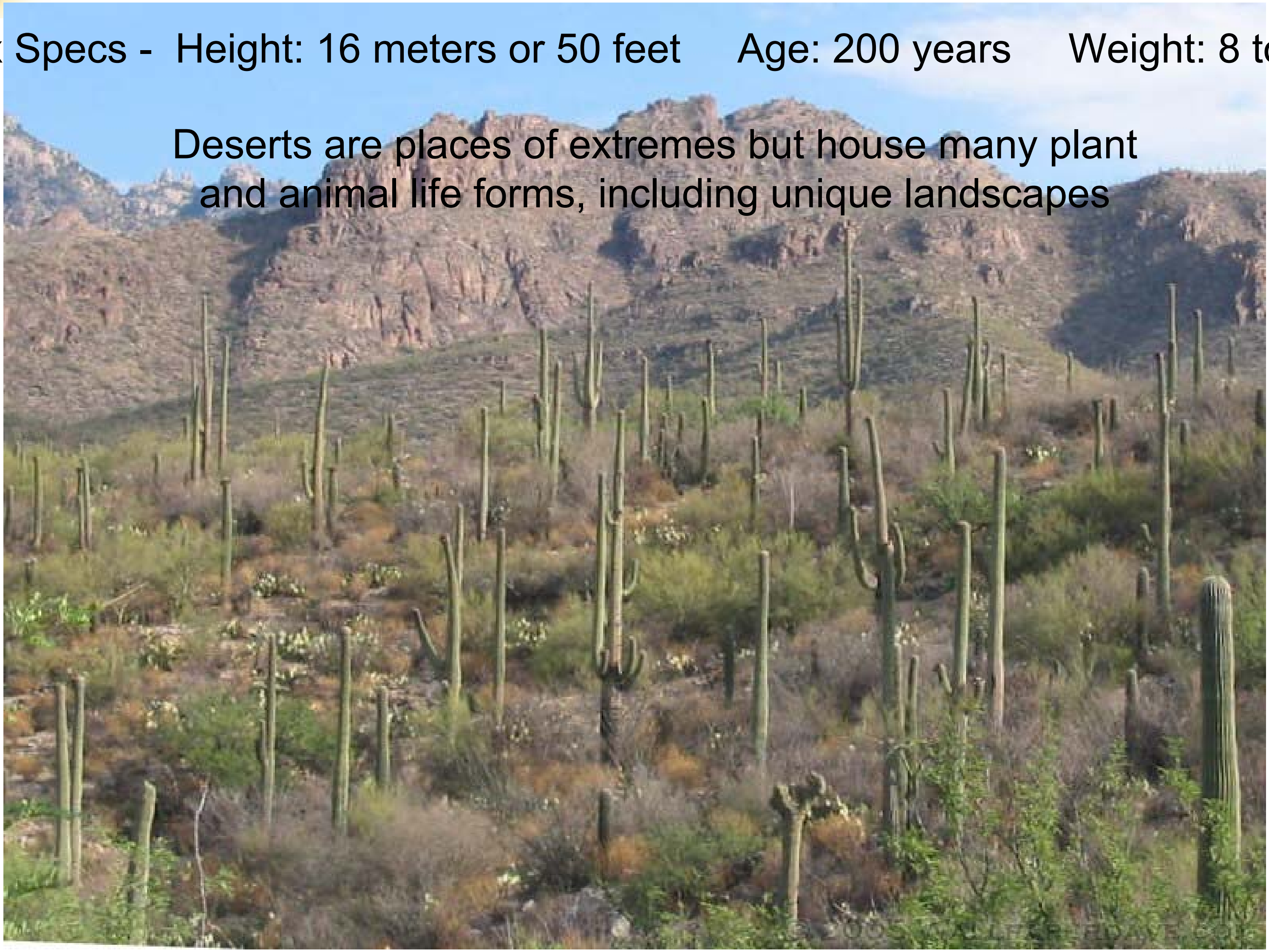
High-Performance Analog

Power Amplifier Seminar, John Brown, Month, 200x

# *Saguaro Cactus Sabino Canyon Tucson, Arizona*

Specifications



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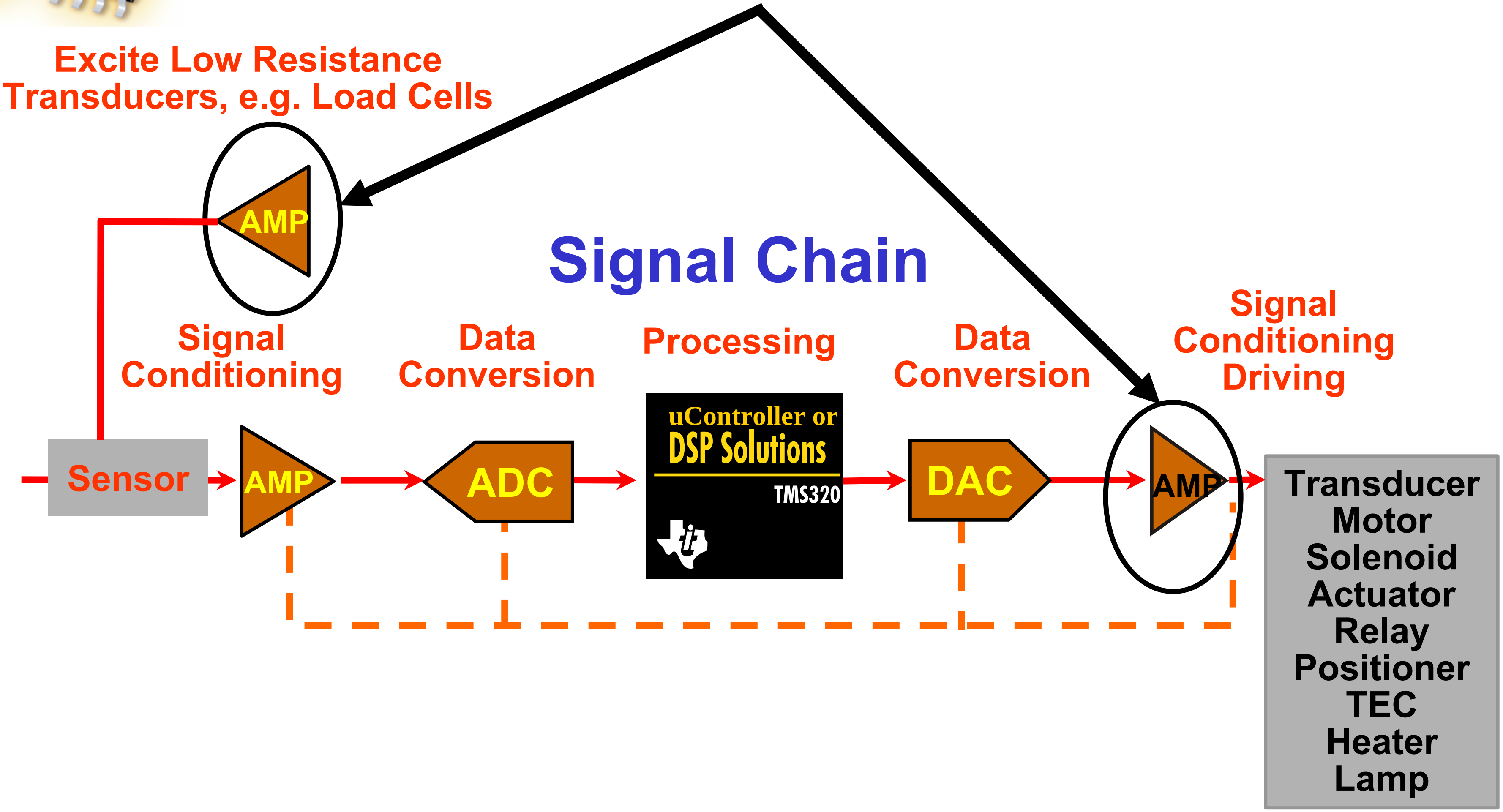
# Power Amplifier Applications



## Power Op Amps

# Crossover Distortion

# Principles & Circuit Applications

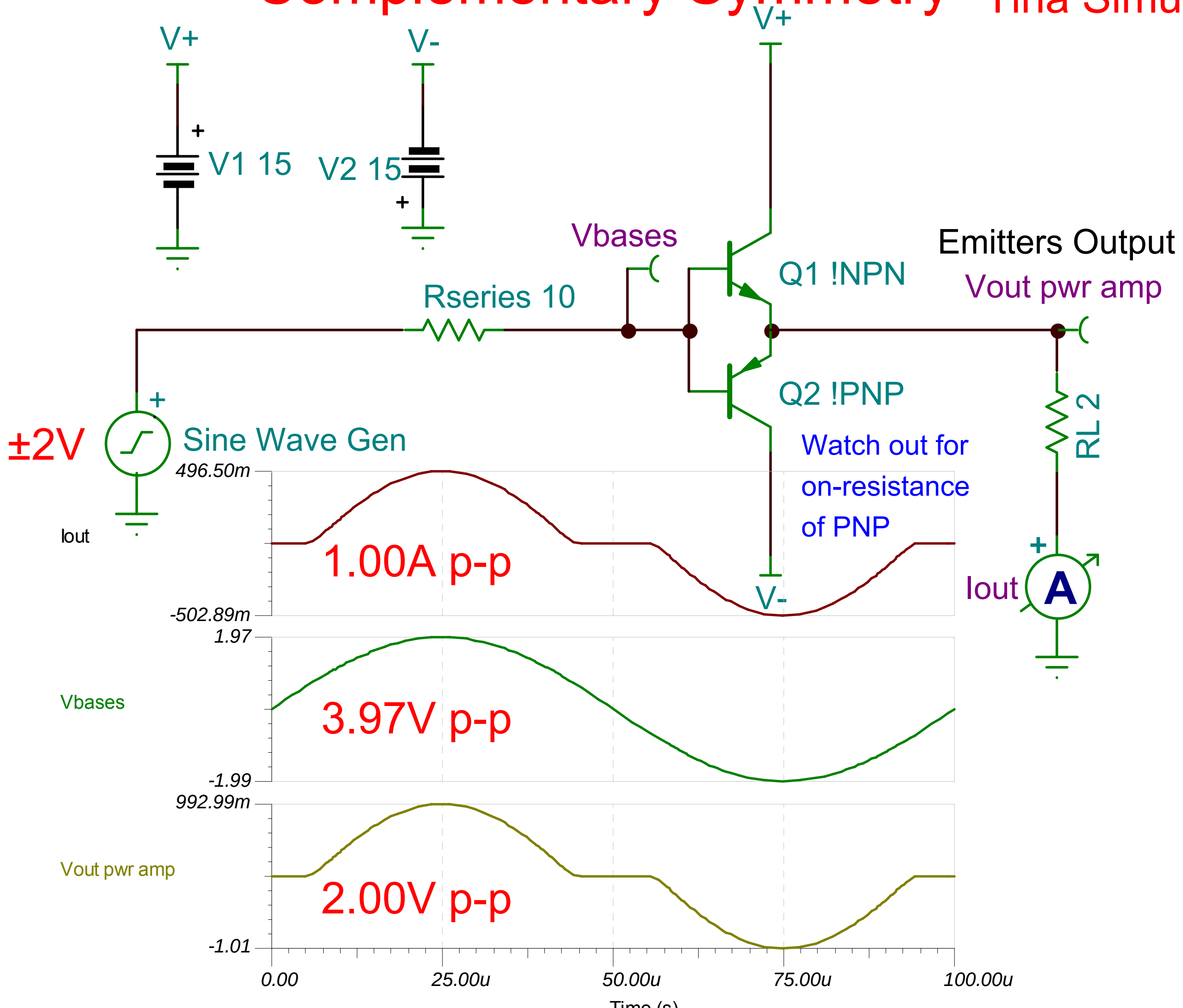
John Brown, 9/12/006

# Essential Diodes / Transistors

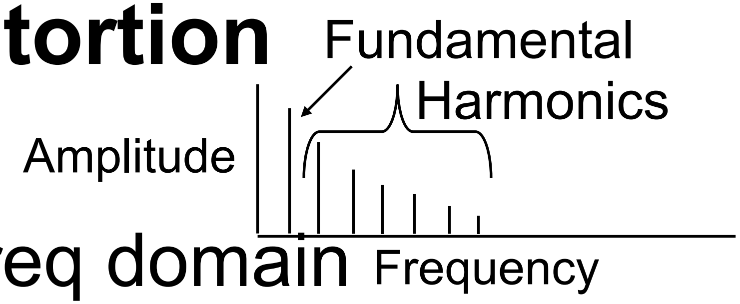
## Power Output Stage, Class C

## Complementary Symmetry

Tina Simulation



# Power Op Amps
## Crossover Distortion

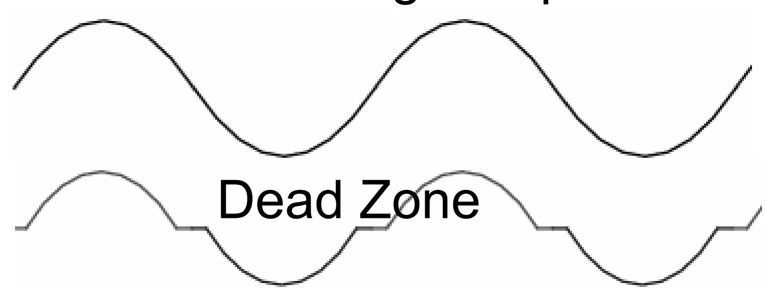



1. Harmonic Distortion – time/freq domain

Appearance - collective frequencies (Fourier Series)

Consequence - harsh sounding audio signals or errors in analyzing spectral purity

Nice looking and pure




2. Dead Band – time domain

Appearance – fast change in signal level, oscillations, hunting

Consequence – servo systems going in the wrong direction

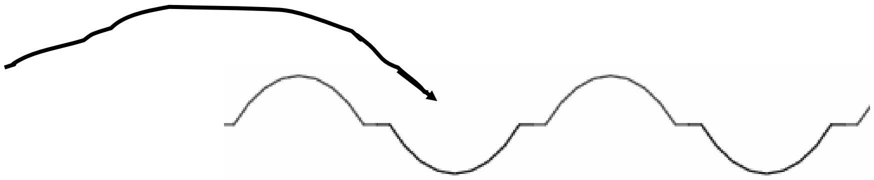
# Power Op Amps
# Crossover Distortion

## 2. Dead Band – time domain

Usually expressed as % of Span.

