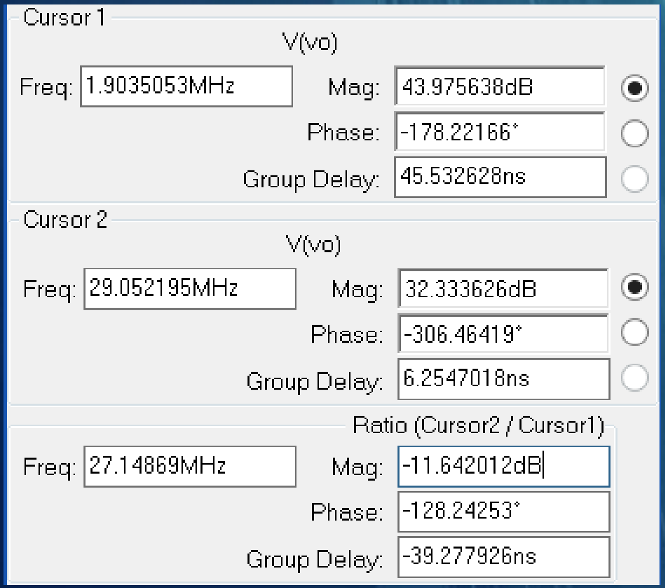
2 dB Roll Off
(BitX 20 transformer issue?)

uBitX Push Pull



Sweep of uBitx Amp

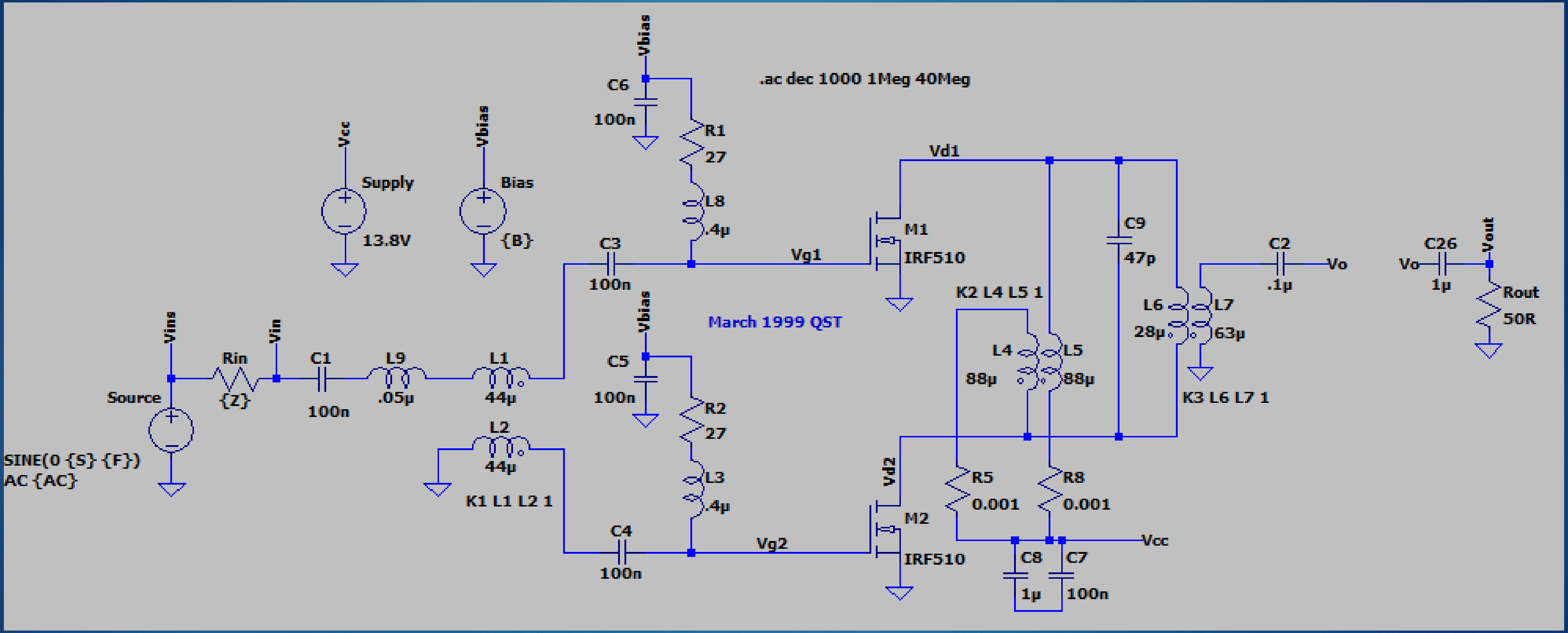




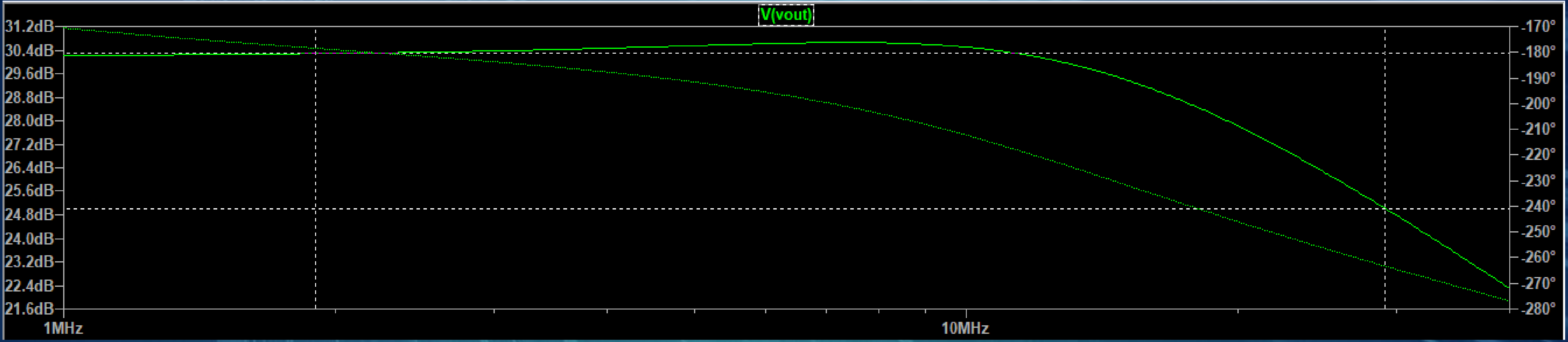
Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	32	32	32	32	32	32	31	29

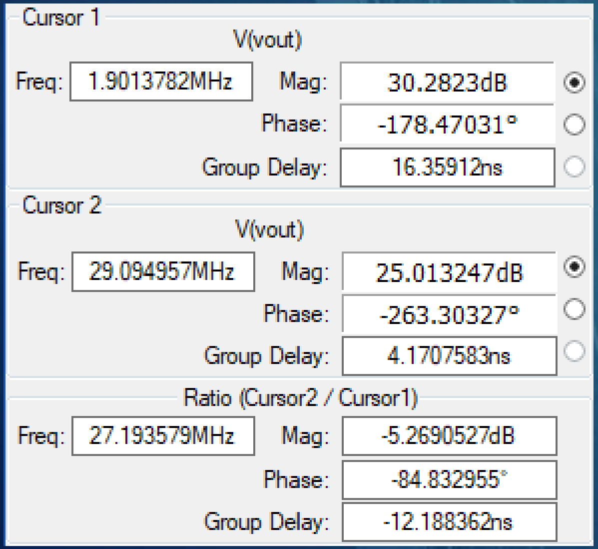
3 dB Roll Off

WA2EBY Push Pull



Sweep of WA2EBY Amp

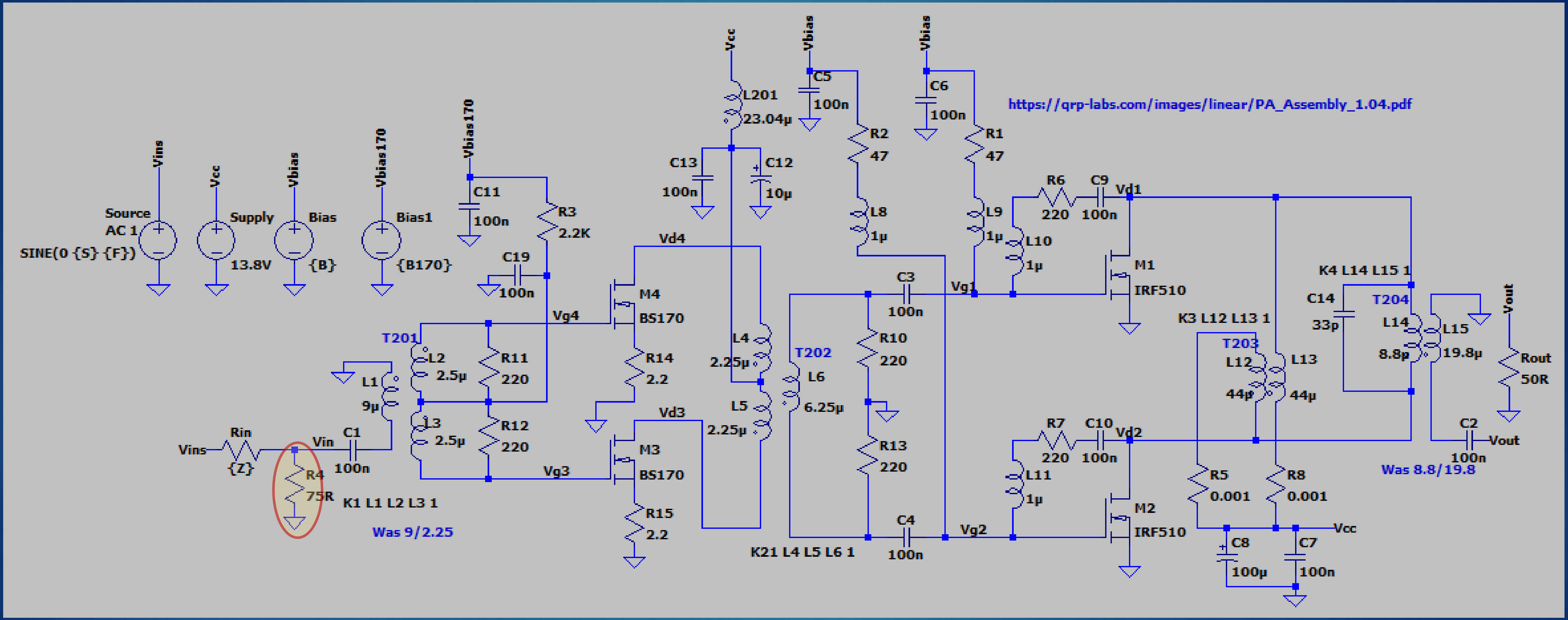




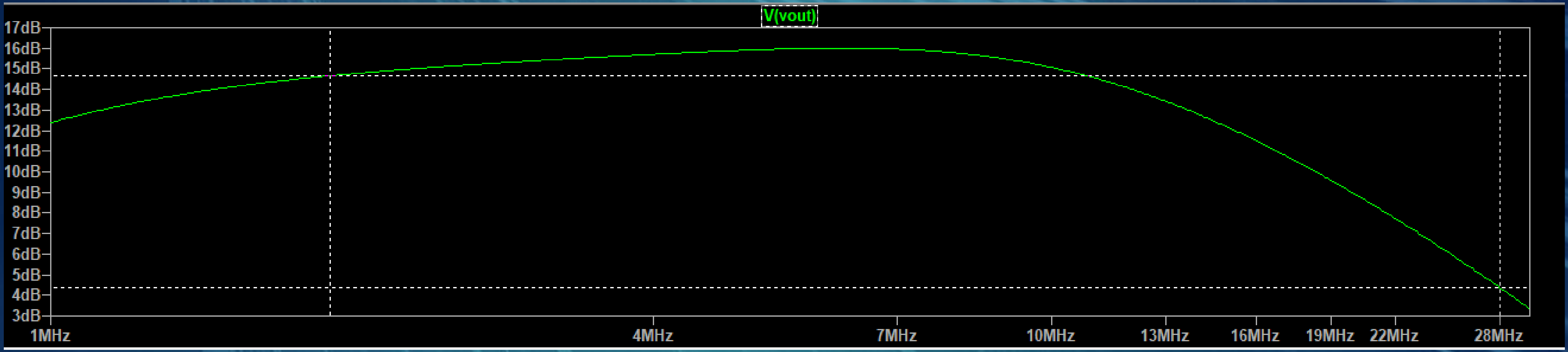
Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	20	20	19	18	18	18	20	20

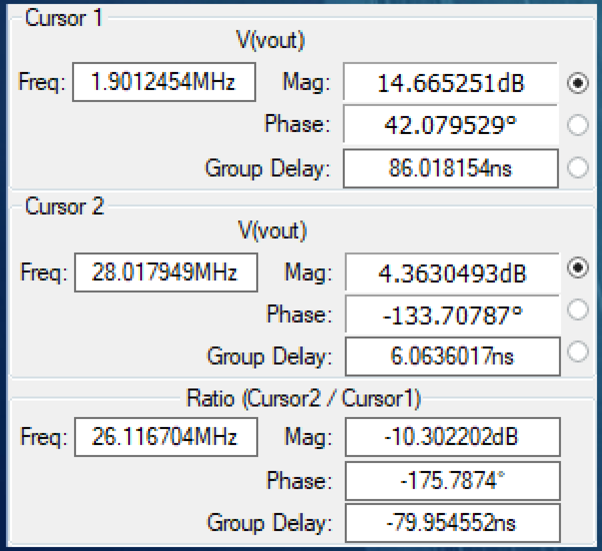
About 2 dB variation

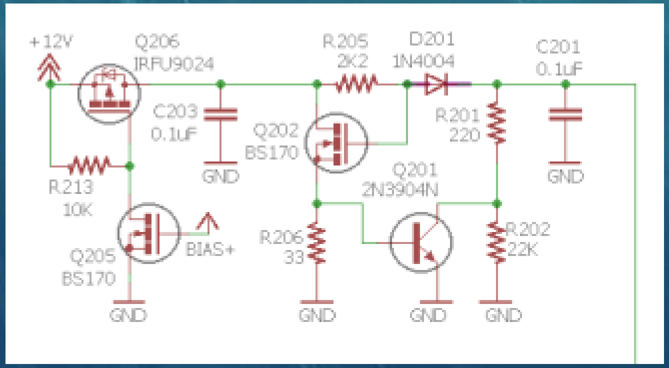
Hans Summers (Tony Parks) Push Pull



Sweep of Hans Summers Amp







Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	20	19	18	18	17	16	12	8

16 dB?

Analysis

- Issues with N6QW, Bitx20 and Hans ~~Summers Push Pull~~.
  - Significant roll off with frequency. uBitx a little flatter.
    - Transformer vs MOSFET Capacitance vs Other?
  - Independent testing of Hans Summers amp indicated broadband…shoot the rabbit

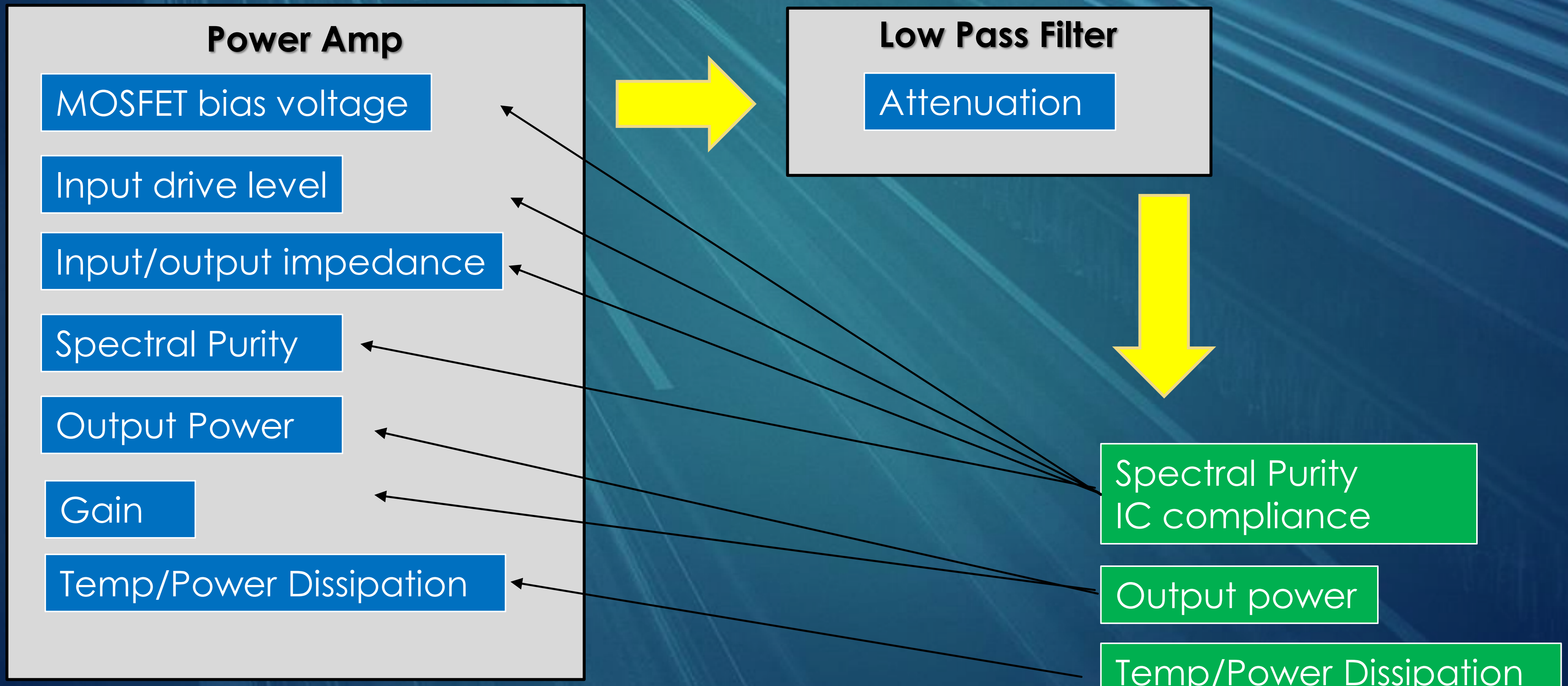
- WA2EBY, BitX40 and uBitX better response
  - WA2EBY needs 1W drive. Preamp may bandwidth limit amp.