Unintentional "dead band" problem in electronics can cause control loss or make control loop go in wrong direction.

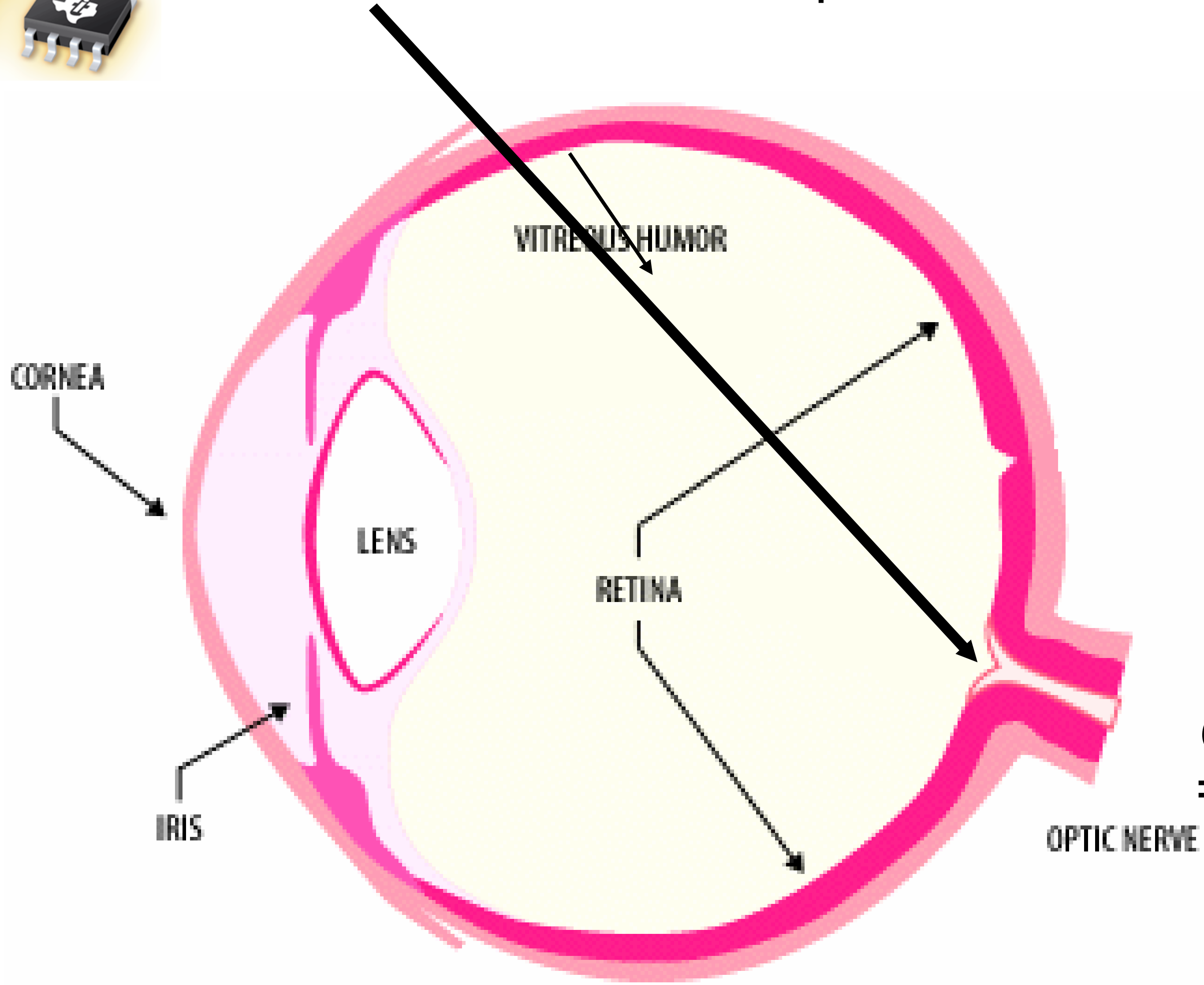
Intentional "dead band" to avoid mechanical valve wear out problem. PID loop calculated output must leave this region before the actual output will change.



Power Amp Dead Zone Can Cause HUNTING,

which is movement back and forth around the set point

# Dead Band or Blind Spot in Human Eye




No Optical Sensors in Retina at Optic Nerve = Blind Spot

# Dead Band or Blind Spot in Human Eye

Directions to find your optical blind spot. Hold head still.

Close Left Eye, focus on letters until black dot disappears

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| a | b | c | d | e | f | g | h |
| i | j | k | l | m | n | o | p |
| q | r | s | t | u | v | w | x |

Close Right Eye, focus on letters until black dot disappears

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| h | g | f | e | d | c | d | a |
| p | o | n | m | l | k | j | i |
| x | w | v | u | t | s | r | q |

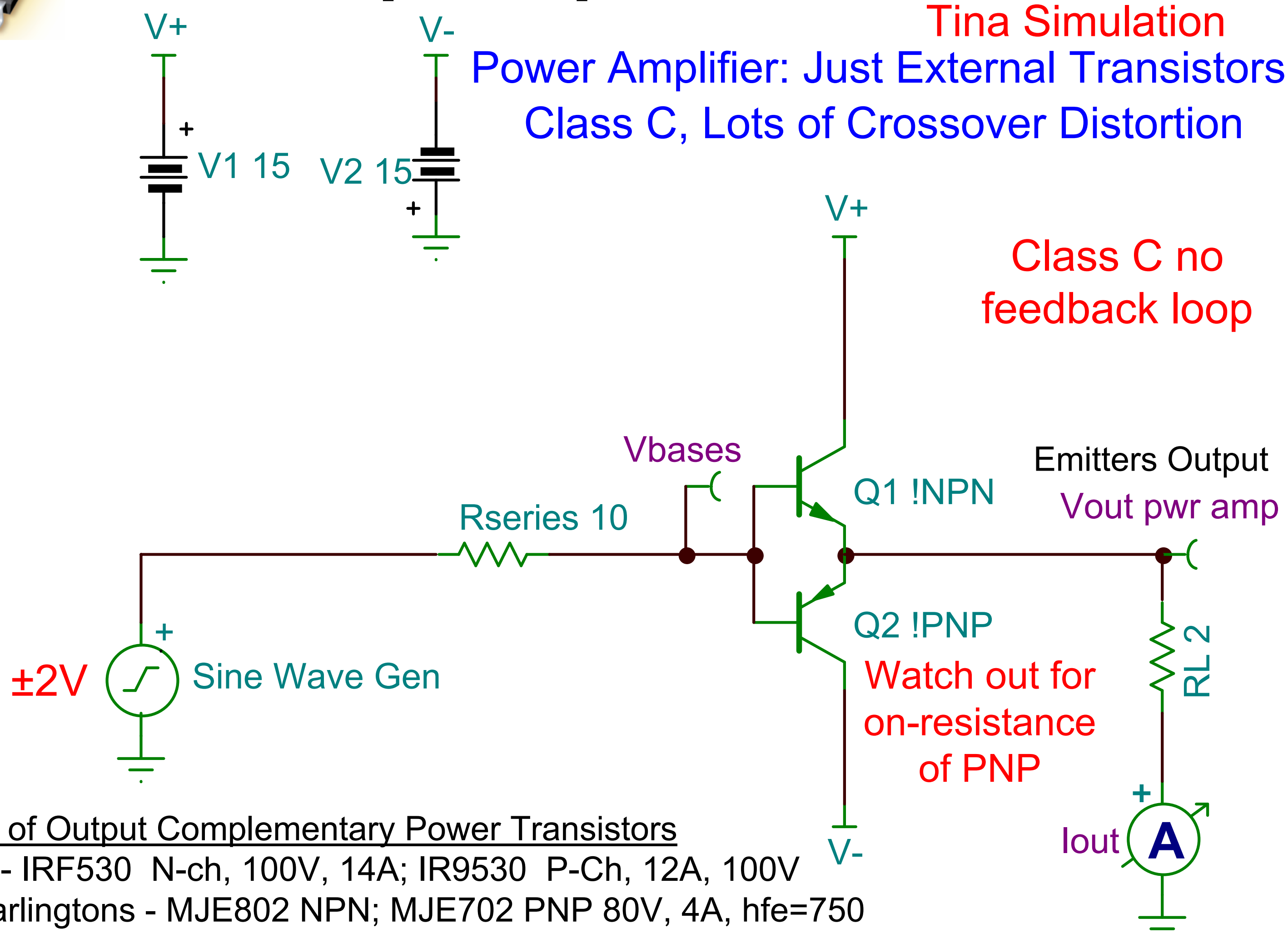
By moving head back and forth you can "HUNT" for spot.

# Power Op Amps - Crossover Distortion

Tina Simulation

Power Amplifier: Just External Transistors, No Diodes

Class C, Lots of Crossover Distortion JMB 5/6/2006




<u>Examples of Output Complementary Power Transistors</u>

MOSFET - IRF530 N-ch, 100V, 14A; IR9530 P-Ch, 12A, 100V

Bipolar Darlingtons - MJE802 NPN; MJE702 PNP 80V, 4A, hfe=750

Bipolar Darlingtons-2N2219+3055; 2N2907+2955, 60V,15A,hfeT>1000

Bipolar FZT851 NPN (6A,200V); FZT951 PNP (5A,100V), hfe=100 ZTEX

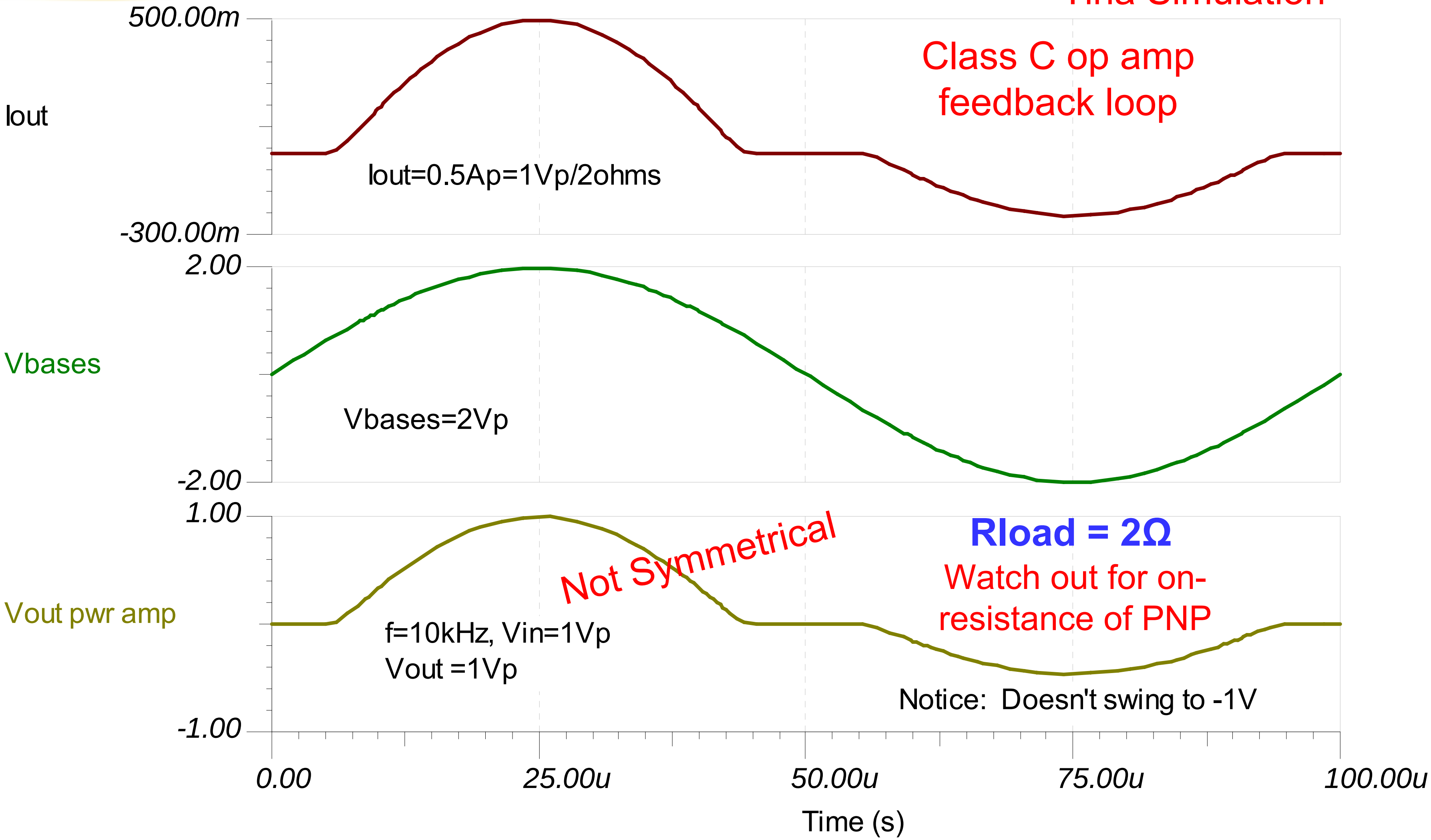
# Power Amplifier: Just External Transistors, No Diodes

## Class C, Lots of Crossover Distortion

JMB 5/6/2006

# Power Op Amps - Crossover Distortion

Tina Simulation



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## Class C, Lots of Crossover Distortion

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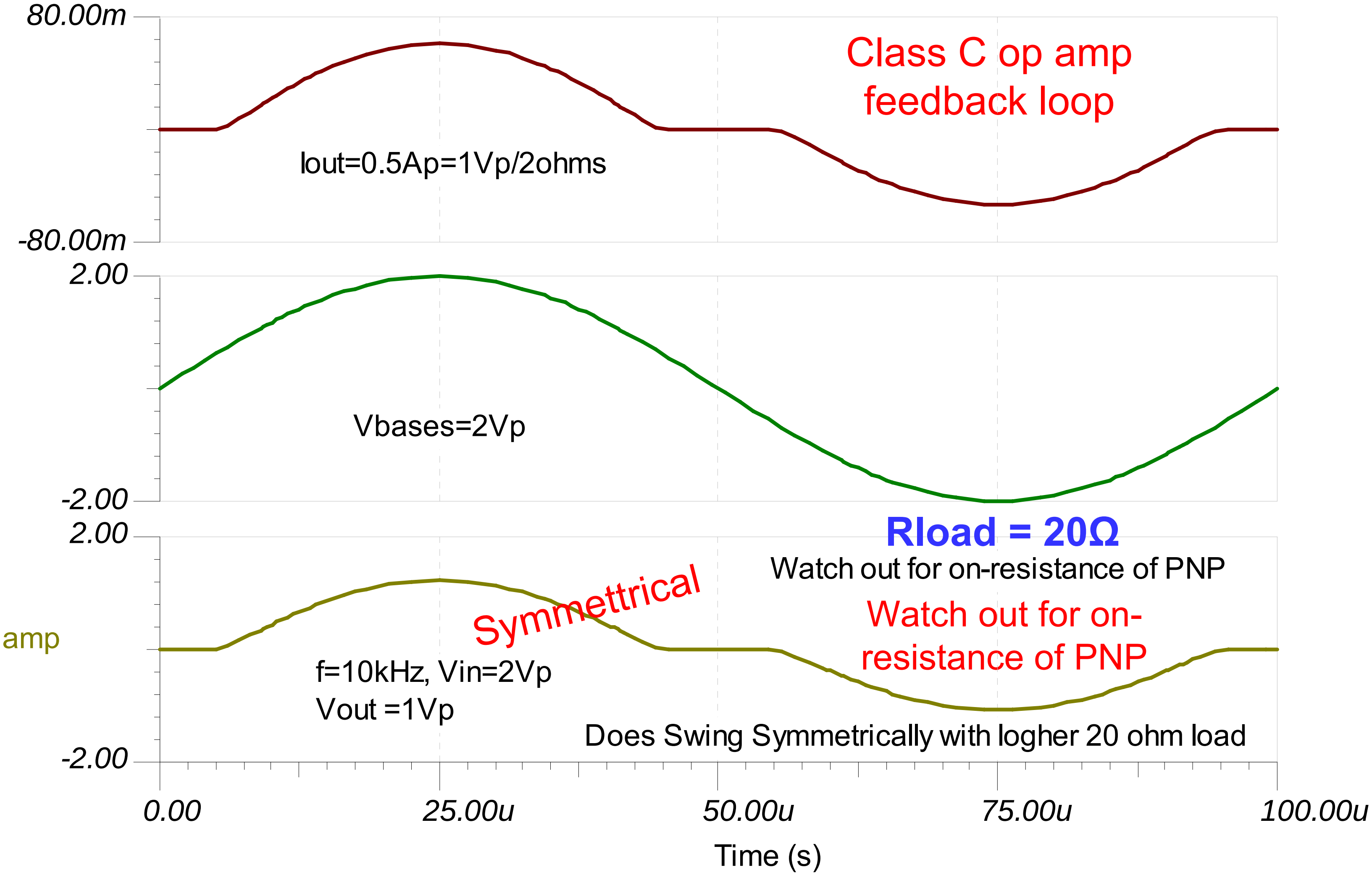
# Power Op Amps - Crossover Distortion

Tina Simulation



# Power Op Amps

## Little ro (static & dynamic)

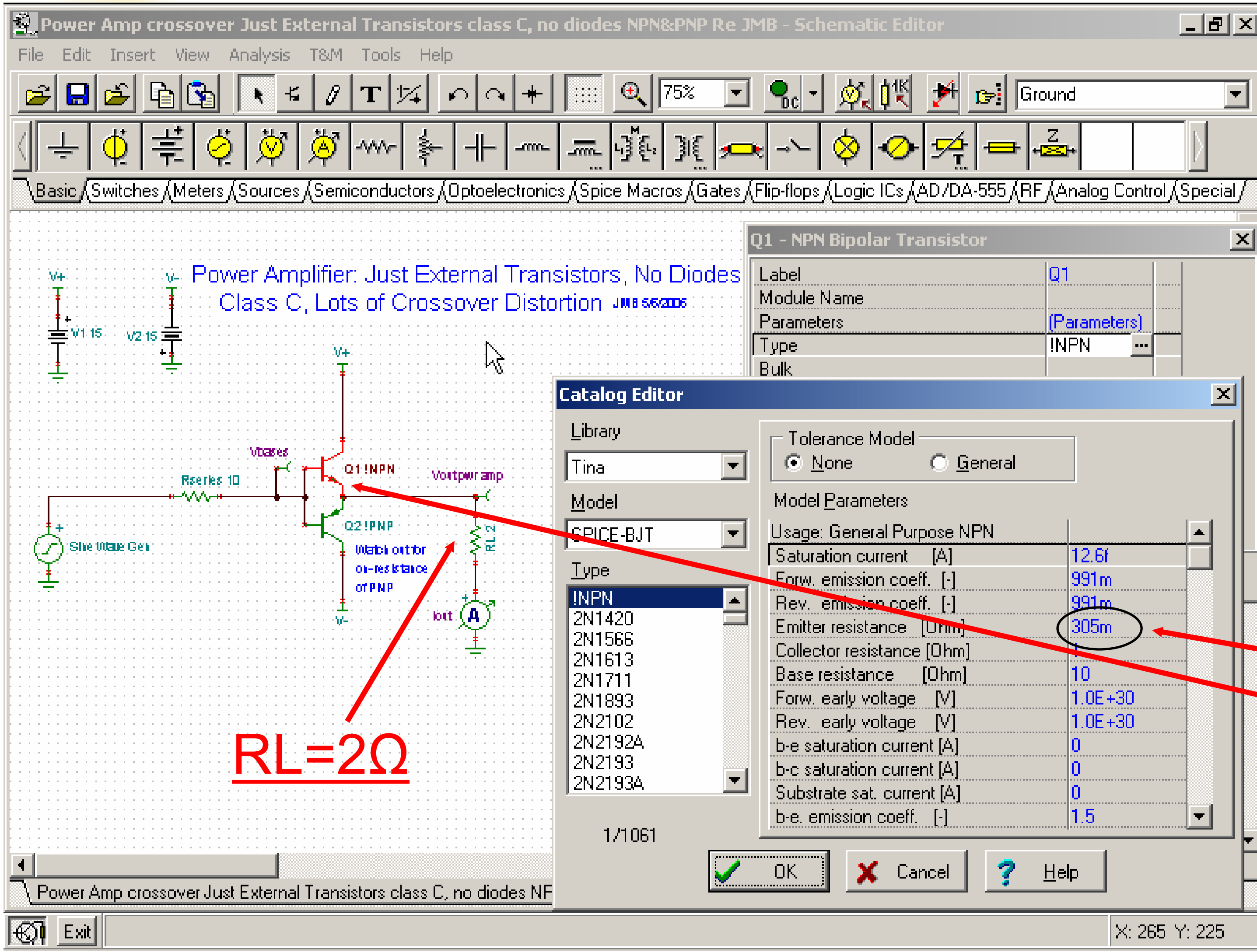
Essential Principles

Output Resistance

(See Tim Green's Presentation)

Power Amplifier: Just External Transistors, No Diodes
Class C, Lots of Crossover Distortion JMB 5/6/2006

# Power Op Amps - Crossover Distortion




Tina Simulation

Class C no feedback loop

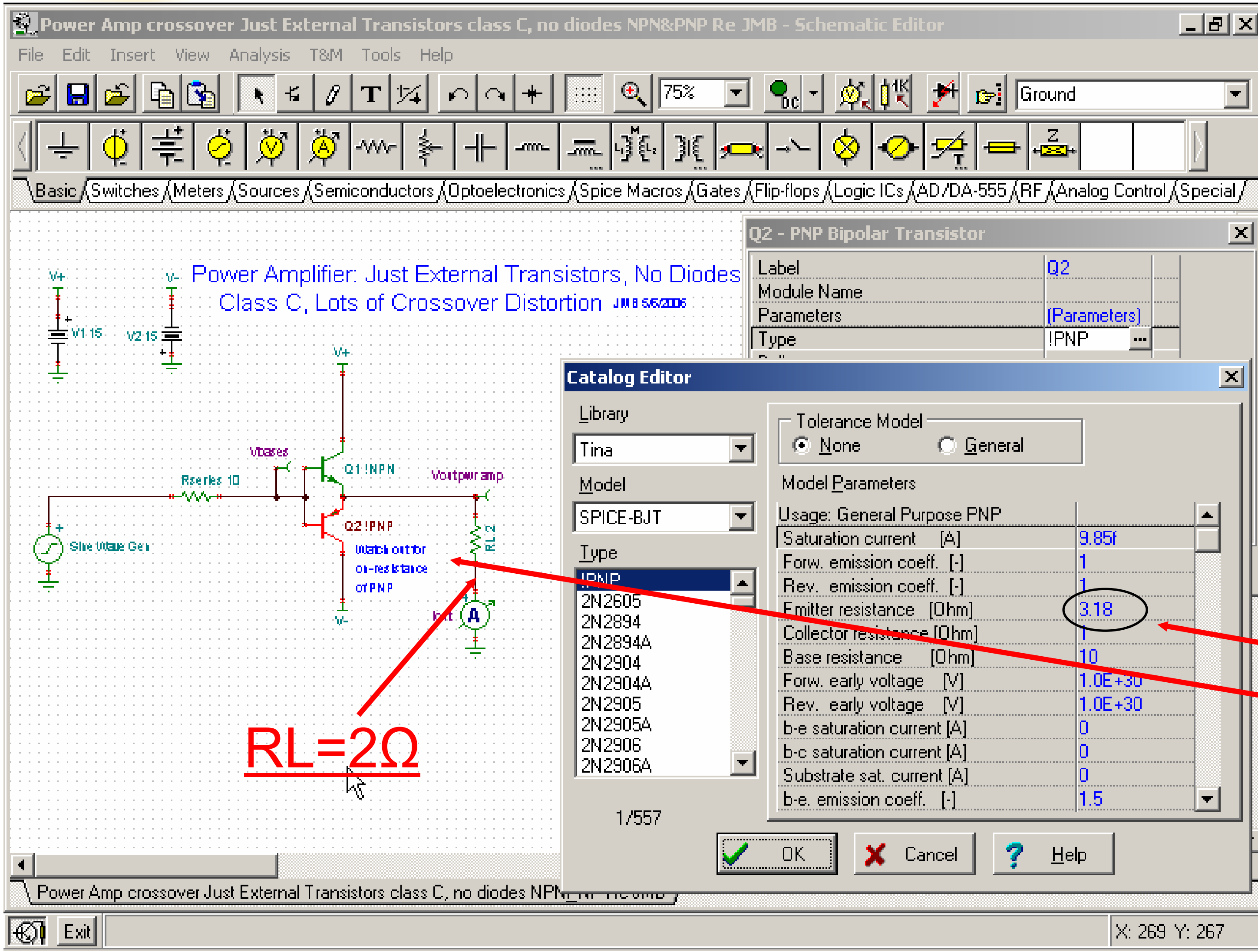
NPN Remitter

Watch out for on-resistance of PNP

Re=0.305Ω in Simulator

Power Amplifier: Just External Transistors, No Diodes
Class C, Lots of Crossover Distortion JMB 5/6/2006