- Don't boil the ocean: Focus on finding a MOSFET that is better than IRF510 with better high frequency response
  - Looked at other MOSFET amps and did a Digikey parameter search for lowest capacitance
  - Found several candidates. Needed to compare their performance

Comparing Performance

- Difficult to make measurement from LTSpice waveforms
  - ✓ Select best MOSFET bias voltages (for Class A operation)
  - ✓ Select optimum input drive level for best and clean output
  - ✓ Measure purity using FFT for IC compliance.
  - ✓ Measure output power
  - ✓ Measure MOSFET power dissipation/temperature
  - ✓ Measure Input/output impedance
- Needed to learn about LTSpice **FFT** and making **automated measurements**.

Fundamental Measurements



Low Pass Filters

c. 43 + 10*log(p) or 70 dB, whichever is less stringent; in any 30 kHz bandwidth removed from the channel frequency by more than 250% of the authorized bandwidth.

- First, what is maximum output voltage for harmonic?
  - -44 = 10*log (Ph/Pf) or -44 = 20*log (Vh/Vf)
  - Solve Vh = 0.00631 * Vf
    - ✓ Any harmonic is "at most" 0.63% of fundamental

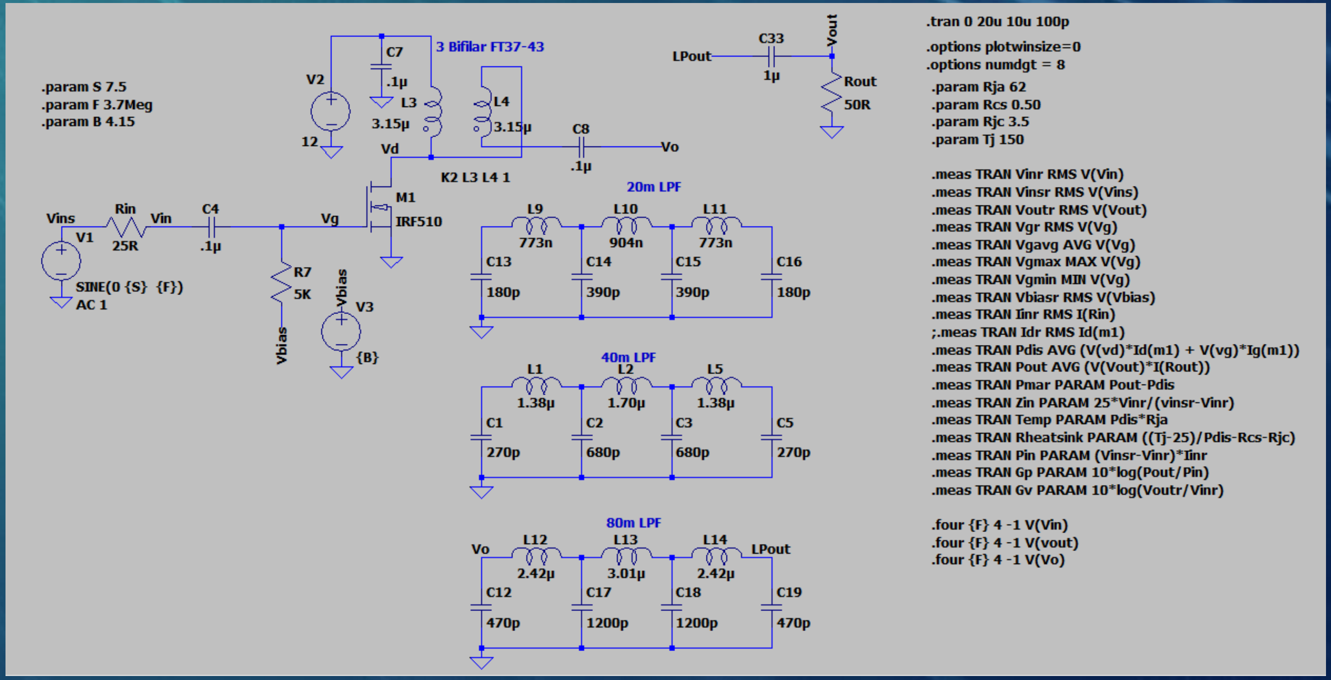
- Second, what attenuation will LPF provide?

Harmonic	80m PA	40m PA	20m PA
2	-11	-14	-17
3	-15	-17	-19
4	-32	-30	-32

~49dB

Harmonic	80m LPF	40m LPF	20m LPF
2	-47	-55	-66
3	-76	-82	-93
4	-98	-107	-114

Ok if output from PA is < 0 dBc

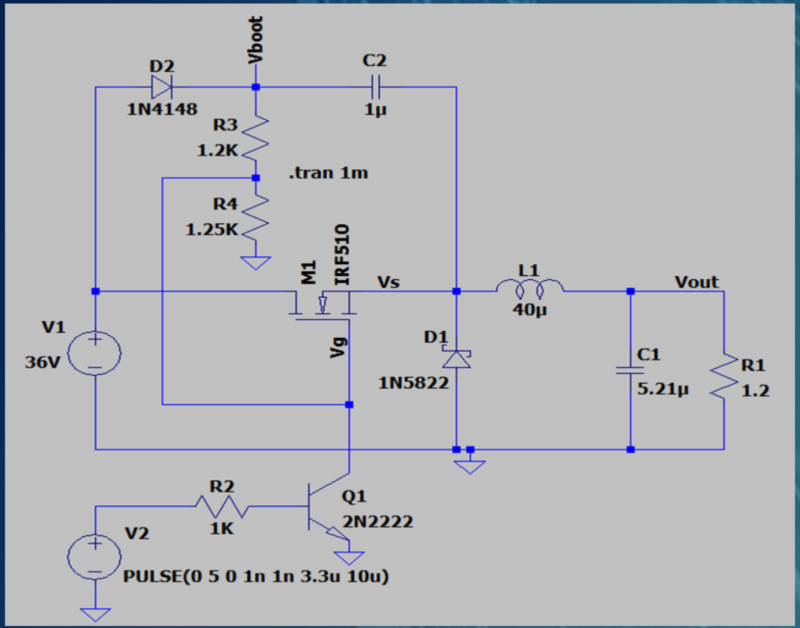


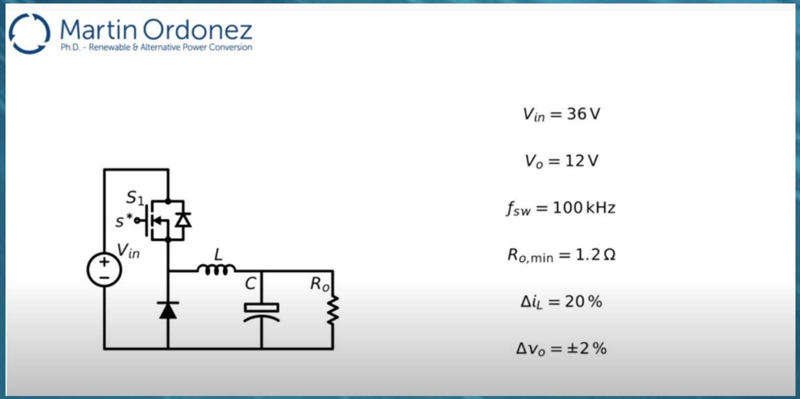
Summary

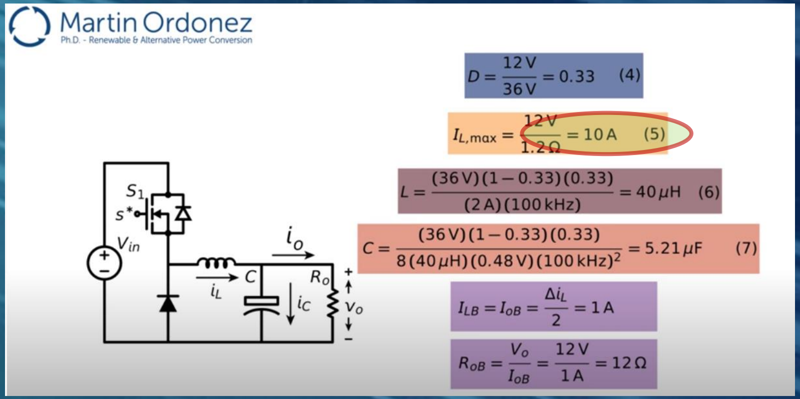
- For Bitx and Hans Summers PAs
  - ✓ Assume component are all ok – only adjust bias
  - ✓ For several "potentially good" MOSFETs
  - ✓ Measure Spectral Purity, Power Output, Power Dissipated
    - ✓ Measure without LPF and keep harmonic dBc as low as possible. Pick arbitrary value
  - ✓ Select optimum bias and drive
  - ✓ Compare and select best MOSFET

Rabbit Hole #3.1: LTSpice FFT

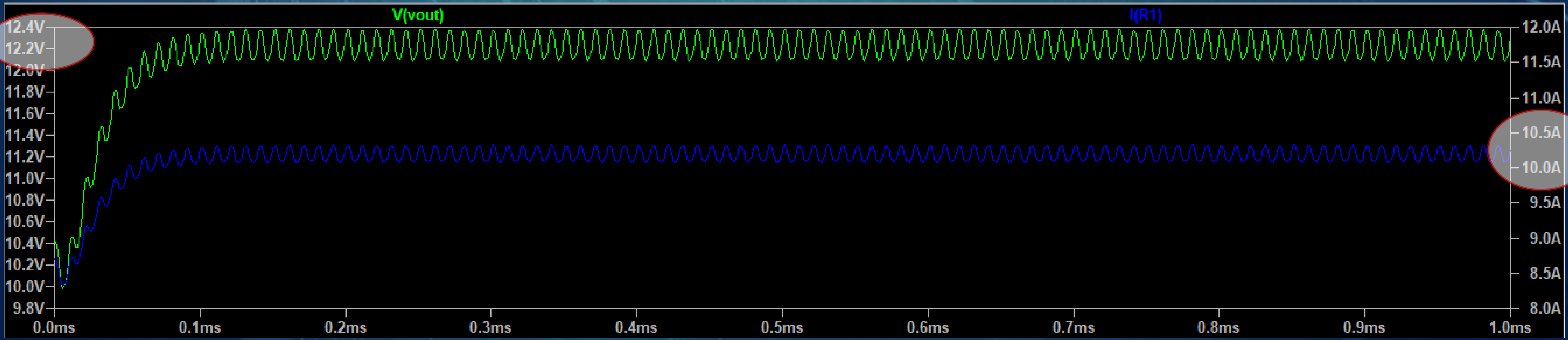
In our last episode…



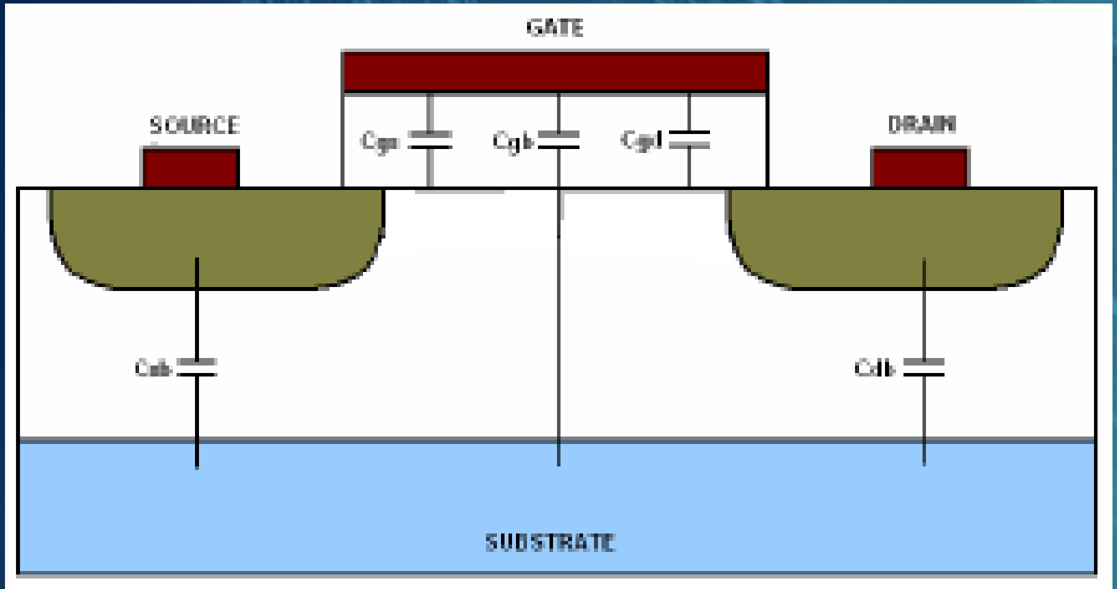


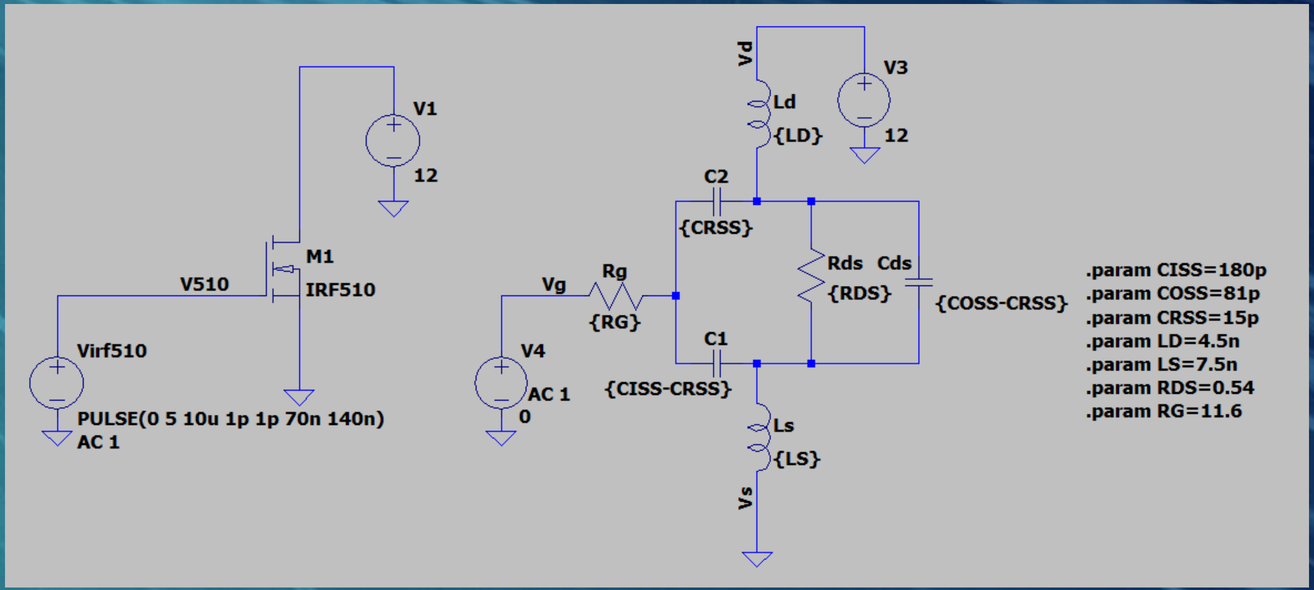


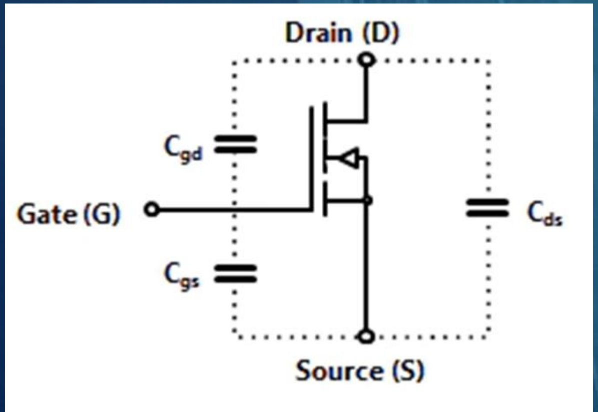
Buck converter woes solved by high side bootstrap to turn on MOSFET properly