# Power Op Amps - Crossover Distortion




Tina Simulation

Class C no feedback loop

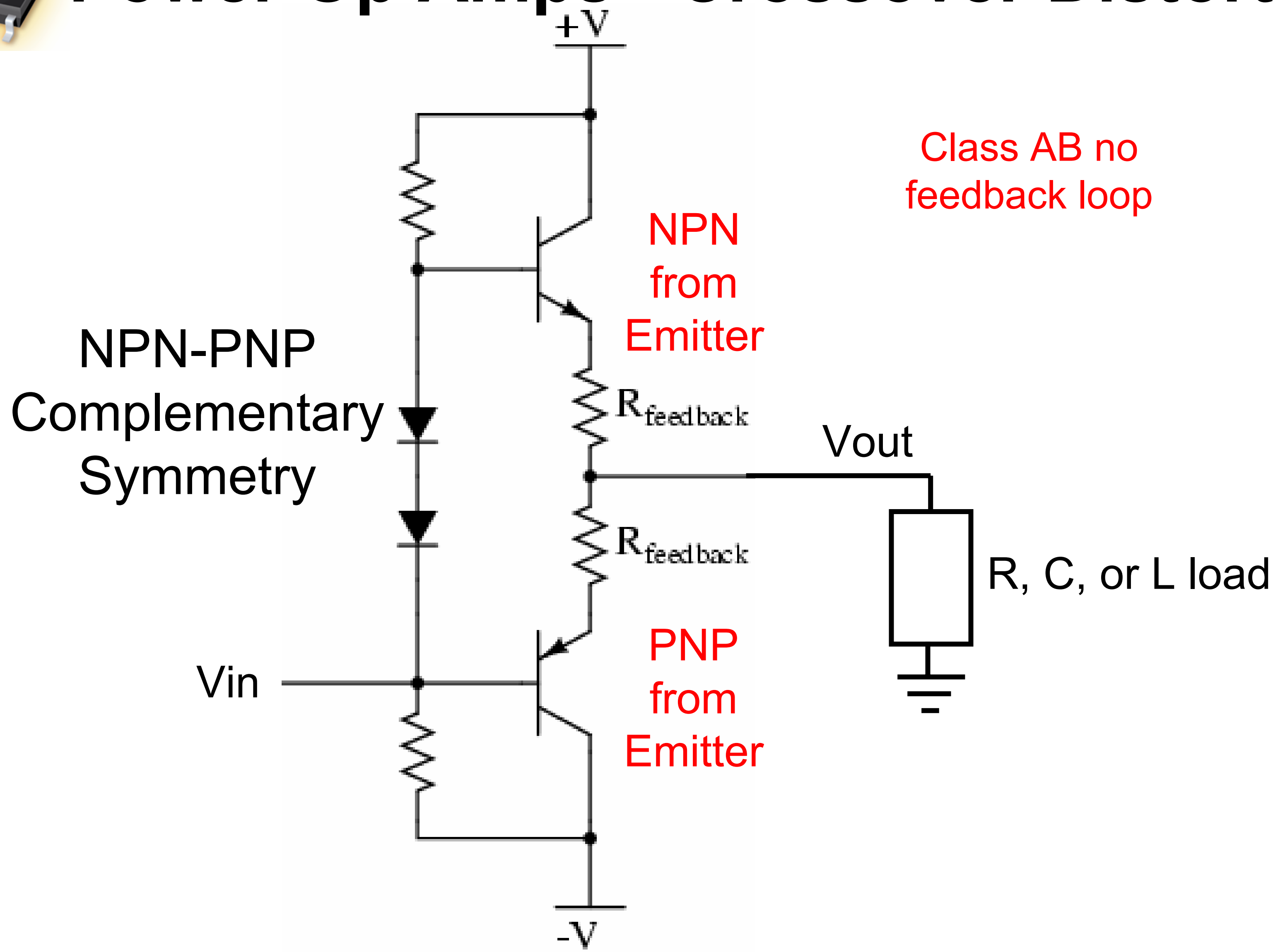
PNP Remitter

Watch out for on-resistance of PNP

Re=3.18Ω in Simulator

Lot's or Ro

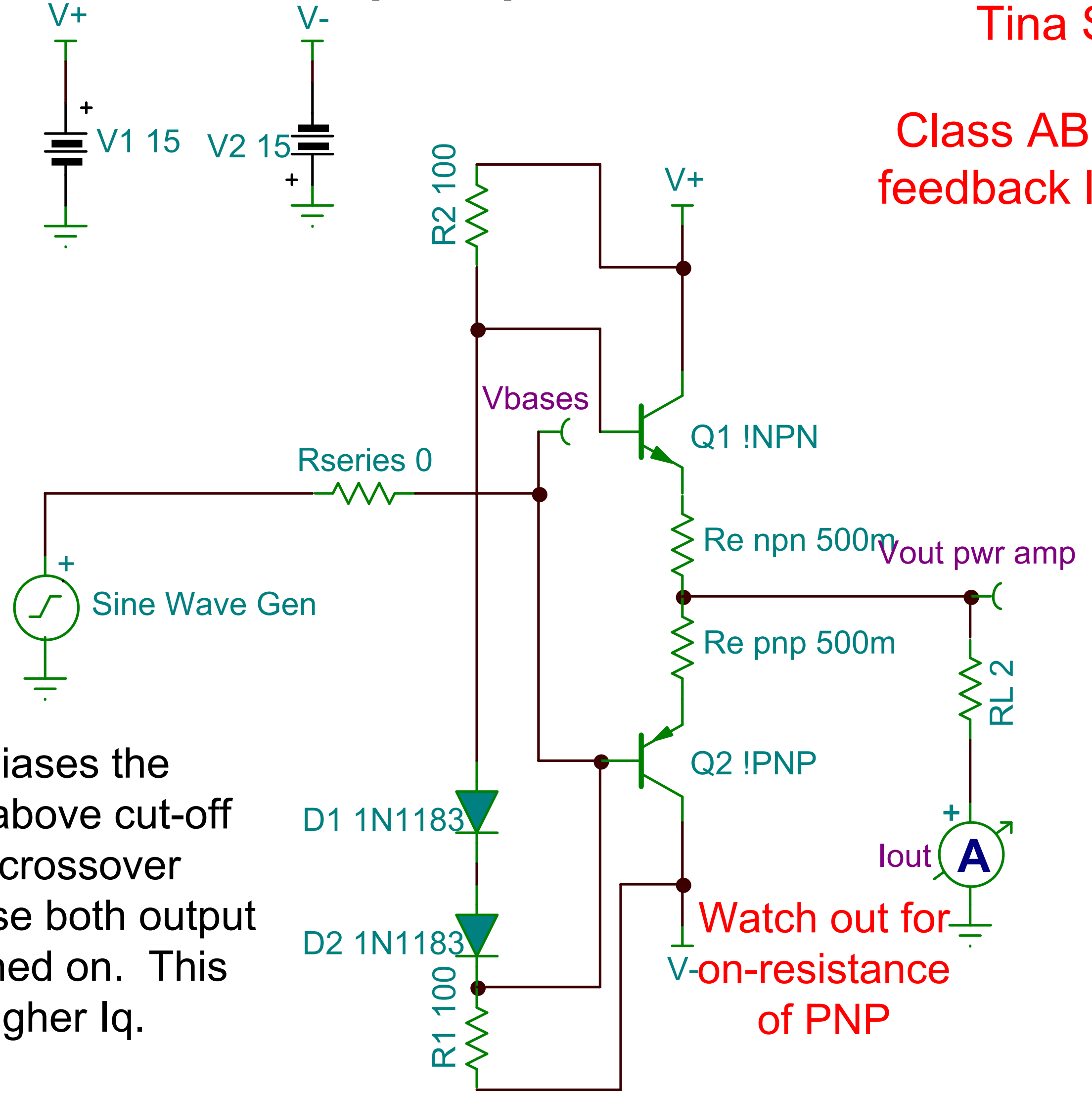
# Power Op Amps - Crossover Distortion



Power Amplifier: Just External Transistors, 2 Diodes & Remitters
Class AB, Less Crossover Distortion JMB 5/6/2006

# Power Op Amps - Crossover Distortion

Tina Simulation



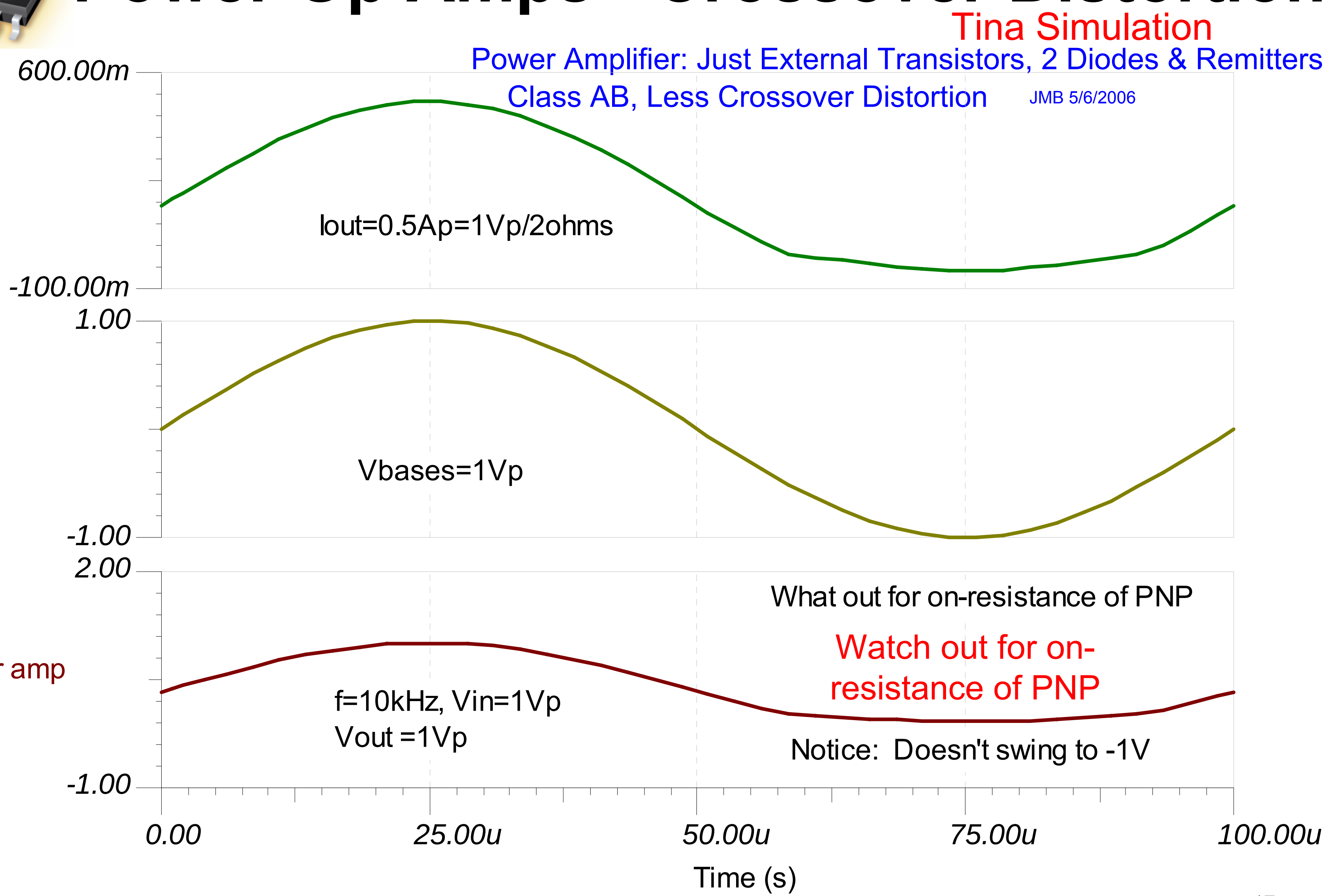

Class AB no feedback loop

±1V

This circuit biases the transistors just above cut-off and reduces crossover distortion, because both output devices are turned on. This results in higher Iq.

Watch out for on-resistance of PNP

# Power Op Amps - Crossover Distortion



# Power Amplifier: Just External Transistors, 2 Diodes & Remitters & Vbe Mul

## Class AB, Less Crossover Distortion

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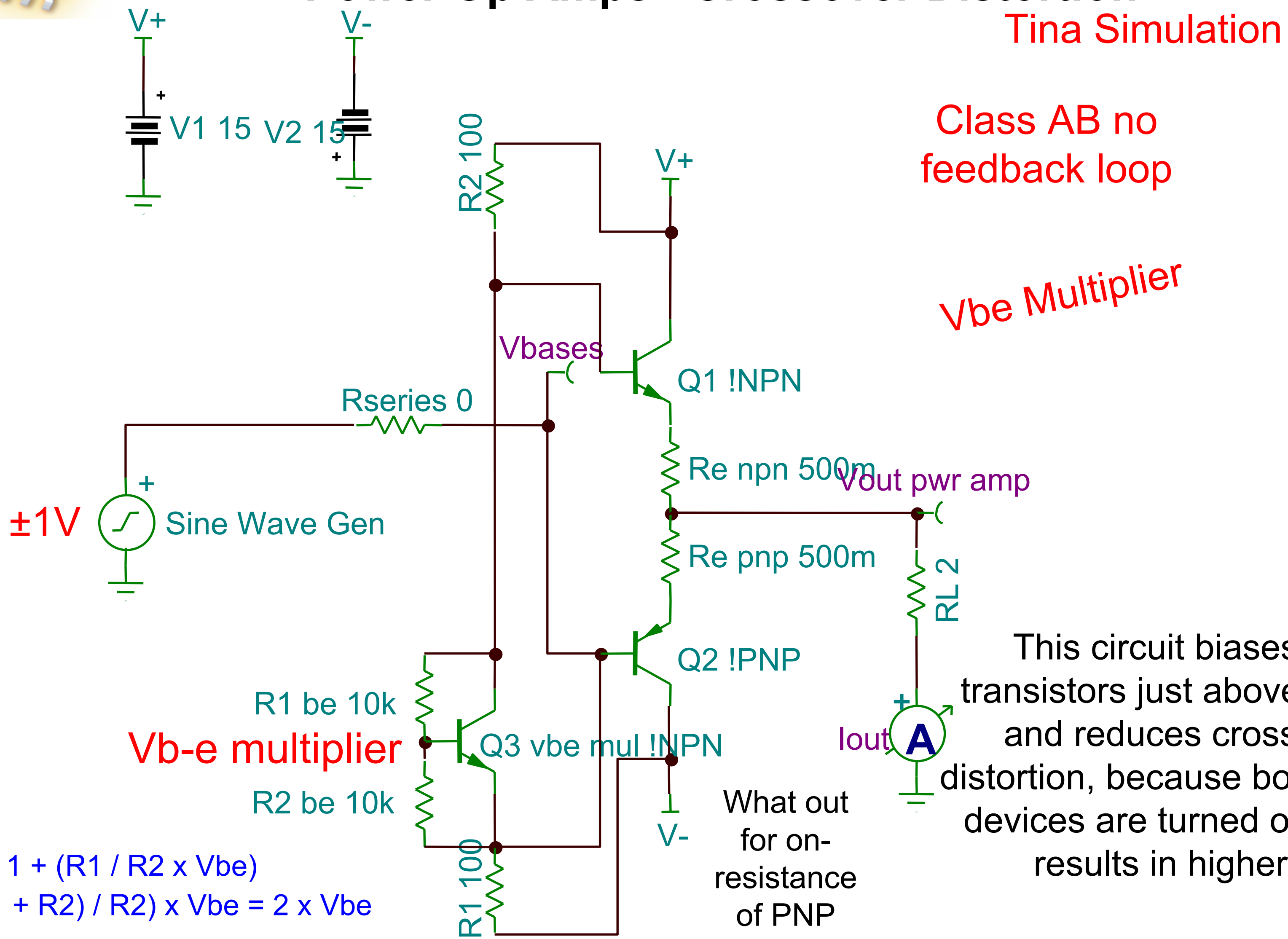
# Power Op Amps - Crossover Distortion

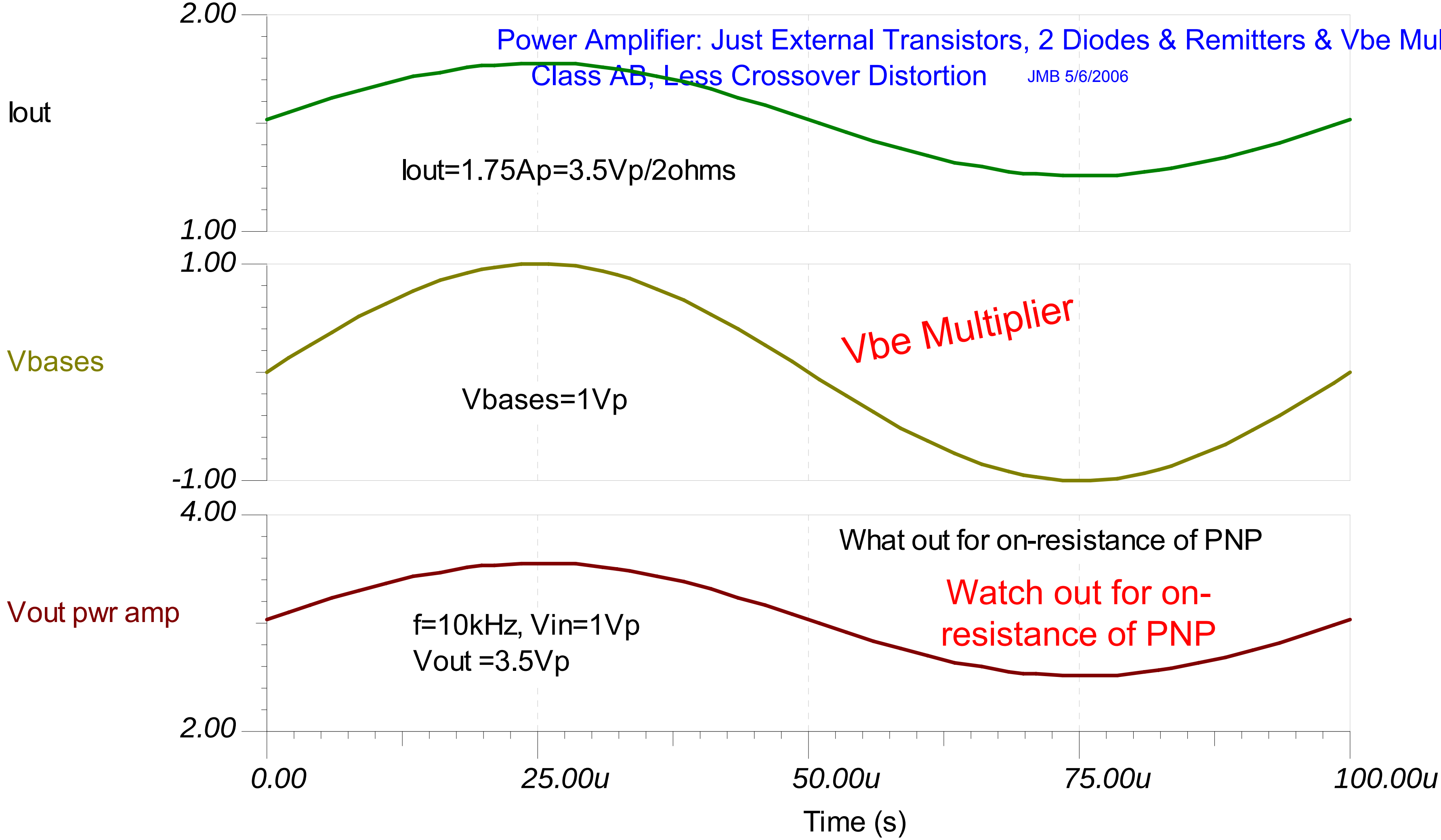



This circuit biases the transistors just above cut-off and reduces crossover distortion, because both output devices are turned on. This results in higher Iq.

Vce = 1 + (R1 / R2 x Vbe)
= ((R1 + R2) / R2) x Vbe = 2 x Vbe

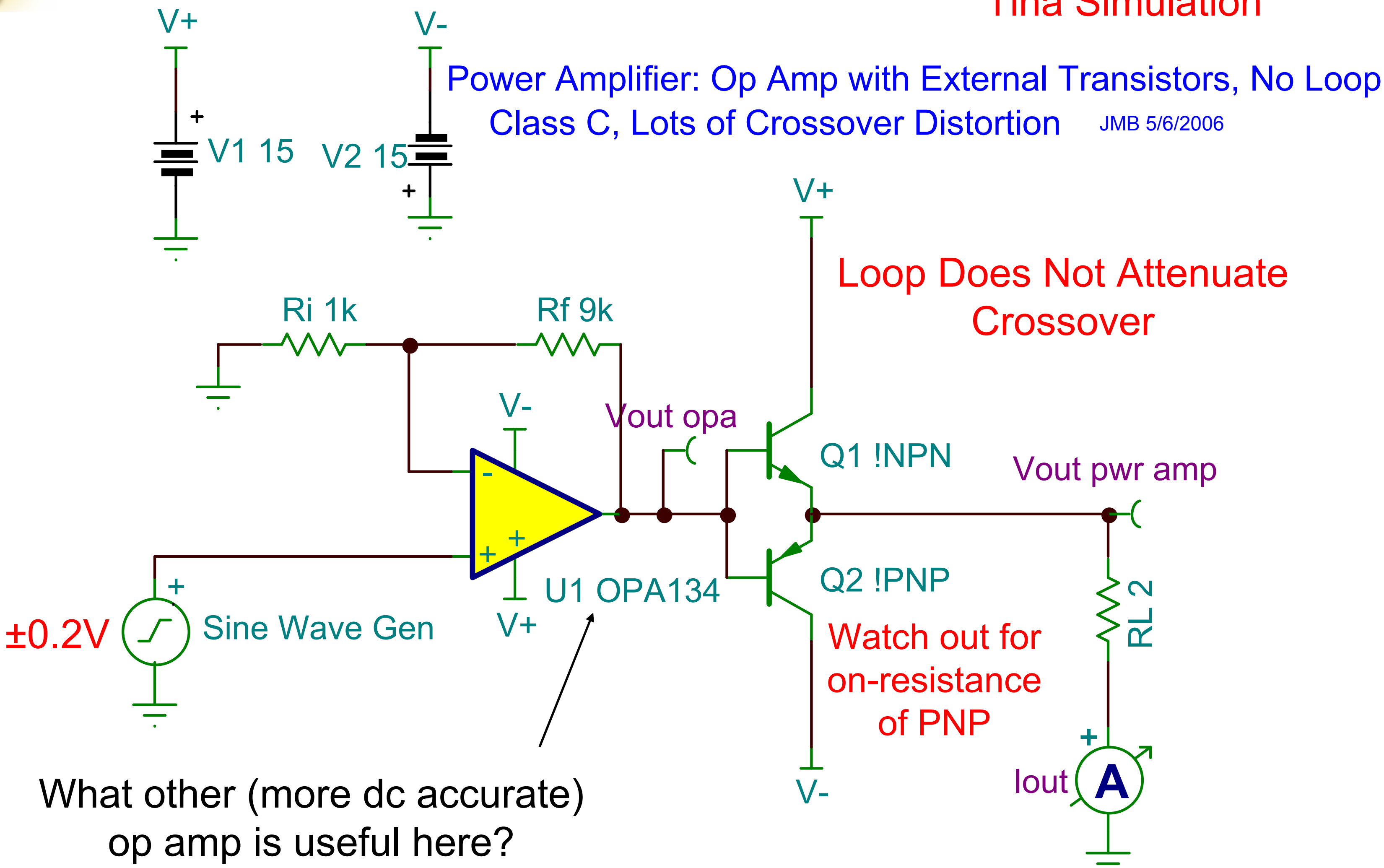
# Power Op Amps - Crossover Distortion

Tina Simulation



# Power Op Amps - Crossover Distortion

Tina Simulation




What other (more dc accurate) op amp is useful here?

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# Power Amplifier: Op Amp with External Transistors, No Loop
## Class C, Lots of Crossover Distortion

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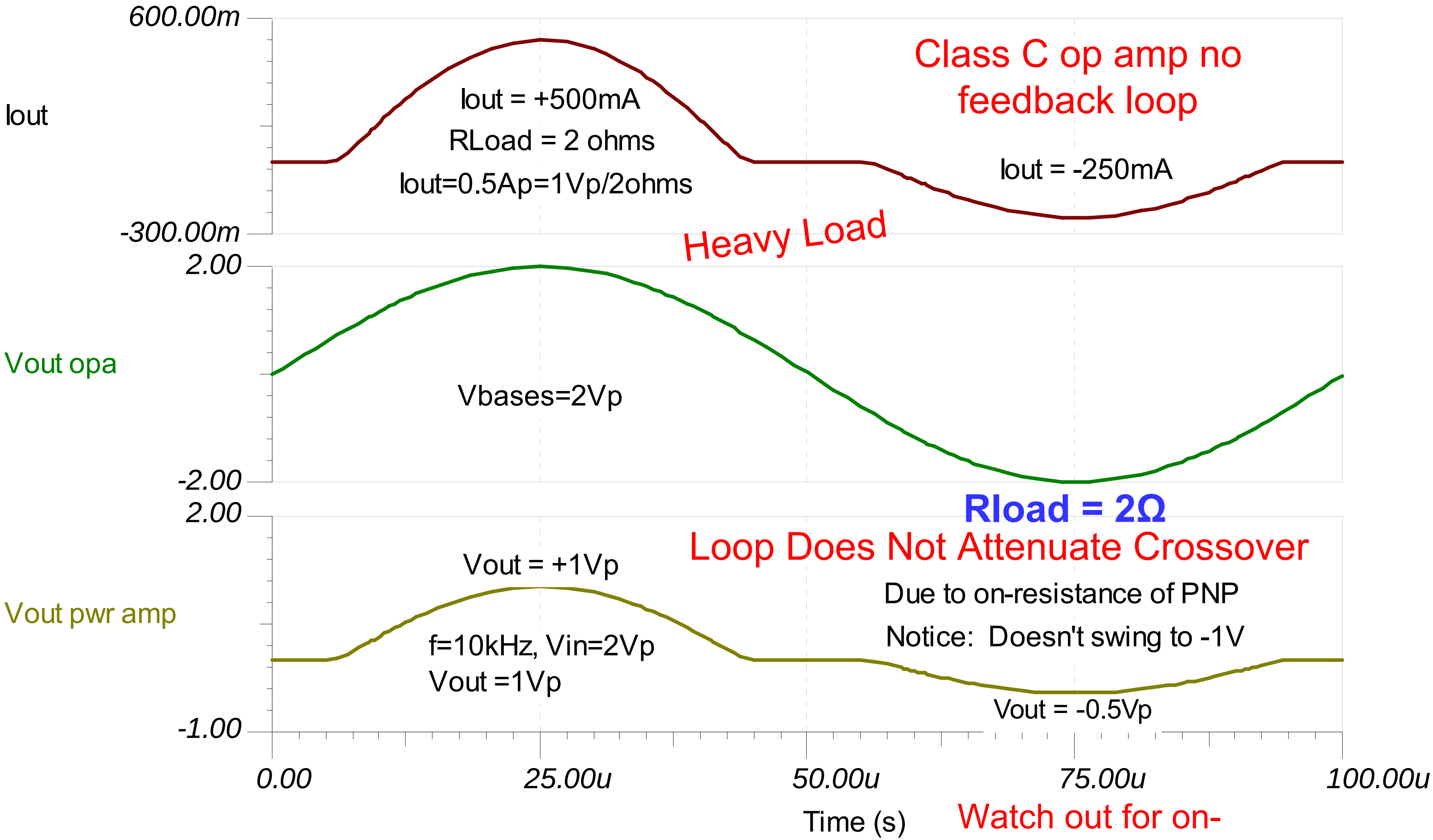
# Power Op Amps - Crossover Distortion