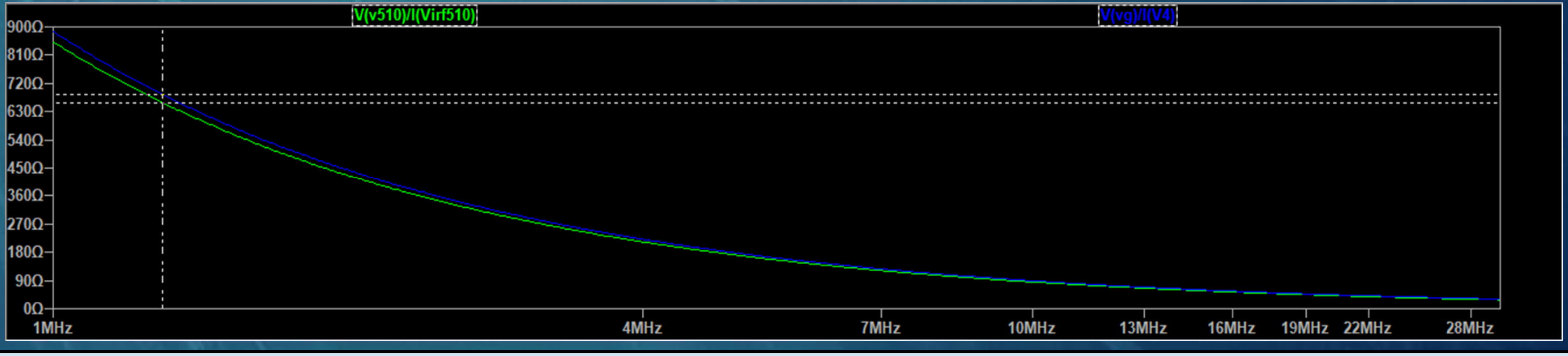


In our last episode…









Dynamic						
Input capacitance	C_{iss}	V_{GS} = 0 V, V_{DS} = 25 V, f = 1.0 MHz, see fig. 5	-	180	-	pF
Output capacitance	C_{oss}		-	81	-	
Reverse transfer capacitance	C_{rss}		-	15	-	

In our last episode…

Errata

- All gains presented for various PA was incorrect
  - Use of Log vs Log10 in LTSpice
  - E.g., $\log_{10}(10) = 1$, $\ln(10) = 2.3025…$
  - Log_{10} is based on 10^x
  - Log_e or ln is based on e^x
- No consideration for conduction angle
  - PA were not "linear".

ln(x) log (x)	Natural logarithm of x.	LTspice	E, I, B
log10(x)	Base 10 logarithm. Generates a real valued output for all x.	LTspice	E, I, B

The natural logarithm of a number is its **logarithm to the base of the mathematical constant e**, which is an irrational and transcendental number approximately equal to 2.718281828459. The natural logarithm of x is generally written as ln x, $\log_e x$, or sometimes, if the base e is implicit, simply log x.

Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	46	46	44	42	41	42	45	46

Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	20	20	19	18	18	18	20	20

Values are multiple of 2.3

Note:
- ✓ Log10(10)=1, ln(10)=2.3
- ✓ Log10(3) = 0.48, ln(3)=1.1

In our last episode…

Bug in Dueling 612 (D612)

The power of unwanted emissions shall be attenuated below the transmitter's output power, P (dBW) as follows:

a. 25 dB; on any frequency removed from the channel frequency by more than 50% and up to 100% of the authorized bandwidth measured with a resolution bandwidth of 300 Hz;

b. 35 dB; on any frequency removed from the channel frequency by more than 100% up to 250% of the authorized bandwidth measured with a resolution bandwidth of 300 Hz;

c. 43 + 10*log(p) or 70 dB, whichever is less stringent; in any 30 kHz bandwidth removed from the channel frequency by more than 250% of the authorized bandwidth.

Where:

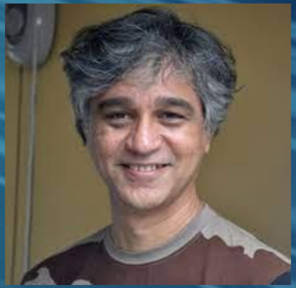
p refers to the transmitter's output power expressed in watts.

https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf01240.html

In Canada:

- For 5W, emission: 43.7 dBc
- For 10W, emission: 44.0 dBc
  - ✓ 44 dBc

☹ **D612 was less than 40dBc**



**Use Log10()

Orig. D612 PA

Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	63	64	65	65	65	65	62	57
Pwr (W)	9	10	12	13	14	12	6	2

8 dB Roll Off

BITX20 Power Amp

Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	28	27	26	25	25	24	23	21

7 dB Roll Off

BITX40 Power Amp

Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	27	27	27	27	27	27	26	25

2 dB Roll Off

uBITX Power Amp

Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	32	32	32	32	32	32	31	29

3 dB Roll Off

WA2EBY Power Amp

Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	20	20	19	18	18	18	20	20

2 dB variation

Hans S. Power Amp

Freq (MHz)	1.5	3.7	5.37	7.1	10.1	14.1	21.1	28.7
Gain (dB)	20	19	18	18	17	16	12	8

12 dB?

In our last episode…

Power Amp

- MOSFET bias voltage
- Input drive level
- Input/output impedance
- Spectral Purity
- Output Power
- Gain
- Temp/Power Dissipation

~~**Low Pass Filter**~~

~~Attenuation~~

Spectral Purity
IC compliance

Output power

Temp/Power Dissipation

Agenda

1. Fourier Transform Background

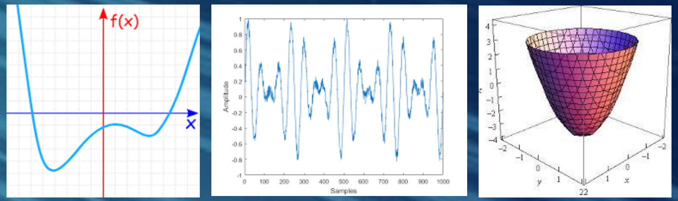
2. Fourier Transform vs Fast Fourier vs Discrete Fourier Transform

3. Important Parameters for FFT

4. LTSpice FFT

Fourier Expansion

- A mathematical mechanism to break down any periodic function in terms of an infinite sum of sines and cosines.
- In mathematics, its convenient to solve equations with sines and cosines.
- This was originally developed for "*continuous* functions"



Coefficients used to define a function

Coefficients (volume control) for Cosine Terms

$$f(t) = a_0 + a_1 \cos(t) + a_2 \cos(2t) + a_3 \cos(3t) + \cdots$$
$$+ b_1 \sin(t) + b_2 \sin(2t) + b_3 \sin(3t) + \cdots$$

Coefficients (volume controls) for Sine Terms

Fourier Coefficients

With a bit of math can figure out:

$$f(x) = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} a_n \cos(n x) + \sum_{n=1}^{\infty} b_n \sin(n x),$$

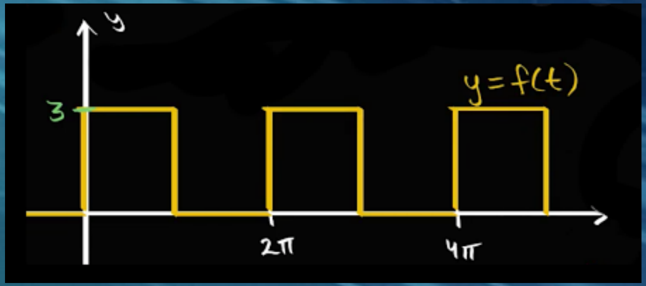
Notice summation is n=1 to infinity. This is the continuous Fourier Transform

$$a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x)\, dx$$

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos(n x)\, dx$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin(n x)\, dx$$

Unipolar Square Wave with DC Offset



As an example, what are the coefficients for a square wave? Turns out that cosine terms integrate to 0 and only sine terms ("a" coefficients apply).

A_0 = Amp / 2

For n even: $B_n = 0$ ($B_2 = B_4 = B_6 = B_8 = 0$….)

For n odd: B_n = 2Amp/ n pi (Amp is amplitude)

For a 3Vp Square Wave: $B_0 = 1.5$, $B_1 = 1.9$, $B_3 = 0.63$, $B_5 = 0.38$, …

For a waveform (e.g., square wave), the coefficients are the amount (volume) of a particular frequency (i.e., the "nx" term in the sine terms)

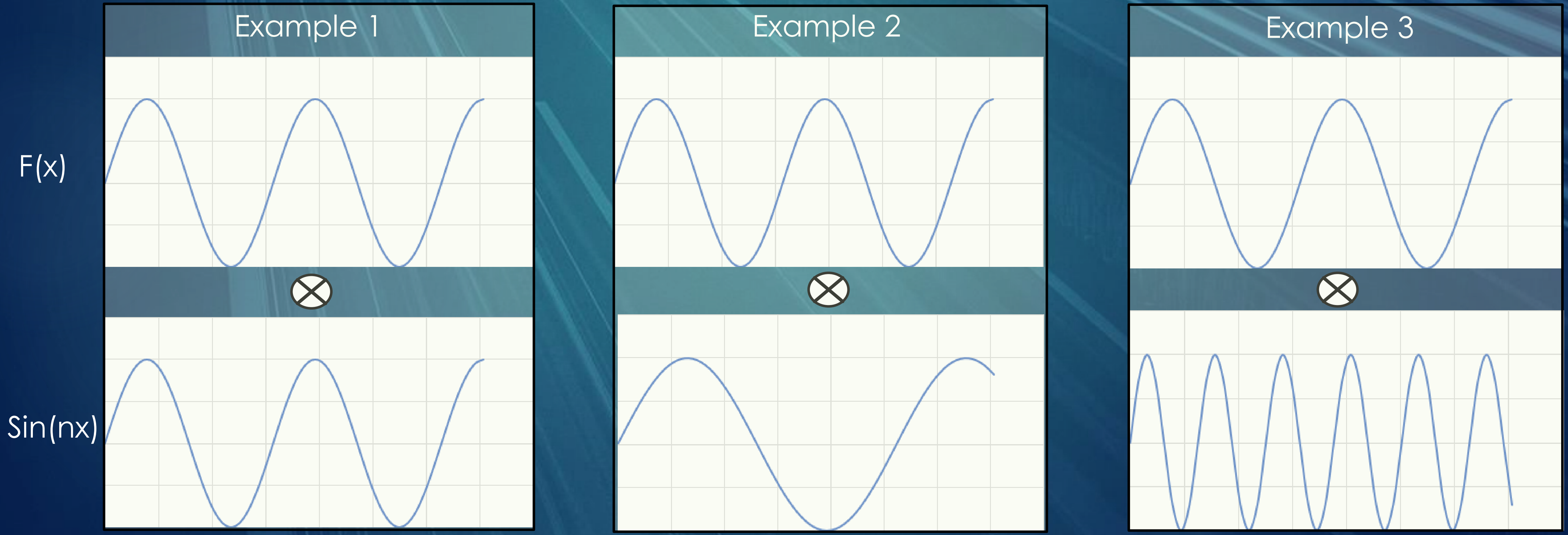
Correlation

$$a_0 = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\,dx$$

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\cos(nx)\,dx$$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\sin(nx)\,dx$$

Performing a summation of a multiplication of two functions F(x) and Sin(nx) is used to determine if the two functions are similar. i.e., is there a correlation between the two functions.



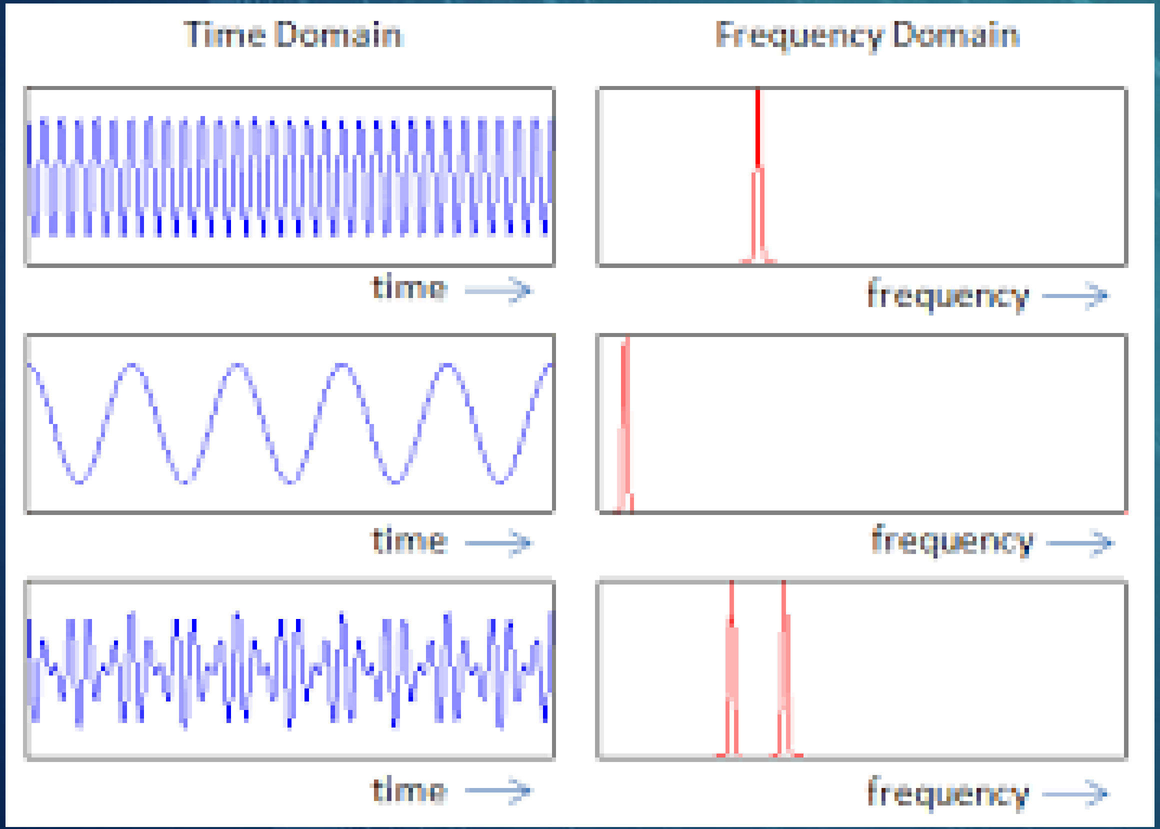
Fourier Transform

$$a_0 = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\,dx$$

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\cos(nx)\,dx$$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\sin(nx)\,dx$$

The Fourier coefficients a_0, a_n, b_n are telling us the strength (volume) of frequencies in a function or signal or waveform



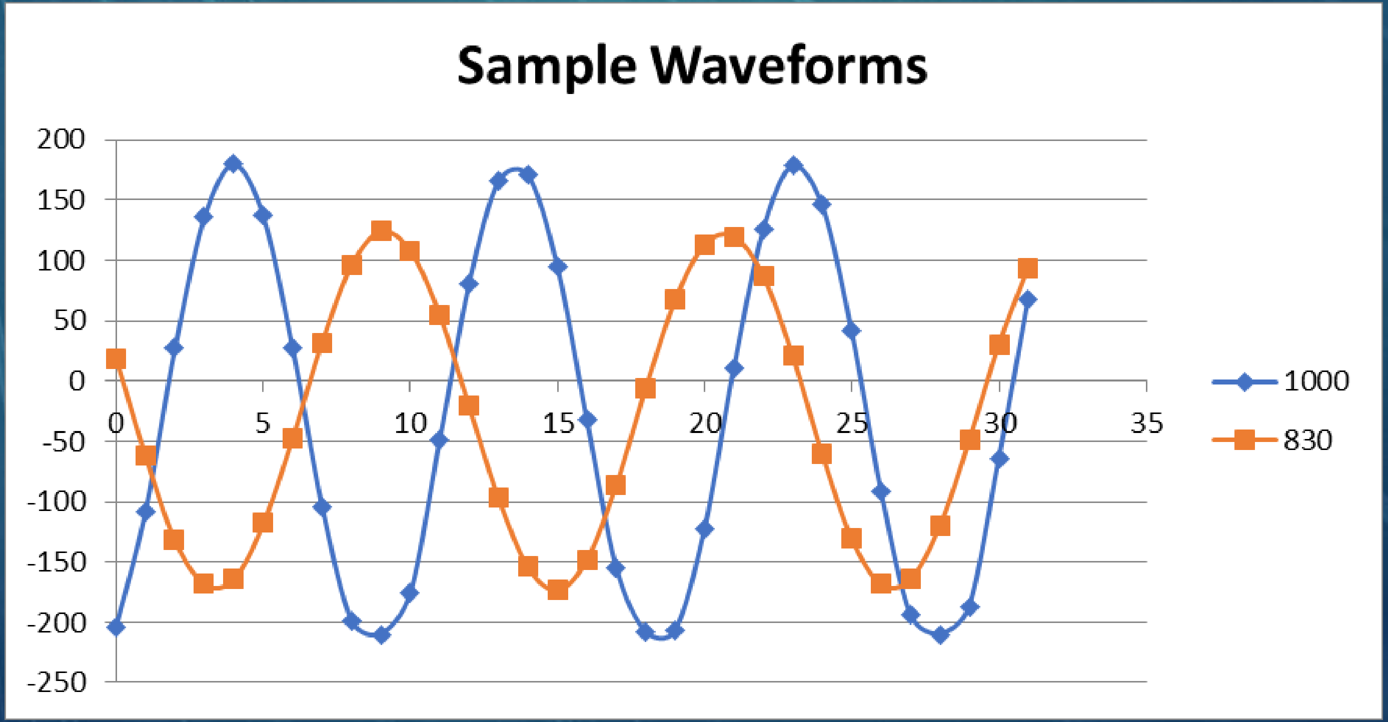
What does this Fourier mumbo jumbo mean?

- ✓ We can us it to tell us the frequency components of an electronic waveform
- ✓ We need to figure out the coefficients for each frequency component
  - ❖ i.e., How much of 1MHz is there? How much of 13 MHz is there?
- ✓ Spectrum Analyzers do this in hardware (FPGA) at extremely fast speeds. Some scopes do this as well
- ✓ To do this using continuous “Fourier” expansion, this takes time and computing power

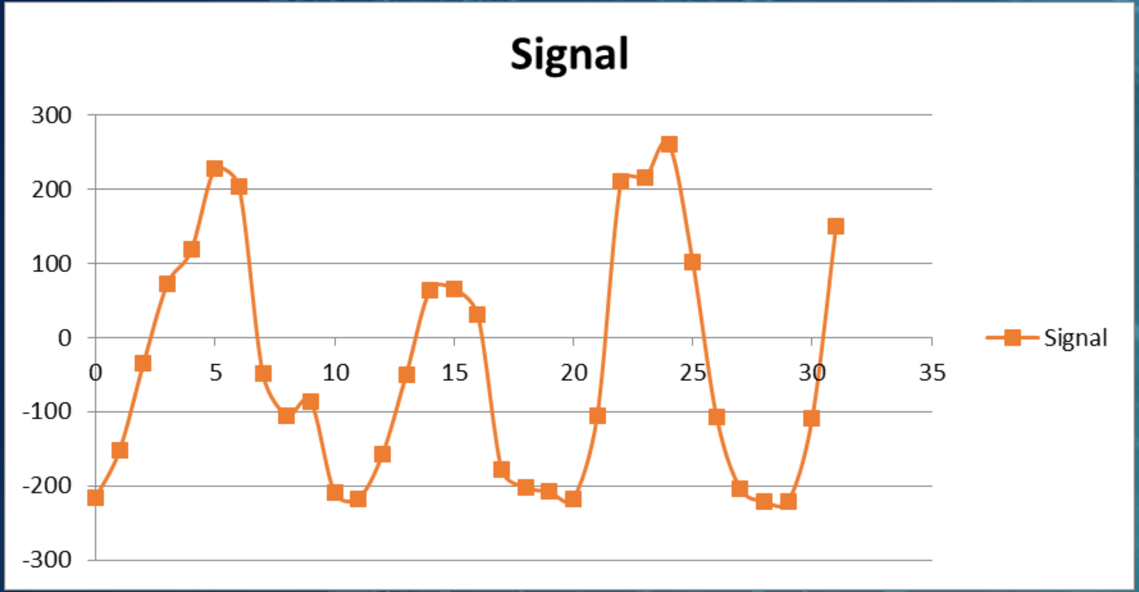
Correlation Example

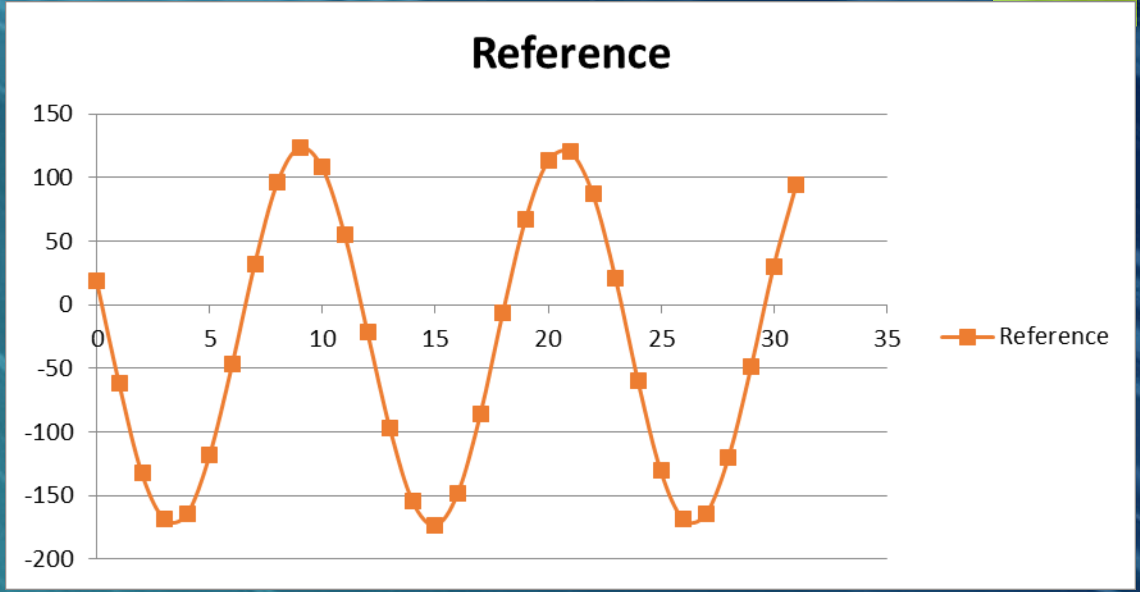
In 2017 Built a RTTY/PSK Transceiver based on an Arduino Mega

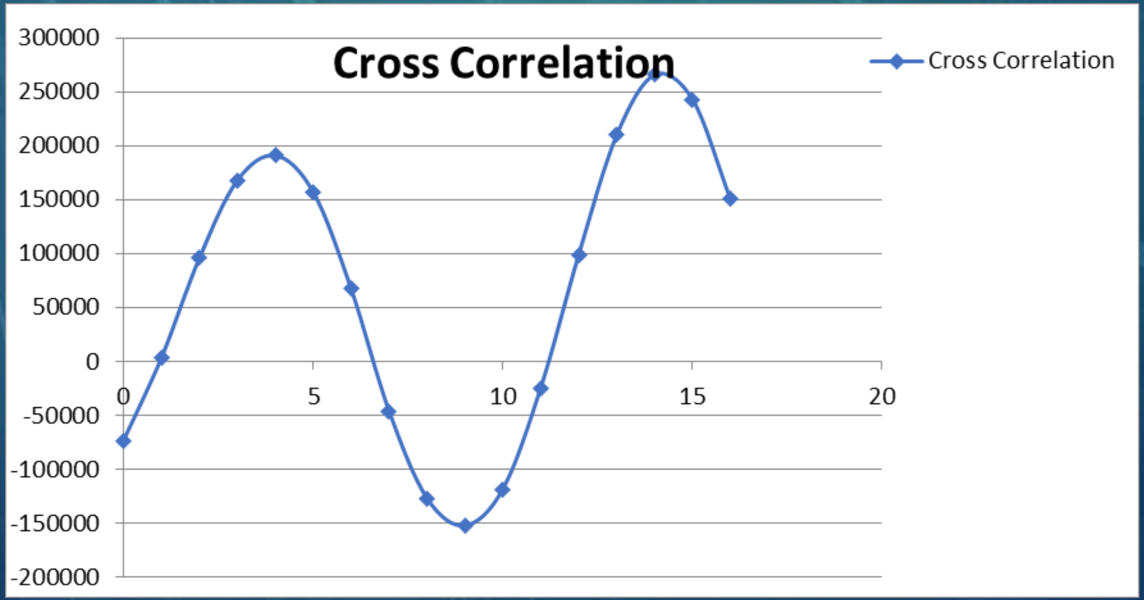
- Based conversation with Paul Darlington (M0XPD) “An 16bit Arduino Cannot Decode RTTY/PSK”
- Used MOXPD/KANGA “sudden” Rx and Tx modules
- Took audio signal and digitized at 9600 Hz for 10bit samples
- Used two tones for RTTY 830 & 1000 Hz
- Used correlation (not FFT)to detect presence of 830/1000 Hz in real time for a buffer of 30 samples



Correlation Example





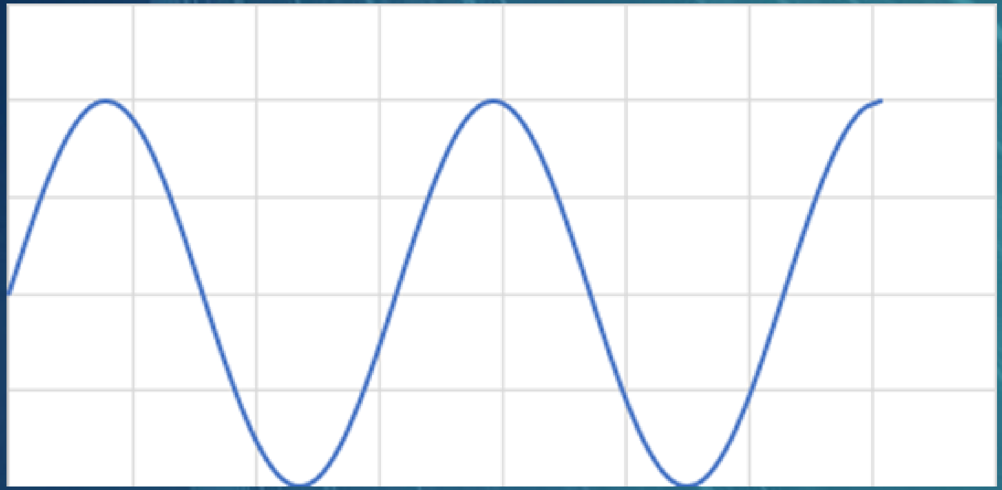


Autocorrelation Demo

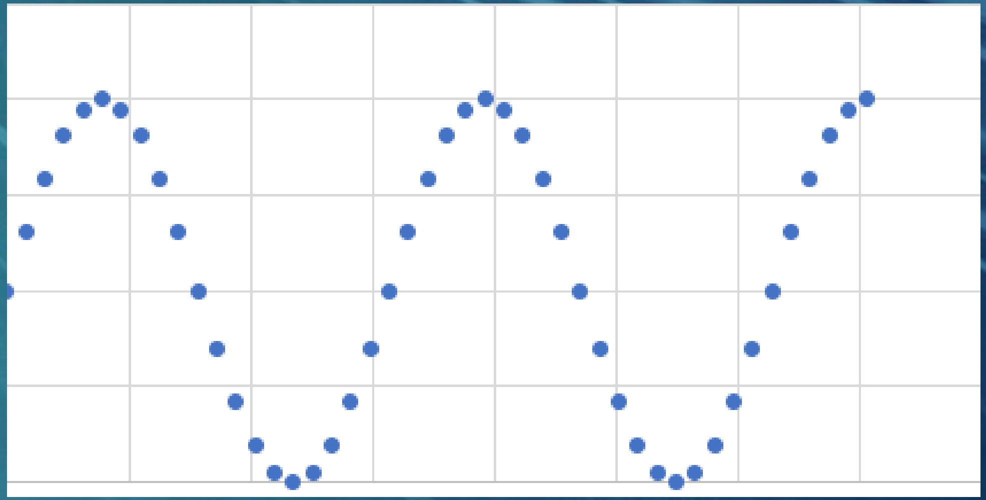
Continuous vs Discrete

- Not practical to use continuous Fourier expansion
- In the real world we deal with digitized waveforms/signals. i.e., discrete numbers

Continuous

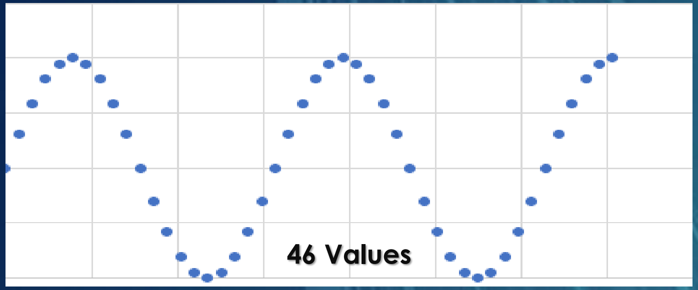


Discrete



The Discrete Fourier Transform

With some clever math, can use the Discrete Fourier Transform for data points



- Waveform is made of N values (e.g., 46)
- Values are denoted as x_n x_1, x_2, x_3,…x_n
  e.g., 1, 1.3, 1.5, 1.8, 1.9,…

$$X_k = \sum_{n=0}^{N-1} x_n \exp^{\frac{-j2\pi}{N}kn}$$

$$X_k = \sum_{n=0}^{N-1} x_n \left[\cos\left(\frac{2\pi}{N}kn\right) - j\sin\left(\frac{2\pi}{N}kn\right)\right]$$

e is Euler's number 2.71828

“e” term is simply sine and cosine

N is total number of samples (e.g., 46)

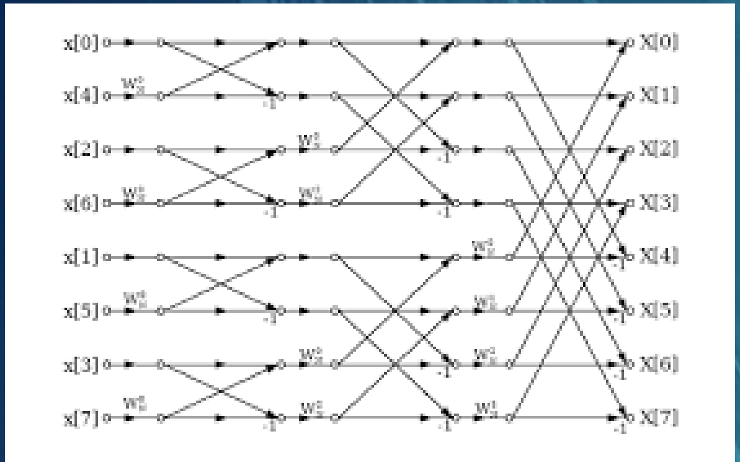
n is the values (index) in the waveform

k is “bin” number…wait for it

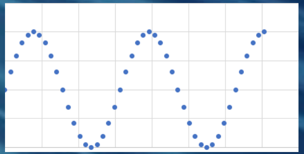
X_k is the strength of frequency component for the k^{th} bin

The Fast Fourier Transform (FFT)

- With some more clever math, can optimize the calculations to complete FFT on computers and microcontrollers.