Tina Simulation




Watch out for on-resistance of PNP

# Power Amplifier: Op Amp with External Transistors, No Loop
## Class C, Lots of Crossover Distortion

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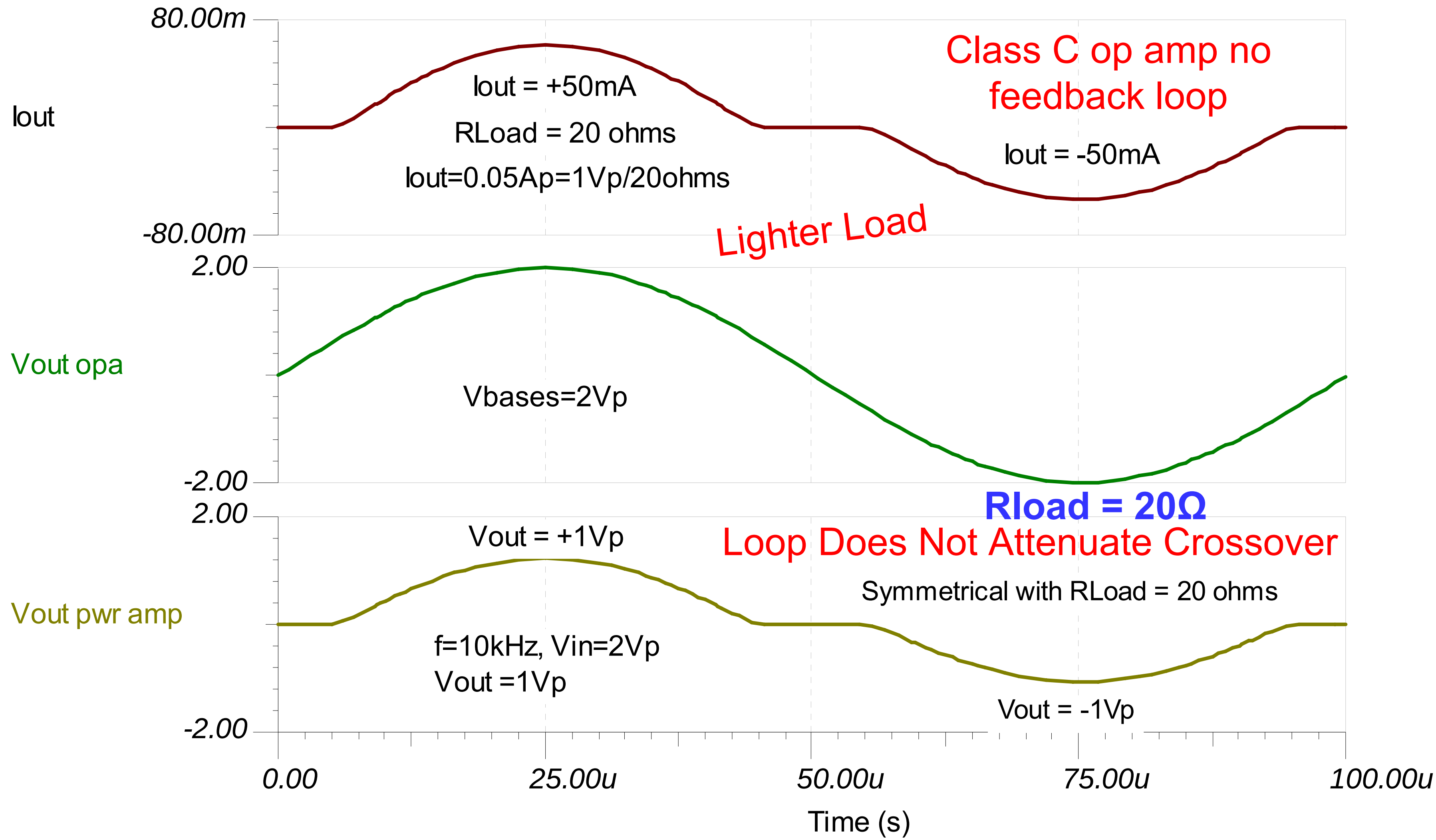
# Power Op Amps - Crossover Distortion

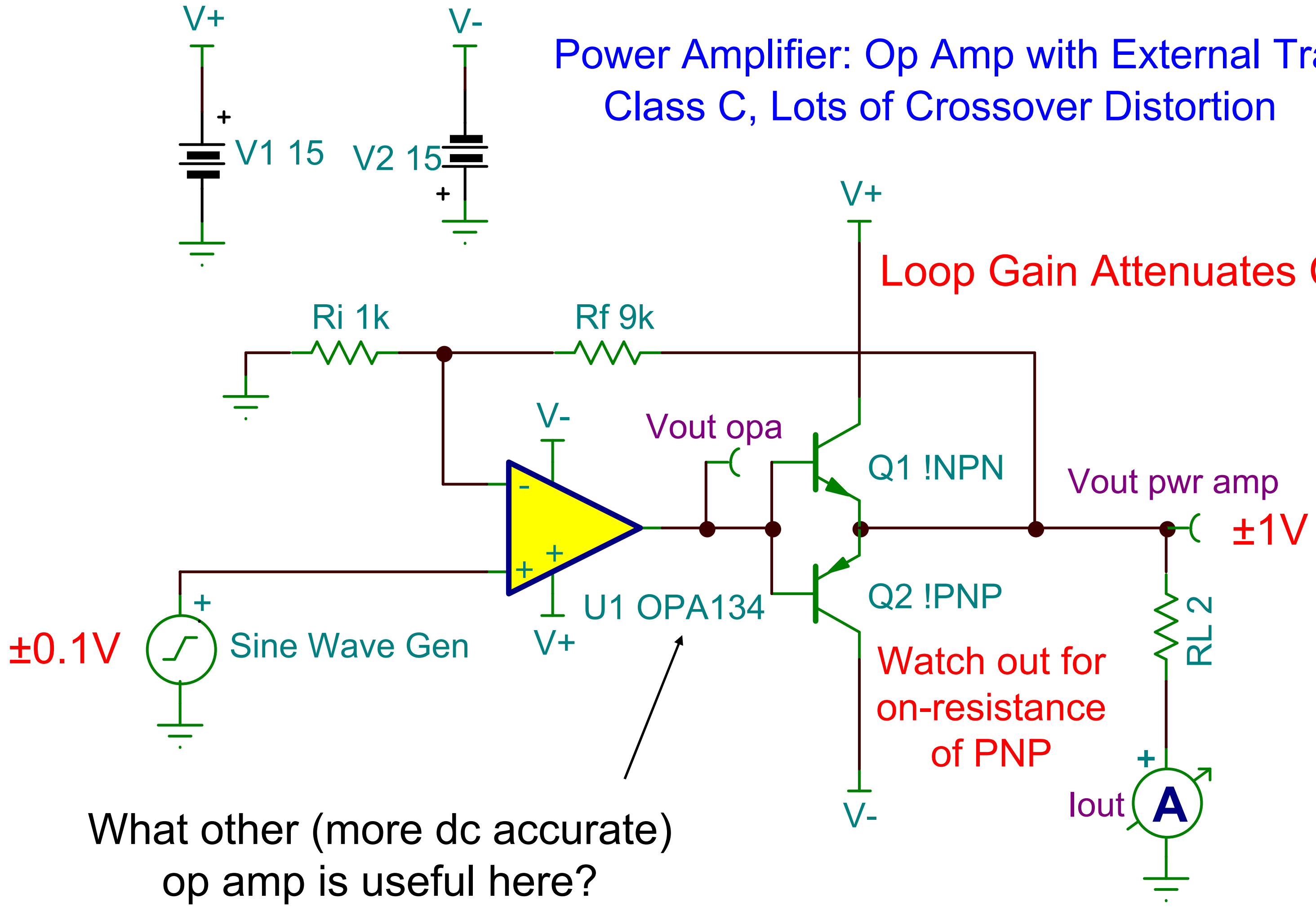
Tina Simulation



# Power Op Amps - Crossover Distortion

Tina Simulation

Power Amplifier: Op Amp with External Transistors
Class C, Lots of Crossover Distortion JMB 5/6/2006

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# Power Op Amps - Crossover Distortion

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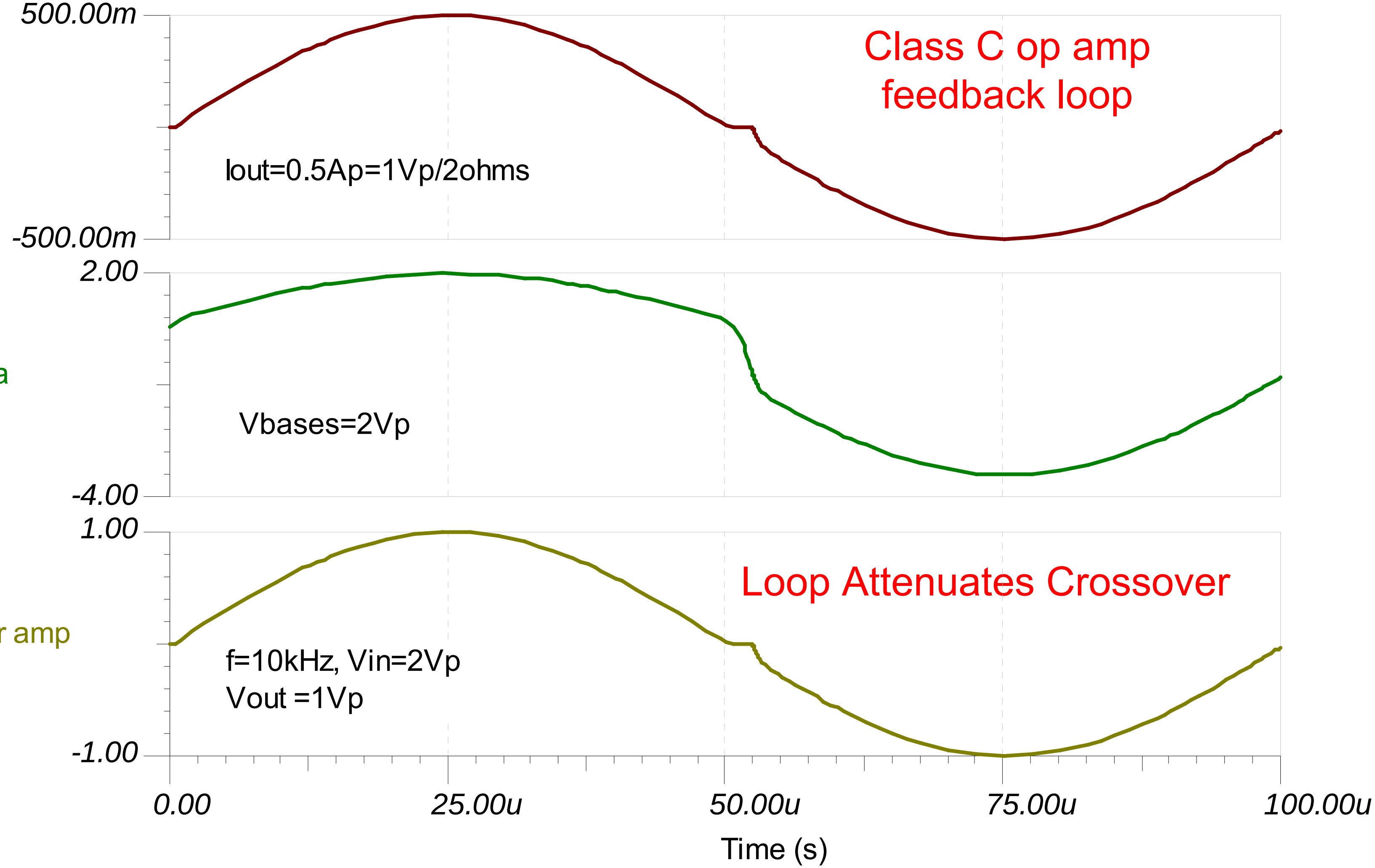
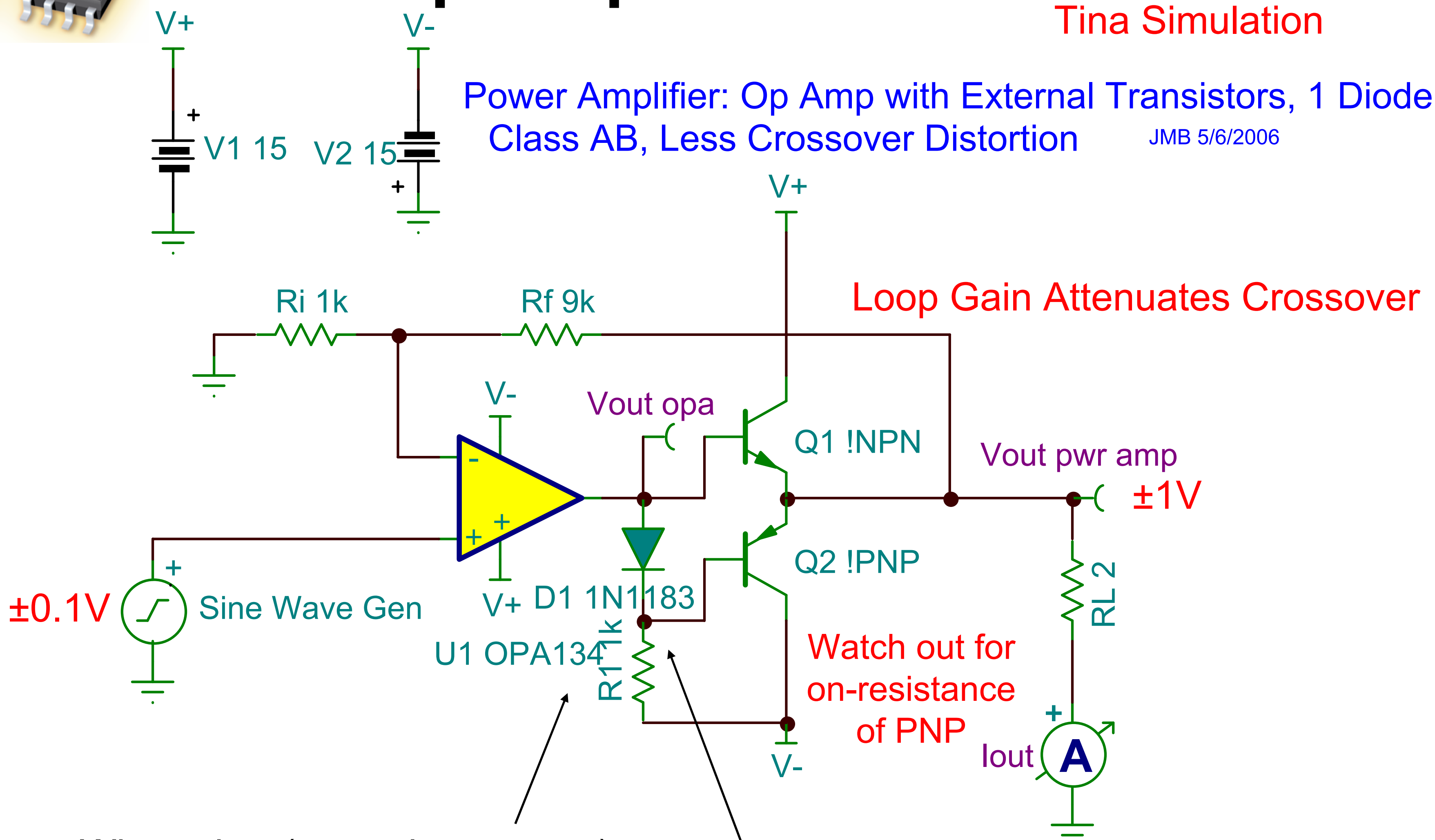