✓ For the FFT to work you need the number of samples to be an exponent of 2 (e.g., 4, 8, 16, 32, 64, 128…2^y). Let's assume 32 samples

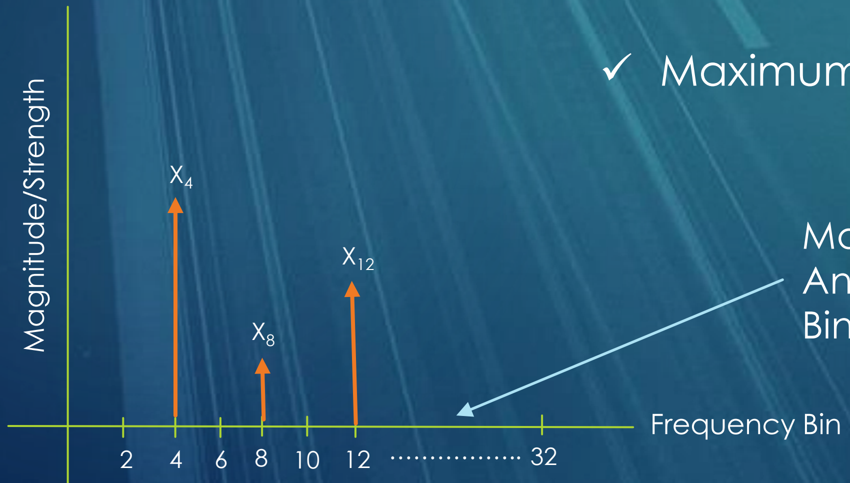


✓ The sample Frequency determines the resolution.

✓ Let's assume we sample at 128 KHz, then maximum frequency can resolve is 64 KHz (Nyquist–Shannon sampling theorem)

✓ The bins (k) are the frequency resolution. For N samples, frequency resolution for each bin it 64 KHz/32 or 2 KHz

✓ Maximum Frequency we an "detect" is Nyquist Frequency or 32 KHz

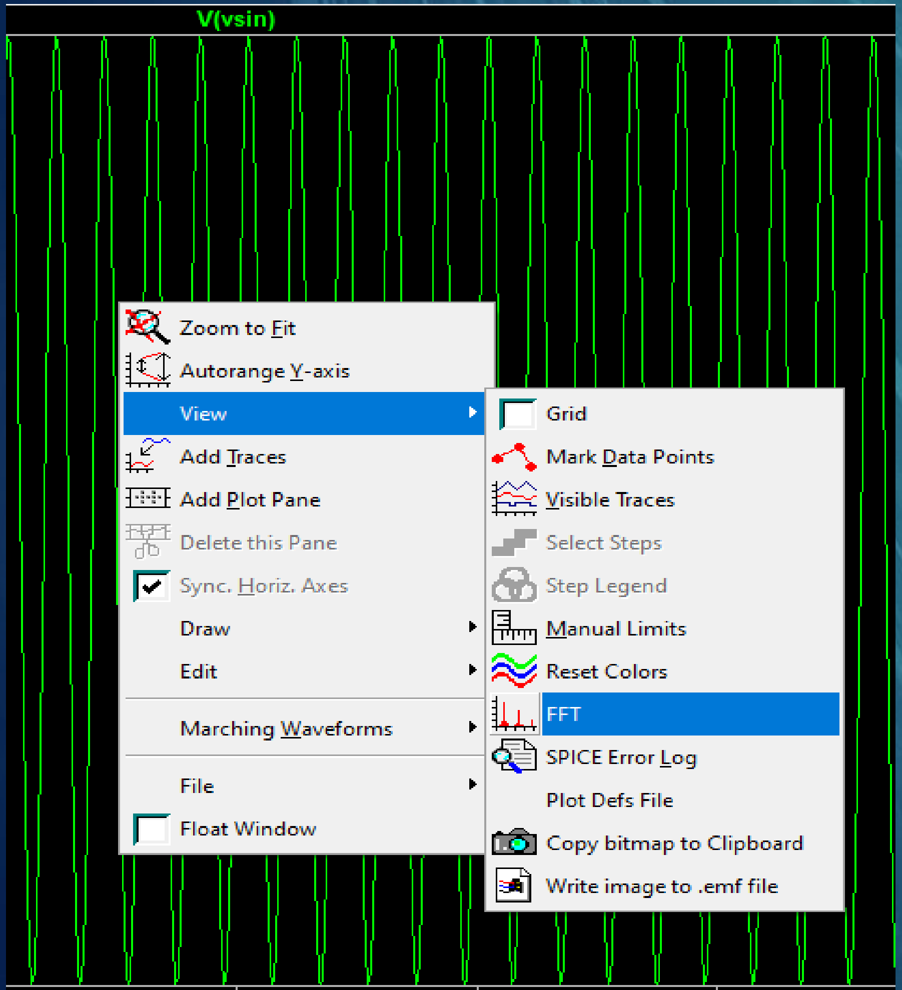


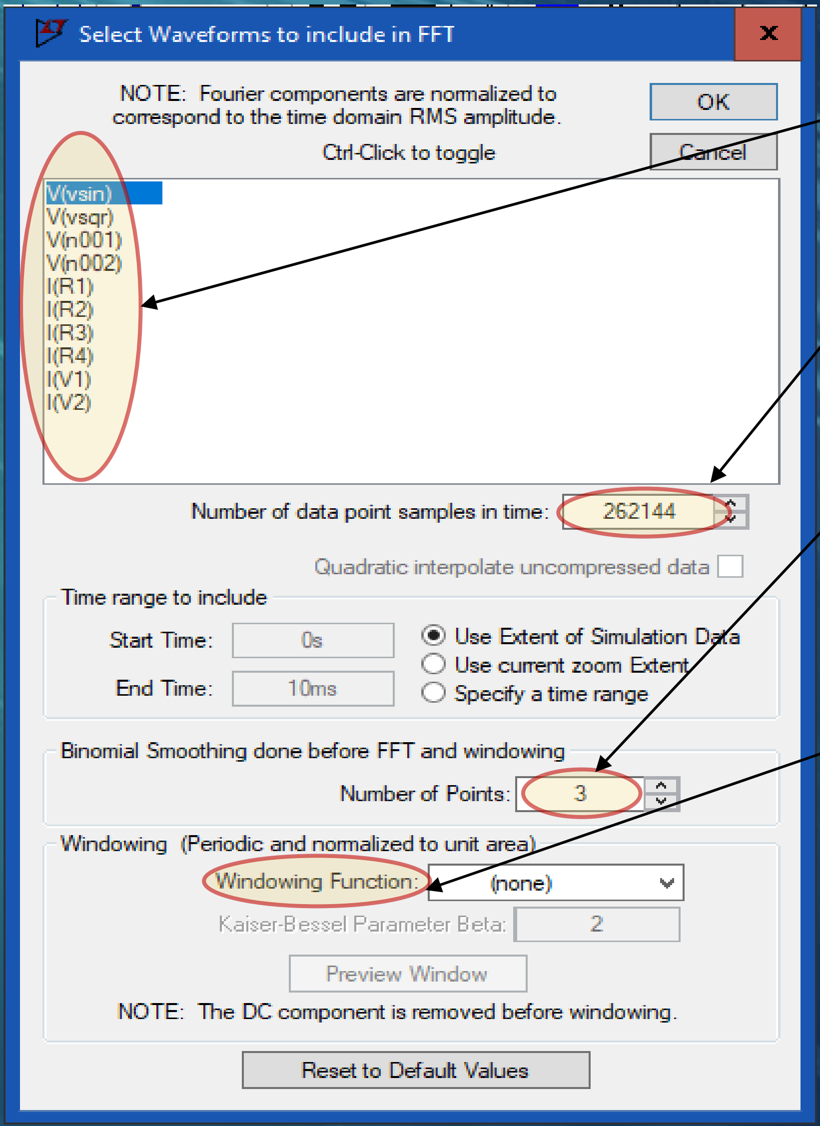
Max Frequency is 32 KHz. Which bin is for 32 KHz?
Answer: 2KHz x Bin 16 = 32 KHz.
Bins higher that 16 is a mirror image of bins 0-16 (Aliased…wraps around)

FFT Demo

LTSpice FFT

Can plot FFT for any signal plotted. Right Click on plot area. Select View, FFT





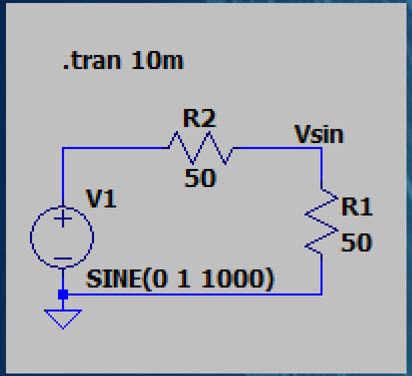
Select Signal

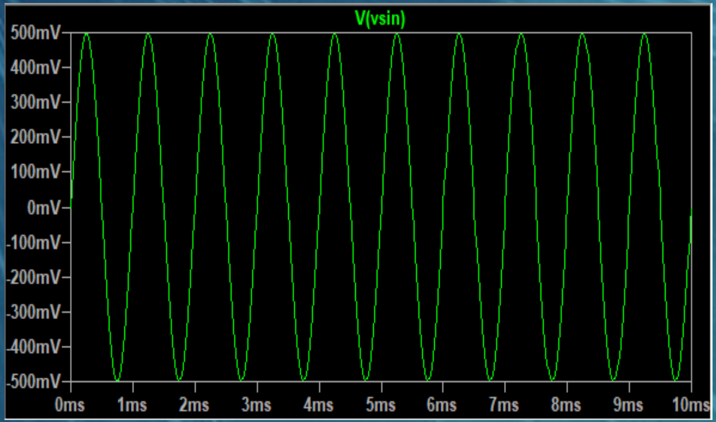
Select "N" ($2^{18} = 262144$)

Average Samples. Smooth noise

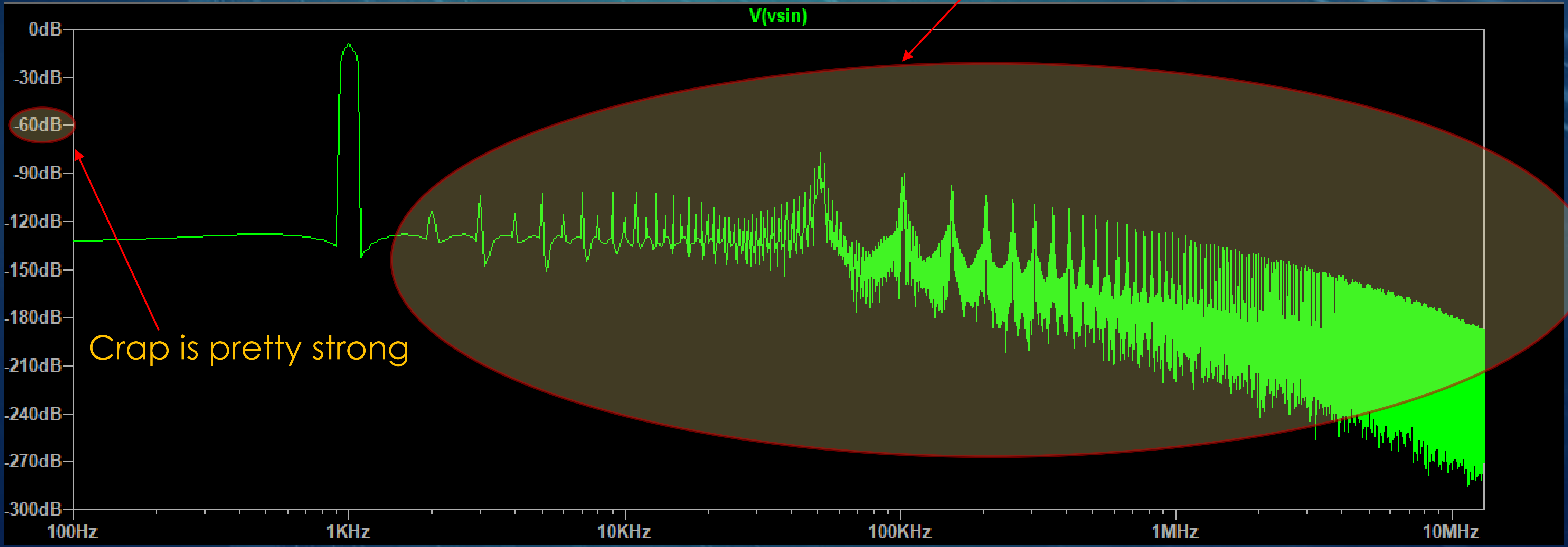
For discontinuity in stream. More for real time data.

LTSpice FFT Issues





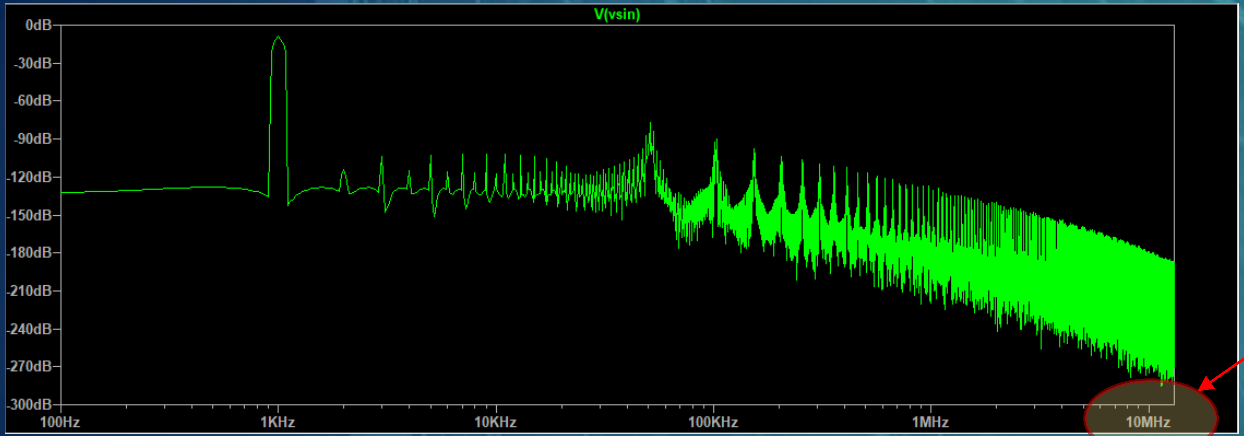
WTF?! This is a pure sine wave. Should only be one frequency component

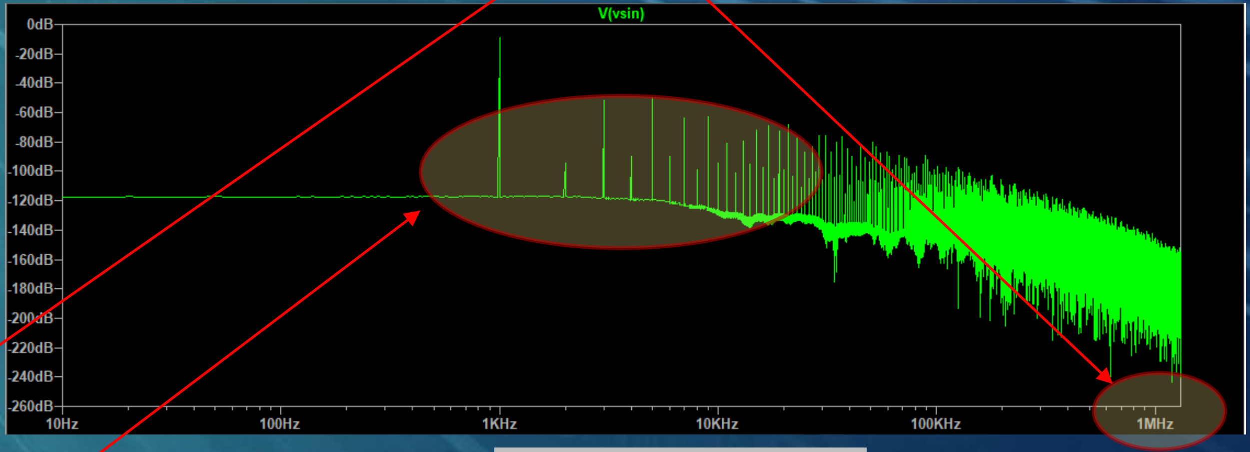


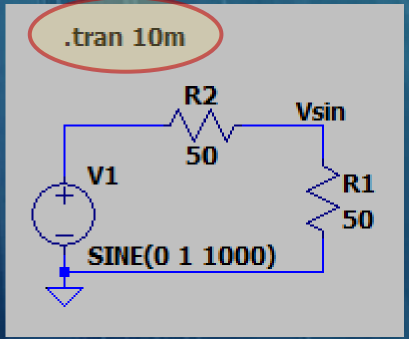
LTSpice FFT: Issue #1 - Resolution

- The number of samples taken N determines resolution. More points the more resolution. E.g. 1024 samples will have smaller "bin" size than 262144.
- LTSpice takes the timespan & number of samples to calculate the maximum frequency to resolve

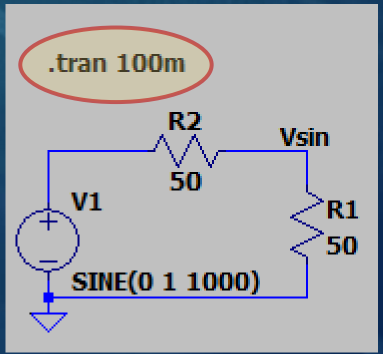
Same horizontal bandwidth. 10 MHz really?