# Power Op Amps - Crossover Distortion

Tina Simulation




What other (more dc accurate) op amp is useful here?

Bias makes only a little difference in crossover, due to loop gain

# Power Amplifier: Op Amp with External Transistors, 1 Diode Class AB, Less Crossover Distortion

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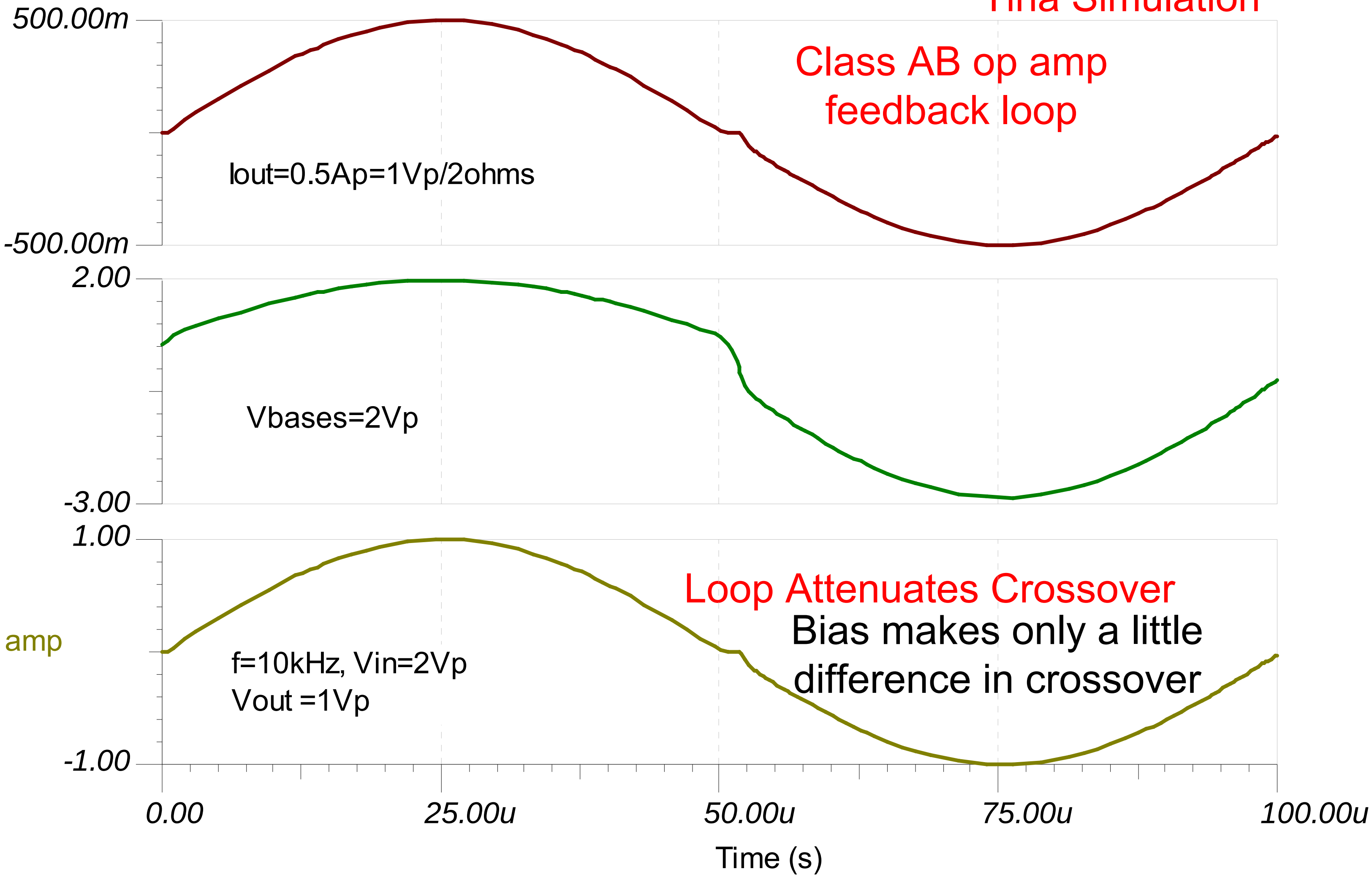
## Power Op Amps - Crossover Distortion

Tina Simulation



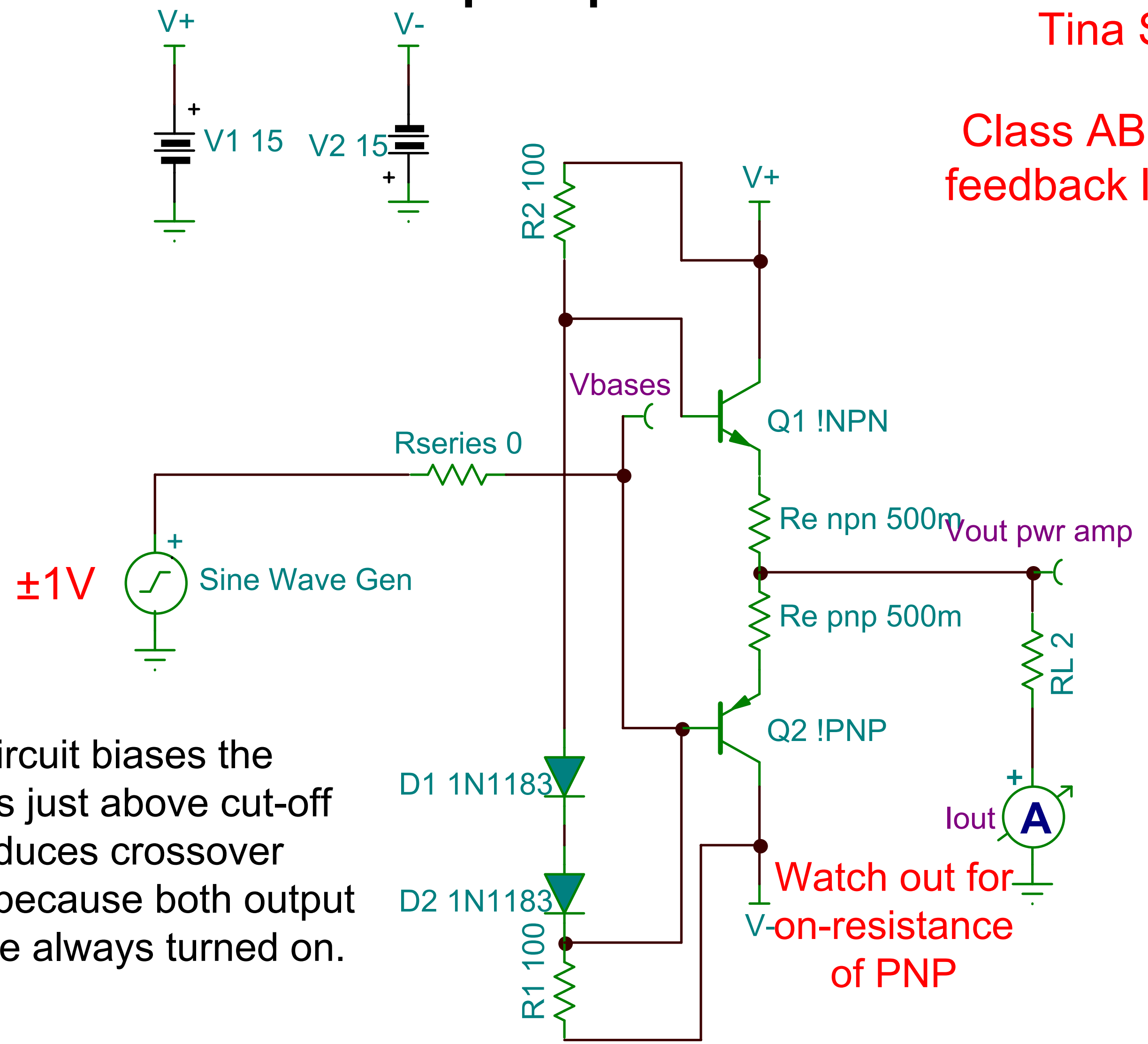
Power Amplifier: Just External Transistors, 2 Diodes & Remitters

Class AB, Less Crossover Distortion JMB 5/6/2006

# Power Op Amps - Crossover Distortion

Tina Simulation

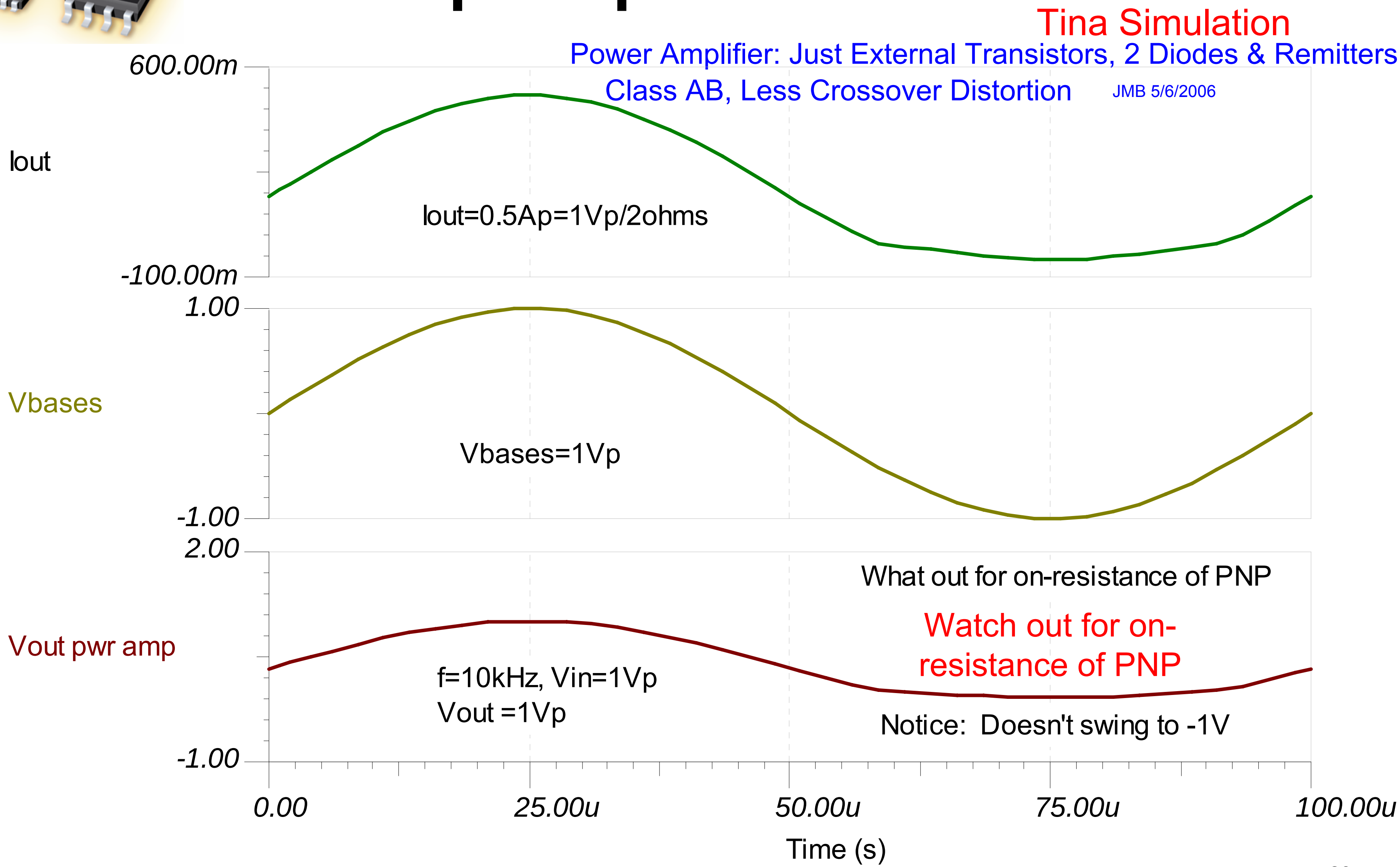
Class AB no feedback loop




Watch out for on-resistance of PNP

This circuit biases the transistors just above cut-off and reduces crossover distortion, because both output devices are always turned on.