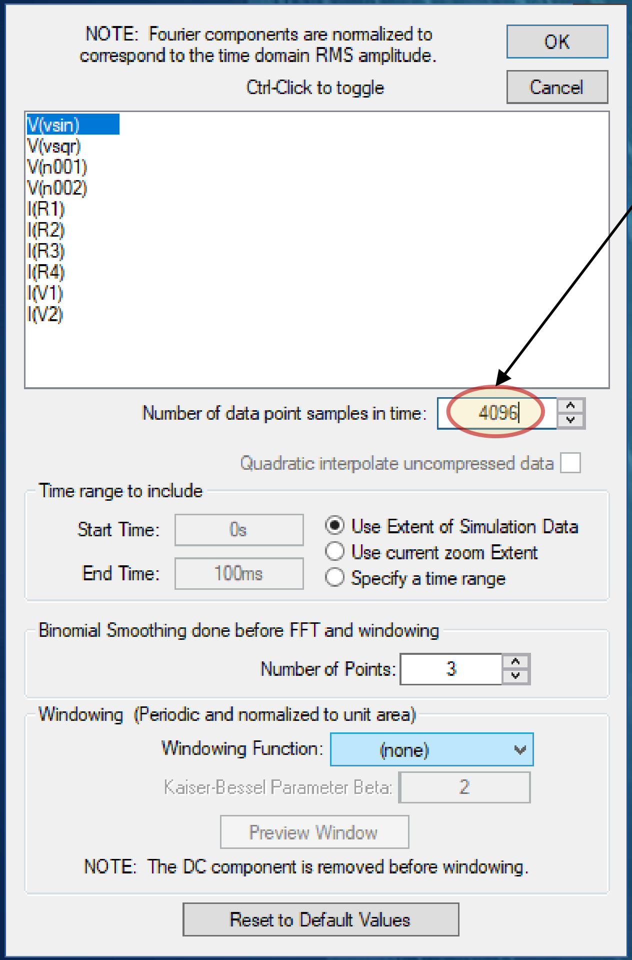


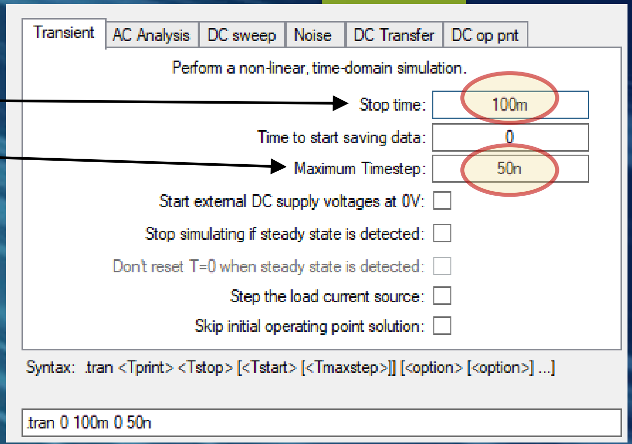
Narrower peaks. Better resolution

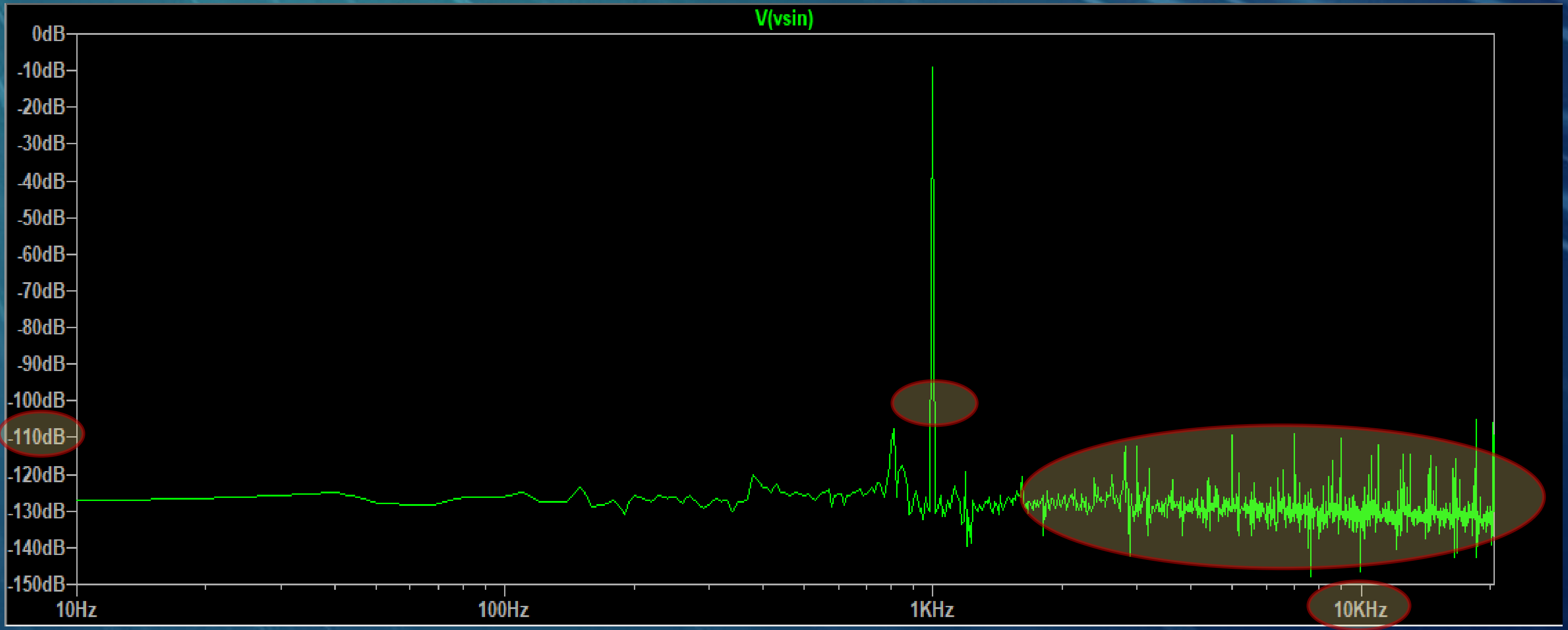


LTSpice FFT: Issue #1 – Resolution Fixes

- ✓ Need to increase timespan for more resolution
- ✓ Need to decrease time step (sample frequency)
- ✓ Need to reduce the number of samples to process to reduce horizontal bandwidth



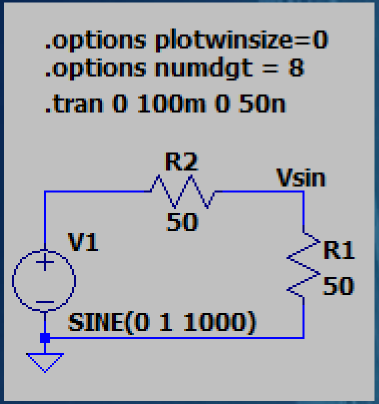




https://www.youtube.com/watch?v=rVAvW1Jh2AE

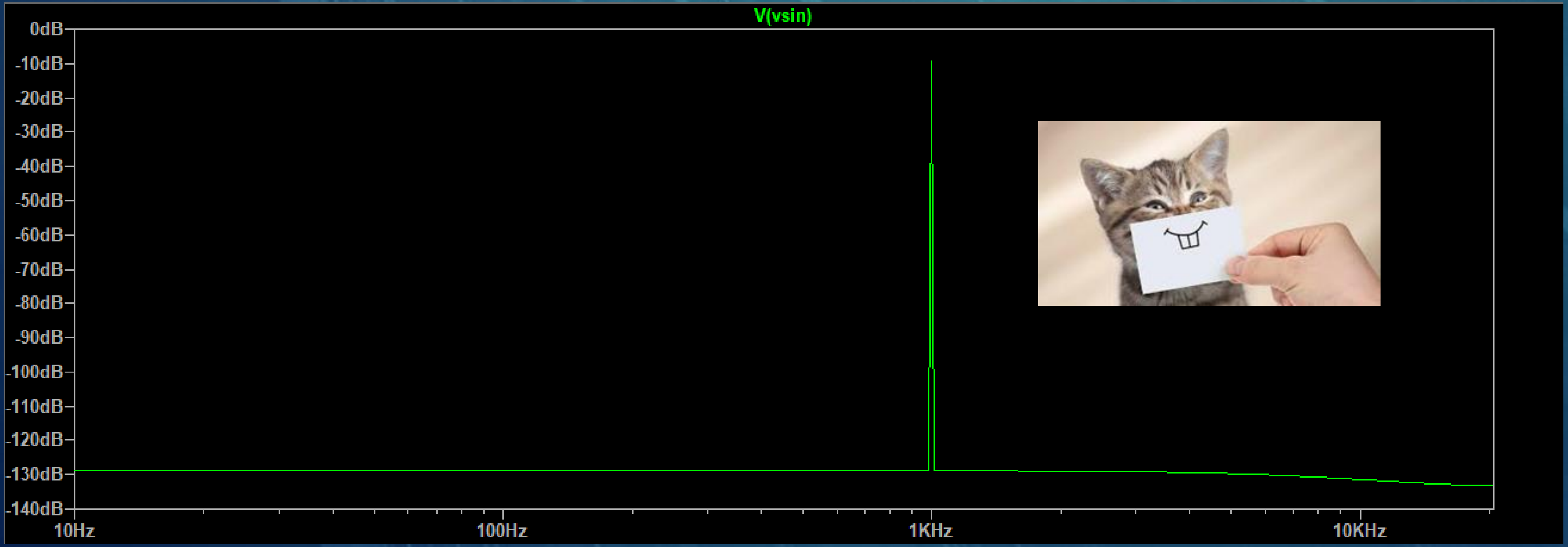
LTSpice FFT: Issue #2 - Defaults

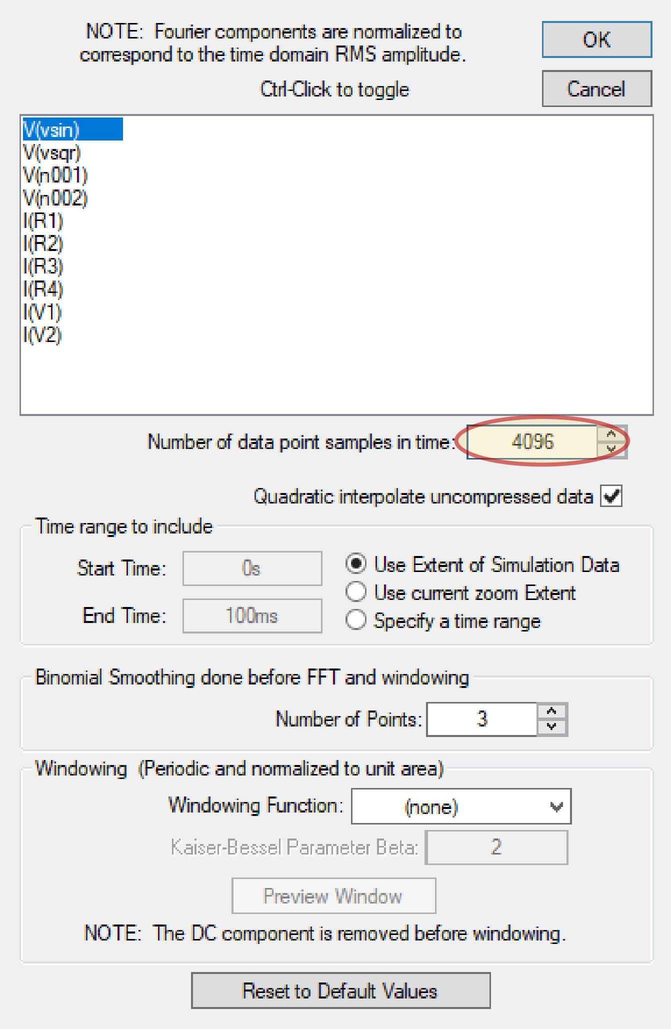
LTSpice samples calculated are compressed and with limited number of decimal digits



plotwinsize	Num.	300	Number of data points to compress in one window. Set to zero to disable compression.
numdgt	Num.	6	Historically "numdgt" was used to set the number of significant figures used for output data. In LTspice, if "numdgt" is set to be > 6, double precision is used for dependent variable data.

http://ltwiki.org/LTspiceHelp/LTspiceHelp/_OPTIONS_Set_simulator_options.htm





Please don't shoot me…

There is a **FAR** easier way to get the FFT data that we typically need

SIMULATE TOTAL HARMONIC DISTORTION USING LTSPICE

1. Setup a transient analysis with the analysis time a multiple of your signal generator's period

2. Add ***.four*** command using the "**SPICE directive**" button. .op

   Syntax: `.four <frequency> [Nharmonics] [Nperiods] <datatrace1> [<data trace2> ...]`

   Note: The frequency in ***.four*** command is the same as the frequency of an input source. For example, if your signal generator is set to 1kHz and you want to watch the node named "out." The command would be:

   Example: `.four 1kHz V(out)`
3. After running the simulation, you can see the results of THD using ***View*** >> ***SPICE error log***

https://eecs.oregonstate.edu/education/docs/ece323/Appendix.pdf

For harmonic distortion, we an identify how strong are the harmonics

.four 1000 4 -1 V(Vsin)

Fourier components of V(vsin)
DC component:-0.000156885

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component
1	1.000e+03	2.500e-01	1.000e+00
2	2.000e+03	1.248e-07	4.994e-07
3	3.000e+03	1.575e-03	6.300e-03
4	4.000e+03	6.242e-08	2.497e-07

Total Harmonic Distortion: 0.629967%(0.630096%)

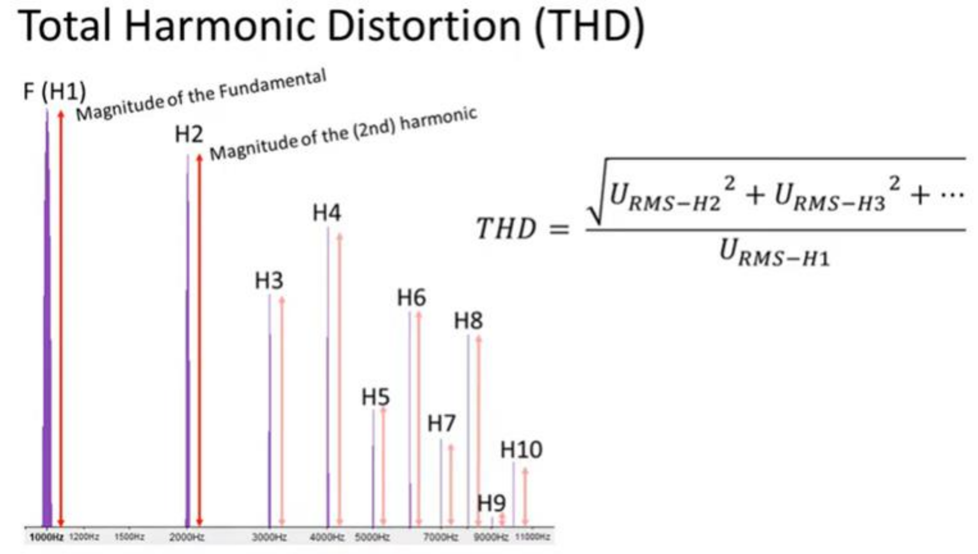
Total Harmonic Distortion

The **total harmonic distortion** (**THD** or **THDi**) is a measurement of the harmonic distortion present in a signal and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. **Distortion factor**, a closely related term, is sometimes used as a synonym.

In radio communications, devices with lower THD tend to produce less unintentional interference with other electronic devices. Since harmonic distortion tends to widen the frequency spectrum of the output emissions from a device by adding signals at multiples of the input frequency, devices with high THD are less suitable in applications such as spectrum sharing and spectrum sensing.[1]

$$\mathrm{THD_F} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1}$$

where V_n is the RMS value of the nth harmonic voltage and V_1 is the RMS value of the fundamental component.



Take the square rot of the sums of the squares for the harmonic strength and divide by the strength of the fundamental

https://www.youtube.com/watch?v=YPO3DEVzk90

What does this mean…

✓ Use THD to check purity of output when I compare power amps, MOSFETS, etc

c. 43 + 10*log(p) or 70 dB, whichever is less stringent; in any 30 kHz bandwidth removed from the channel frequency by more than 250% of the authorized bandwidth.

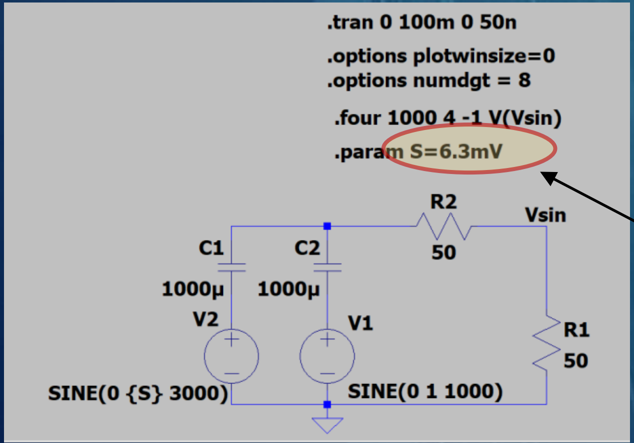
In Canada:

- For 5W, emission: 43.7dBc
- For 10W, emission: 44 dBc
- ✓ Assume 44 dBC

Some math….

- ➢ -44 = 10*log (Ph/Pf) or -44 = 20*log (Vh/Vf)
- ➢ Solve Vh = 0.00631 * Vf
  - ✓ Any harmonic is "at most" 0.63% of fundamental

Largest harmonic must be 0.63% to meet IC



dB = 20*log (0.0063/1)
dB = 20*log(6.3mV)
dB = -44

Fourier components of V(vsin)
DC component:-0.000156885

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component
1	1.000e+03	2.500e-01	1.000e+00
2	2.000e+03	1.248e-07	4.994e-07
3	3.000e+03	1.575e-03	6.300e-03
4	4.000e+03	6.242e-08	2.497e-07

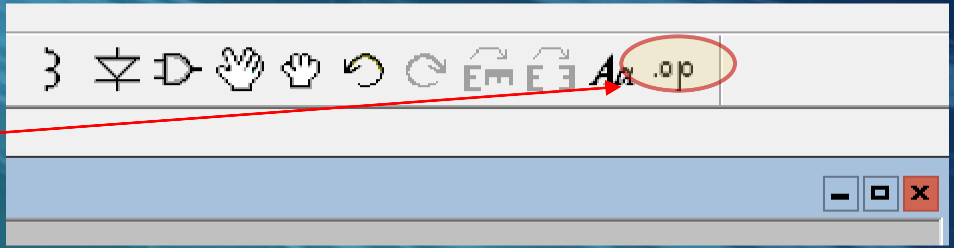
Total Harmonic Distortion: 0.629967%(0.630096%)

Summary

- Use Fourier Transform to decompose a frequency into fundamental components
- Use Discrete Fourier Transform to decomposes sampled waveform (e.g. Spectrum Analyzer, Scope with FFT)
- Use Fast Fourier Transform to optimize Discrete Fourier Transform
- There are rules when using FFT
  - ✓ e.g., 2n data points, Sample Frequency, bin size, etc.)
- LTSpice by default does a crappy job of doing FFT.
  - ✓ Disable compression
  - ✓ Change decimal precision
  - ✓ Increase number of data points (longer simulation time, faster computation interval)
  - ✓ Reduce the number of data points in FFT to match resolution
- For Harmonic Analysis use the .four directive
  - ✓ Gives strength of harmonics
  - ✓ Provides DC level
  - ✓ Provides Total Harmonic Distortion (THD)

Rabbit Hole #3.2: LTSpice Measurements

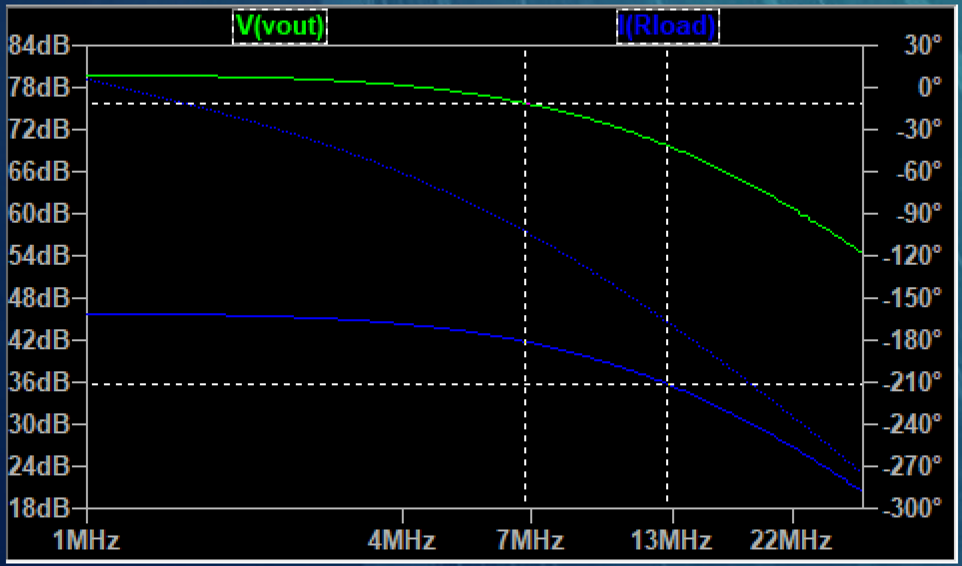
Measure Command



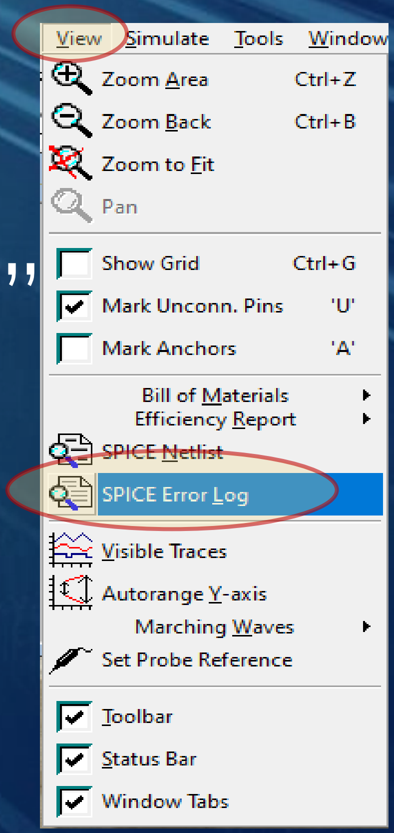
- Spice Directive
- Details at:

  http://ltwiki.org/LTspiceHelp/LTspiceHelp/_MEASURE_Evaluate_User_Defined_Electrical_Quantities.htm

  http://km2000.us/franklinduan/articles/hspice/hspice_2001_2-48.html
- Walkthrough at: https://www.youtube.com/watch?v=DqLXW4qn6j0
- Mechanism to make measurements without using Graph and Cursors



- Values given in "Error Log"



LTSpice Measurements

Measure a point

```
Syntax: .MEAS[SURE] [AC|DC|OP|TRAN|TF|NOISE] <name>
 + [<FIND|DERIV|PARAM> <expr>]
 + [WHEN <expr> | AT=<expr>]]
 + [TD=<val1>] [<RISE|FALL|CROSS>=[<count1>|LAST]]
```

```
.meas AC Irl FIND I(Rload) WHEN Freq=1.5Meg
.meas AC V1 FIND V(Vout) WHEN Freq=1.5Meg
.meas AC X1 PARAM V1/Irl
```

Measure over a range

```
Syntax: .MEAS [AC|DC|OP|TRAN|TF|NOISE] <name>
 + [<AVG|MAX|MIN|PP|RMS|INTEG> <expr>]
 + [TRIG <lhs1> [[VAL]=]<rhs1>] [TD=<val1>]
 + [<RISE|FALL|CROSS>=<count1>]
 + [TARG <lhs2> [[VAL]=]<rhs2>] [TD=<val2>]
 + [<RISE|FALL|CROSS>=<count2>]
```

```
.meas TRAN Vi RMS V(Vin)
.meas TRAN Vo RMS V(Vout)
.meas TRAN Io RMS I(Rload)
.meas TRAN P PARAM Vo*Io
.meas TRAN Gv PARAM 20*log(Vo/Vi)
```

Keyword	Operation perform over interval
AVG	Compute the average of <expr>
MAX	Find the maximum value of <expr>
MIN	Find the minimum value of <expr>
PP	Find the peak-to-peak of <expr>
RMS	Compute the root mean square of <expr>
INTEG	Integrate <expr>

Example Measurements

Measure sometime at a specific time/frequency:

- ✓ .meas AC Irl FIND I(Rload) WHEN Freq=1.5Meg //This is at a specific frequency
- ✓ .meas TRAN Vx FIND V(Vout) WHEN time=37us //This is at a specific time

```
vx: v(vout)=29.6018 at 3.7e-005
```

```
irl: i(rload)=(-54.1277dB,-10.5573°) at 1.5e+006
```

```
v1: v(vout)=(79.6417dB,-10.496°) at 1.5e+006
v3: v(vout)=(78.4865dB,-56.2326°) at 3.7e+006
v7: v(vout)=(75.4355dB,-106.72°) at 7.1e+006
v14: v(vout)=(68.1973dB,-179.061°) at 1.41e+007
v18: v(vout)=(64.2513dB,150.597°) at 1.81e+007
v21: v(vout)=(61.4771dB,131.176°) at 2.11e+007
v29: v(vout)=(54.9895dB,89.0891°) at 2.9e+007
```

```
Syntax: .MEAS[SURE] [AC|DC|OP|TRAN|TF|NOISE] <name>
 + [<FIND|DERIV|PARAM> <expr>]
 + [WHEN <expr> | AT=<expr>]]
 + [TD=<val1>] [<RISE|FALL|CROSS>=[<count1>|LAST]]
```

Measure sometime over a range

- ✓ .meas TRAN P0 RMS (V(Vin)*I(Rload))
- ✓ .meas TRAN P1 RMS (V(Vin)*I(Rload)) trig at 50us //This is from 53us to end)
- ✓ .meas TRAN P2 RMS (V(Vin)*I(Rload)) from 10us to 55us

```
p0: RMS(v(vout)*i(rload))=12.8336 FROM 0 TO 0.0001
p1: RMS(v(vout)*i(rload))=13.0288 FROM 5e-005 TO 0.0001
p2: RMS(v(vout)*i(rload))=13.1959 FROM 1e-005 TO 5.5e-005
vx: v(vout)=29.6018 at 3.7e-005
vi: RMS(v(vin))=0.0140959 FROM 0 TO 0.0001
vo: RMS(v(vout))=24.5653 FROM 0 TO 0.0001
io: RMS(i(rload))=0.491307 FROM 0 TO 0.0001
p: vo*io=12.0691
gv: 20*log(vo/vi)=149.264
```

```
Syntax: .MEAS [AC|DC|OP|TRAN|TF|NOISE] <name>
 + [<AVG|MAX|MIN|PP|RMS|INTEG> <expr>]
 + [TRIG <lhs1> [[VAL]=]<rhs1>] [TD=<val1>]
 + [<RISE|FALL|CROSS>=<count1>]
 + [TARG <lhs2> [[VAL]=]<rhs2>] [TD=<val2>]
 + [<RISE|FALL|CROSS>=<count2>]
```

Keyword	Operation perform over interval
AVG	Compute the average of <expr>
MAX	Find the maximum value of <expr>
MIN	Find the minimum value of <expr>
PP	Find the peak-to-peak of <expr>
RMS	Compute the root mean square of <expr>
INTEG	Integrate <expr>

Example Measurements

Measure sometime at a specific time/frequency:

- ✓ .meas AC Irl FIND I(Rload) WHEN Freq=1.5Meg //This is at a specific point

```
irl: i(rload)=(-54.1277dB,-10.5573°) at 1.5e+006
```

```
Syntax: .MEAS[SURE] [AC|DC|OP|TRAN|TF|NOISE] <name>
 + [<FIND|DERIV|PARAM> <expr>]
 + [WHEN <expr> | AT=<expr>]]
 + [TD=<val1>] [<RISE|FALL|CROSS>=[<count1>|LAST]]
```

Measure sometime over a range

- ✓ .meas TRAN P0 RMS (V(Vin)*I(Rload))
- ✓ .meas TRAN P1 RMS (V(Vin)*I(Rload)) trig at 50us //This is from 50us to end)
- ✓ .meas TRAN P2 RMS (V(Vin)*I(Rload)) from 10us to 55us

```
p0: RMS(v(vin)*i(rload))=0.00649814 FROM 0 TO 0.0001
p1: RMS(v(vin)*i(rload))=0.0065611 FROM 5e-005 TO 0.0001
p2: RMS(v(vin)*i(rload))=0.00661577 FROM 1e-005 TO 5.5e-005
vi: RMS(v(vin))=0.014096 FROM 0 TO 0.0001
vo: RMS(v(vout))=24.5654 FROM 0 TO 0.0001
io: RMS(i(rload))=0.491308 FROM 0 TO 0.0001
p: vo*io=12.0692
gv: 20*log(vo/vi)=149.264
```

```
Syntax: .MEAS [AC|DC|OP|TRAN|TF|NOISE] <name>
 + [<AVG|MAX|MIN|PP|RMS|INTEG> <expr>]
 + [TRIG <lhs1> [[VAL]=]<rhs1>] [TD=<val1>]
 + [<RISE|FALL|CROSS>=<count1>]
 + [TARG <lhs2> [[VAL]=]<rhs2>] [TD=<val2>]
 + [<RISE|FALL|CROSS>=<count2>]
```

Keyword	Operation perform over interval
AVG	Compute the average of <expr>
MAX	Find the maximum value of <expr>
MIN	Find the minimum value of <expr>
PP	Find the peak-to-peak of <expr>
RMS	Compute the root mean square of <expr>
INTEG	Integrate <expr>

Power Amp Measurements

What to measure when comparing power amps?

1. Power Output
2. Power Dissipated (temperature)
3. Power Margin (difference in above)
4. Gain
5. Input impedance
6. Output Impedance
7. Gate characteristics (Voltage, Bias)
8. Drain characteristics
9. Harmonics (THD)
10. Troubleshooting voltages

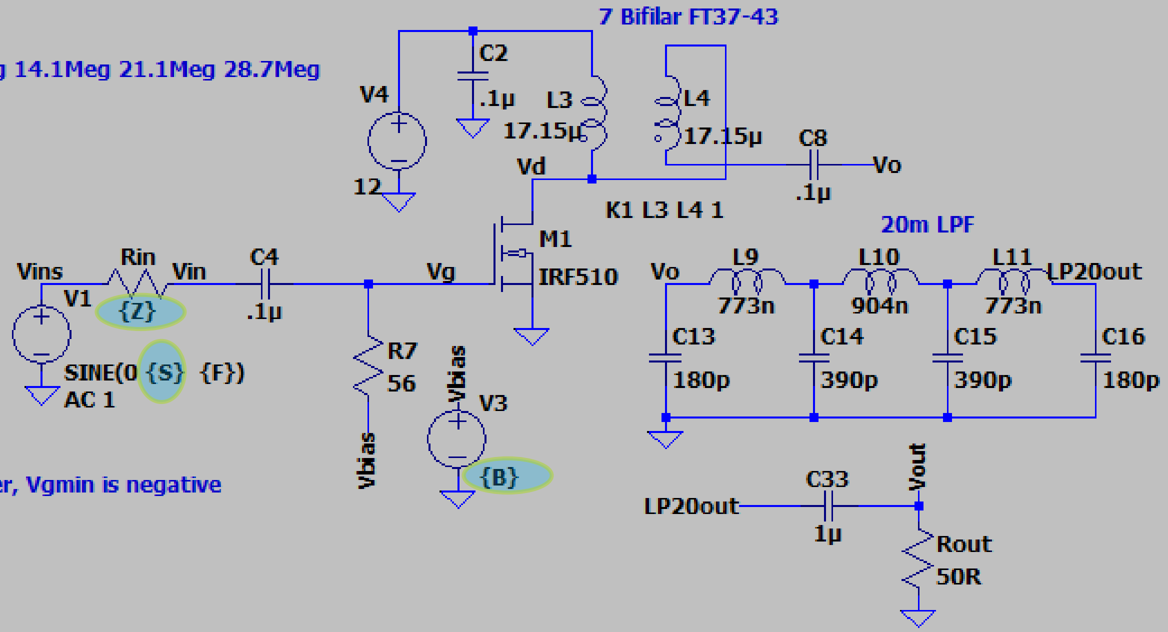
```
.tran 0 100u 95u 100p

.options plotwinsize=0
.options numdgt = 8

.param Rja 62
.param Rcs 0.50
.param Rjc 3.5
.param Tj 150

.meas TRAN Vinr RMS V(Vin)
.meas TRAN Vo1r RMS V(Vo1)
.meas TRAN Vinsr RMS V(Vins)
.meas TRAN Voutr RMS V(Vout)
.meas TRAN Vgr RMS V(Vg)
.meas TRAN Vgavg AVG V(Vg)
.meas TRAN Vgmax MAX V(Vg)
.meas TRAN Vgmin MIN V(Vg)
.meas TRAN Vbiasr RMS V(Vbias)
.meas TRAN Iinr RMS I(Rin)
.meas TRAN Pdis AVG (V(vd)*Id(m1) + V(vg)*Ig(m1))
;.meas TRAN Pdis AVG (V(vd)*Ix(m1:d) + V(vg)*Ix(m1:g))
.meas TRAN Pq1 AVG ( (V(vc)-V(ve))*Ic(Q1) + (V(Vb)-V(ve))*Ib(Q1)
.meas TRAN Po AVG (V(Vo)*V(Vo)/50)
.meas TRAN Pout AVG (V(Vout)*I(Rout))
.meas TRAN Pmar PARAM Pout-Pdis
.meas TRAN Zin PARAM 150*Vinr/(vinsr-Vinr)
.meas TRAN Temp PARAM Pdis*Rja
.meas TRAN Rheatsink PARAM ((Tj-25)/Pdis-Rcs-Rjc)
.meas TRAN Pin PARAM (Vinsr-Vinr)*Iinr
.meas TRAN Gp PARAM 10*log(Pout/Pin)
.meas TRAN Gv PARAM 10*log(Voutr/Vinr)
.meas TRAN Gv1 PARAM 10*log(Vo1r/Vinr)

.four {F} 4 -1 V(vout)
```

Sample Measurements

1) Set bias to sweep between range in data sheet. Set Input to be initially 1.5-2 times bias voltage
2) Select best power margin. Increase/decrease bias to Vgate min is slightly above 0
3) Select base bias and find idle current. Select resonable temperature
3) Select best output Vout harmonics must be smaller than (or equal) 7.08E-3
4) Sweep input to get best power output and power margin and output harmonics

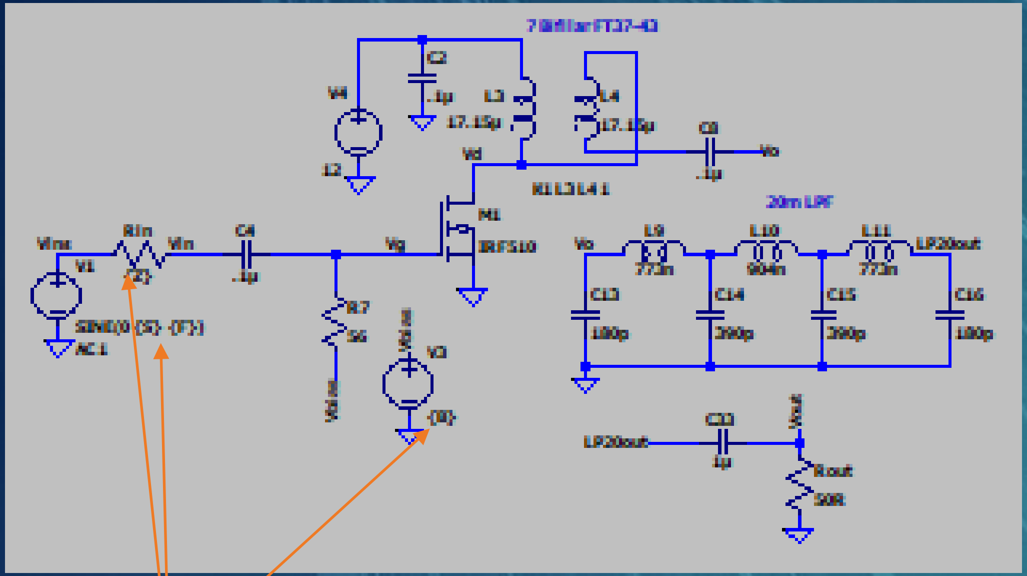
```
;.step param S 1 10 1
.param S 7.5
.param F 14.1Meg
.param B 4.15
.param Z 17
.step param F list 1.5Meg 3.7Meg 5.37Meg 7.1Meg 10.1Meg 14.1Meg 21.1Meg 28.7Meg
.param S 3
.param B 4.375
.step param B 4.0 4.3 0.15
.param F 14.1Meg
.param S 10
.step param B 4.0 4.3 0.15
.param F 14.1Meg
.param S 0
```

Set bias and input to set 28Mhz harmonic about 44dBc
Bias: 4.15V@88mA
Input 7.5 Vp
seems to be 4.15 bias and aboiut 10 to 12V input. However, Vgmin is negative




```
.tran 0 20u 10u 100p

.options plotwinsize=0
.options numdgt = 8

.param Rja 62
.param Rcs 0.50
.param Rjc 3.5
.param Tj 150

.meas TRAN Vinr RMS V(Vin)
.meas TRAN Vinsr RMS V(Vins)
.meas TRAN Voutr RMS V(Vout)
.meas TRAN Vgr RMS V(Vg)
.meas TRAN Vgavg AVG V(Vg)
.meas TRAN Vgmax MAX V(Vg)
.meas TRAN Vgmin MIN V(Vg)
.meas TRAN Vbiasr RMS V(Vbias)
.meas TRAN Iinr RMS I(Rin)
.meas TRAN Idr RMS Id(m1)
.meas TRAN Pdis RMS (V(vd)*Id(m1) + V(vg)*Ig(m1))
.meas TRAN Pout RMS (V(Vout)*I(Rout))
.meas TRAN Pmar PARAM Pout-Pdis
.meas TRAN Zin PARAM Z*Vinr/(vinsr-Vinr)
.meas TRAN Temp PARAM Pdis*Rja
.meas TRAN Rheatsink PARAM ((Tj-25)/Pdis-Rcs-Rjc)
.meas TRAN Pin PARAM (Vinsr-Vinr)*Iinr
.meas TRAN Gp PARAM 10*log10(Pout/Pin)
.meas TRAN Gv PARAM 20*log10(Voutr/Vinr)

.four {F} 4 -1 V(vout)
.four {F} 4 -1 V(Vo)
.four {F} 4 -1 V(Vin)
```

Harmonic Content Drives the Bus



Fourier components of V(vout)
DC component:0.605396

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component
1	1.410e+07	2.830e+01	1.000e+00
2	2.820e+07	1.302e-02	4.599e-04
3	4.230e+07	3.903e-04	1.379e-05
4	5.640e+07	8.220e-04	2.904e-05

Total Harmonic Distortion: 0.046102%(2.194441%)

Below 0.63% for IC & FCC

N-Period=all
Fourier components of V(vo)
DC component:0.562705

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component
1	1.410e+07	2.813e+01	1.000e+00
2	2.820e+07	3.257e+00	1.158e-01
3	4.230e+07	3.561e+00	1.266e-01
4	5.640e+07	4.828e-01	1.716e-02

Total Harmonic Distortion: 17.239882%(17.664440%)

17% Seems to produce reasonable power

```
vinr: RMS(v(vin))=2.75422 FROM 0 TO 1e-005
vinsr: RMS(v(vins))=5.30327 FROM 0 TO 1e-005
voutr: RMS(v(vout))=20.026 FROM 0 TO 1e-005
vgr: RMS(v(vg))=4.96978 FROM 0 TO 1e-005
vgavg: AVG(v(vg))=4.1486 FROM 0 TO 1e-005
vgmax: MAX(v(vg))=7.99737 FROM 0 TO 1e-005
vgmin: MIN(v(vg))=-0.265911 FROM 0 TO 1e-005
vbiasr: RMS(v(vbias))=4.15 FROM 0 TO 1e-005
iinr: RMS(i(rin))=0.196356 FROM 0 TO 1e-005
idr: RMS(id(m1))=1.26583 FROM 0 TO 1e-005
pdis: RMS(v(vd)*id(m1) + v(vg)*ig(m1))=5.83671 FROM 0 TO 1e-005
pout: RMS(v(vout)*i(rout))=9.83714 FROM 0 TO 1e-005
pmar: pout-pdis=4.00043
zin: z*vinr/(vinsr-vinr)=18.3683
temp: pdis*rja=361.876
rheatsink: ((tj-25)/pdis-rcs-rjc)=17.4162
pin: (vinsr-vinr)*iinr=0.500521
gp: 10*log10(pout/pin)=12.9345
gv: 20*log10(voutr/vinr)=17.2319
```

Adjust Mosfet bias and Input Drive for "optimum" results

"Linear-ish. However, dipping below Vgs will produce nasties
This may be ok for CW but may not be good for Phone

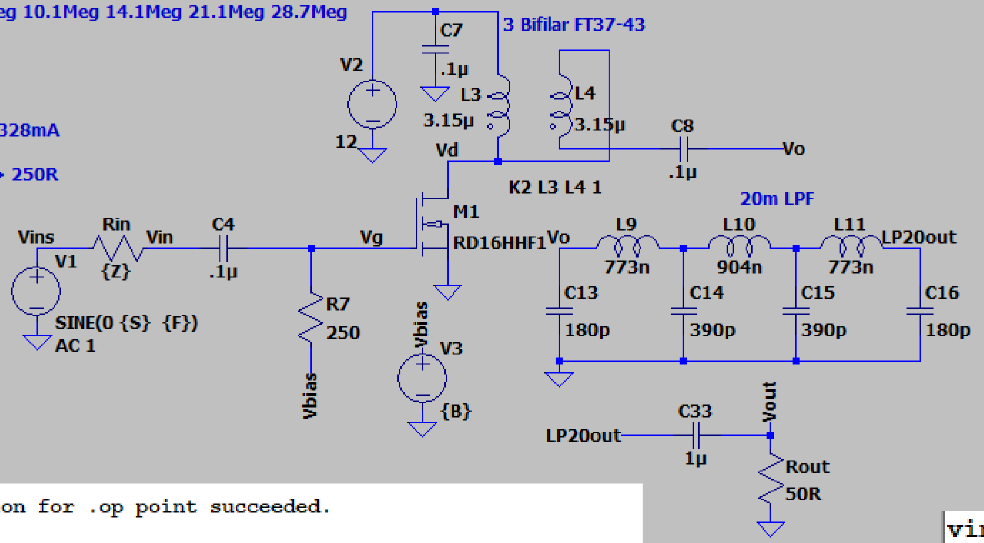
More power dissipated in Load than Mosfet
Assume this is good

Gain of about 17 dB (based on voltage gain)

Rinse and Repeat for each Mosfet

```
.step param F list 1.5Meg 3.7Meg 5.37Meg 7.1Meg 10.1Meg 14.1Meg 21.1Meg 28.7Meg
.param S 3
.param B 4.375

.step param B 4.3 4.6 0.05
.param F 14.1Meg
.param S 6
.param Z 53

.step param S 4 10 1
.param F 14.1Meg
.param B=4.375
.param Z 53

;.step param B 4.3 4.4 0.025
;.step param B 4.5 4.75 0.05
.param B 4.6
.param F 14.1Meg
.param S 0
.param Z 53

.param B 4.375
.param F 14.1Meg
.param S 0
.param Z 178
```

Bias: 4.376V@328mA
Input 5 Vp
Bias Resistor > 250R




```
.tran 0 20u 10u 100p
.options plotwinsize=0
.options numdgt = 8
.param Rja 62
.param Rcs 0.50
.param Rjc 2.2
.param Tj 150

.meas TRAN Vinr RMS V(Vin)
.meas TRAN Vinsr RMS V(Vins)
.meas TRAN Voutr RMS V(Vout)
.meas TRAN Vgr RMS V(Vg)
.meas TRAN Vgavg AVG V(Vg)
.meas TRAN Vgmax MAXV(Vg)
.meas TRAN Vgmin MIN V(Vg)
.meas TRAN Vbiasr RMS V(Vbias)
.meas TRAN Iinr RMS I(Rin)
.meas TRAN Idr RMS Id(m1)
.meas TRAN Pdis RMS (V(vd)*Id(m1) + V(vg)*Ig(m1))
.meas TRAN Pout RMS (V(Vout)*I(Rout))
.meas TRAN Pmar PARAM Pout-Pdis
.meas TRAN Zin PARAM Z*Vinr/(vinsr-Vinr)
.meas TRAN Temp PARAM Pdis*Rja
.meas TRAN Rheatsink PARAM ((Tj-25)/Pdis-Rcs-Rjc)
.meas TRAN Pin PARAM (Vinsr-Vinr)*Iinr
```

```
Direct Newton iteration for .op point succeeded.
N-Period=all
Fourier components of V(vout)
DC component:0.0248644

Harmonic      Frequency      Fourier        Normalized
 Number         [Hz]         Component      Component
    1         1.410e+07      2.388e+01      1.000e+00
    2         2.820e+07      1.112e-02      4.656e-04
    3         4.230e+07      5.771e-04      2.417e-05
    4         5.640e+07      4.009e-05      1.679e-06
Total Harmonic Distortion: 0.046621%(0.106267%)


N-Period=all
Fourier components of V(vo)
DC component:0.0224581

Harmonic      Frequency      Fourier        Normalized
 Number         [Hz]         Component      Component
    1         1.410e+07      2.373e+01      1.000e+00
    2         2.820e+07      3.163e+00      1.333e-01
    3         4.230e+07      2.601e+00      1.096e-01
    4         5.640e+07      8.732e-01      3.679e-02
Total Harmonic Distortion: 17.643436%(17.727908%)
```

```
vinr: RMS(v(vin))=1.76134 FROM 0 TO 1e-005
vinsr: RMS(v(vins))=3.53551 FROM 0 TO 1e-005
voutr: RMS(v(vout))=16.8829 FROM 0 TO 1e-005
vgr: RMS(v(vg))=4.71529 FROM 0 TO 1e-005
vgavg: AVG(v(vg))=4.37442 FROM 0 TO 1e-005
vgmax=1e-005 FROM 0 TO 1e-005
vgmin: MIN(v(vg))=1.76624 FROM 0 TO 1e-005
vbiasr: RMS(v(vbias))=4.375 FROM 0 TO 1e-005
iinr: RMS(i(rin))=0.0124584 FROM 0 TO 1e-005
idr: RMS(id(m1))=1.00682 FROM 0 TO 1e-005
pdis: RMS(v(vd)*id(m1) + v(vg)*ig(m1))=4.10395 FROM 0 TO 1e-005
pout: RMS(v(vout)*i(rout))=6.98176 FROM 0 TO 1e-005
pmar: pout-pdis=2.87782
zin: z*vinr/(vinsr-vinr)=176.713
temp: pdis*rja=254.445
rheatsink: ((tj-25)/pdis-rcs-rjc)=27.7585
pin: (vinsr-vinr)*iinr=0.0221033
gp: 10*log10(pout/pin)=24.9951
gv: 20*log10(voutr/vinr)=19.6321
```

Rinse and Repeat for Power Amp

MOSFET Results

This is from a "Theoretical" simulation. The MOSFT model could not be accurate.

	Parameters			Basic Amp @ 14.1 MHz						
Mosfet	Power	Cioss	Rin	Input	Bias	Zin	Pout	Pmar	Har Dist	Idle mA
FQPF20N06	30	590p	10	3.0	3.7	7.0	10.8	5.8	17%	0.83uA
IRF510	43	180p	25	7.5	4.2	18.0	9.6	4.2	17%	88
IRFZ24N	45	370p	10	5.0	3.1	10.0	9.6	3.6	17%	5.4uA
RD16HHF1	57	50p	320	5.0	4.4	168.0	7.0	2.9	17%	328
stp16nf06	40	315p	12	3.2	4.0	10.0	8.8	3.9	16%	135
IRF530	88	670p	5	6.0	4.2	5.0	10.6	1.5	17%	125
SH8K25	3	100p	54	2.5	2.3		5.9	1.7	18%	4.7
5010LLC	520	4360p	4	3.8	4.1		3.3	-6.1	17%	113

Based on input impedance only, the RD16HHF1 appears to be a better choice that IRF510

RD16HHF1 appears to have a "reasonable" power output

FIN

Stay Safe