# Power Op Amps - Crossover Distortion



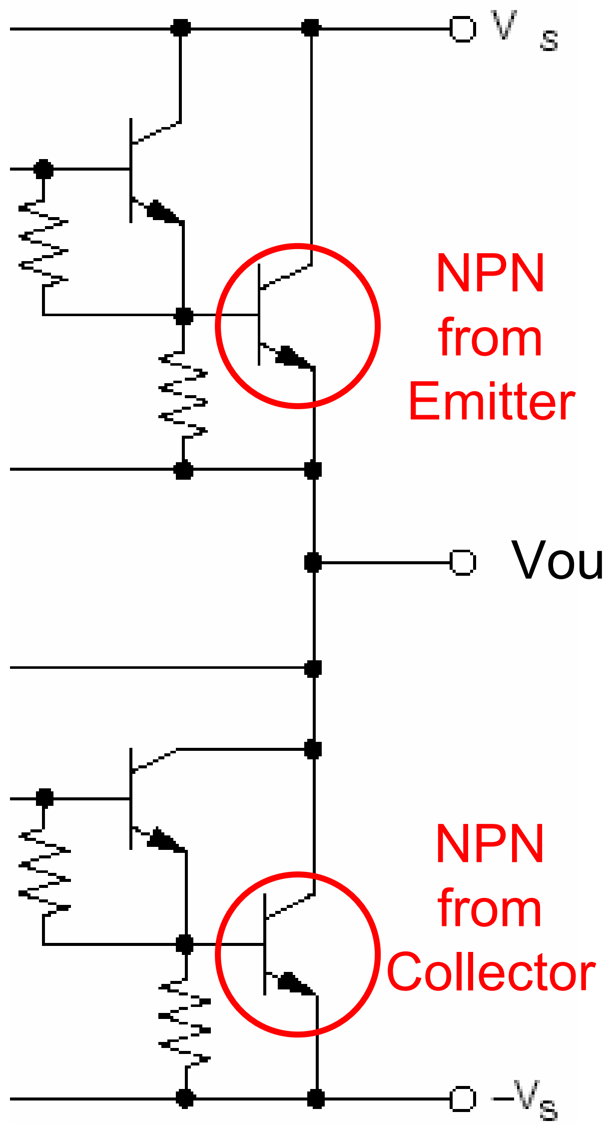
# Power Op Amps

All NPN Power Output Stage

(not NPN-PNP complementary symmetry)

# Power Op Amps – Crossover Distortion

Notice
Darlington
Connection




All NPN Power Output Stage

(not NPN-PNP
complementary symmetry)

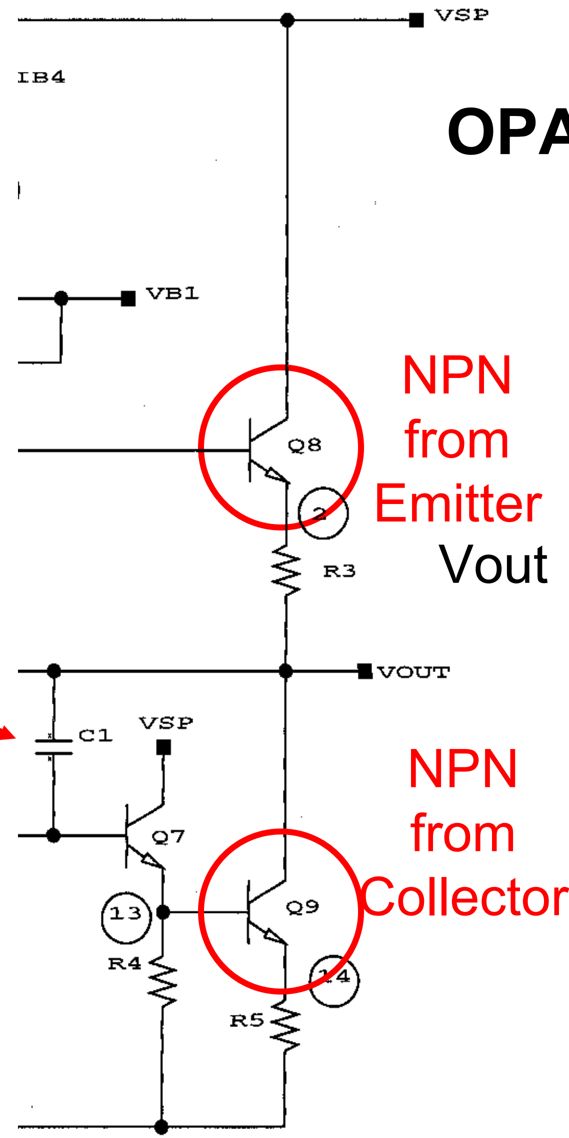
# Power Op Amps – Crossover Distortion

All NPN Power Output Stage (not NPN-PNP complementary symmetry)

**OPA547**

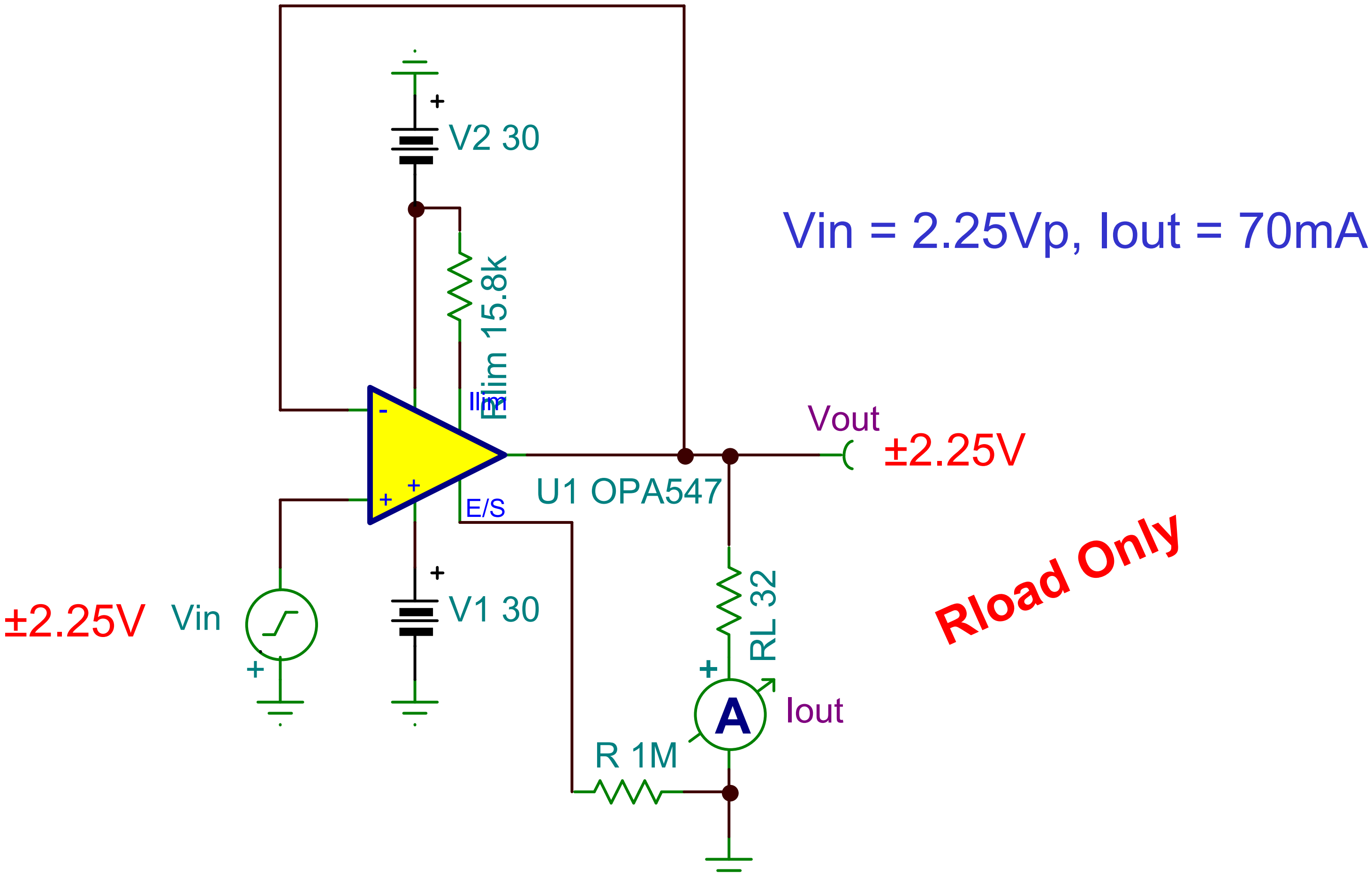
Actually Darlington Connection

**Local Compensation Loop, Independent of Overall Op Amp Compensation**



# OPA547
# Power Op Amp Measurement

OPA547 RLoad = 32 ohms



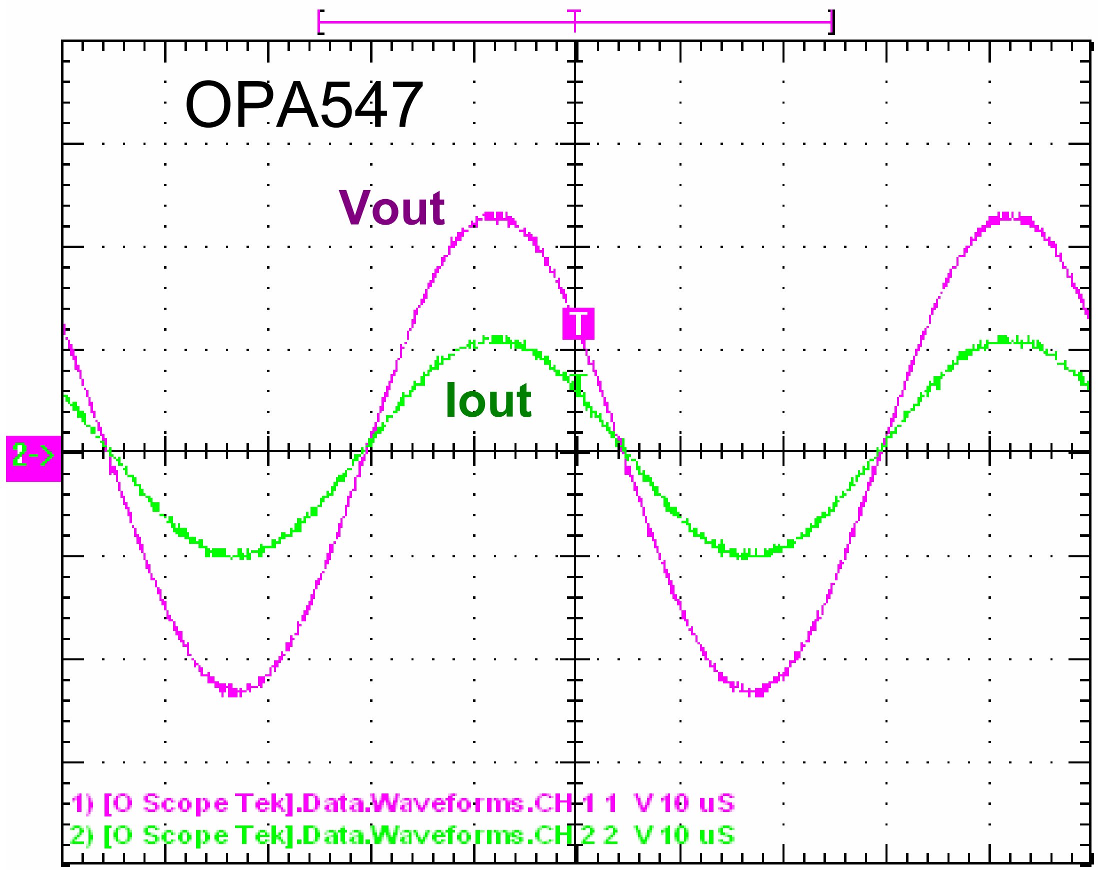
# OPA547
# Power Op Amp Measurement

RLoad = 31.25 ohms, Satisfactory Within OPA547 Bandwidth Limitation

**f = 20kHz**

Green Waveform

Notice output current is in phase with output voltage. The cross-over occurs at Iout = 0 amps, which is at Vout = 0V. The slew rate of 20kHz at 2.25V peak is 0.3V/us. This does not exceed the overall 6V/us in the OPA547 data sheet, and negative slew condition causes very little cross-over. The OPA548 behaves similarly.



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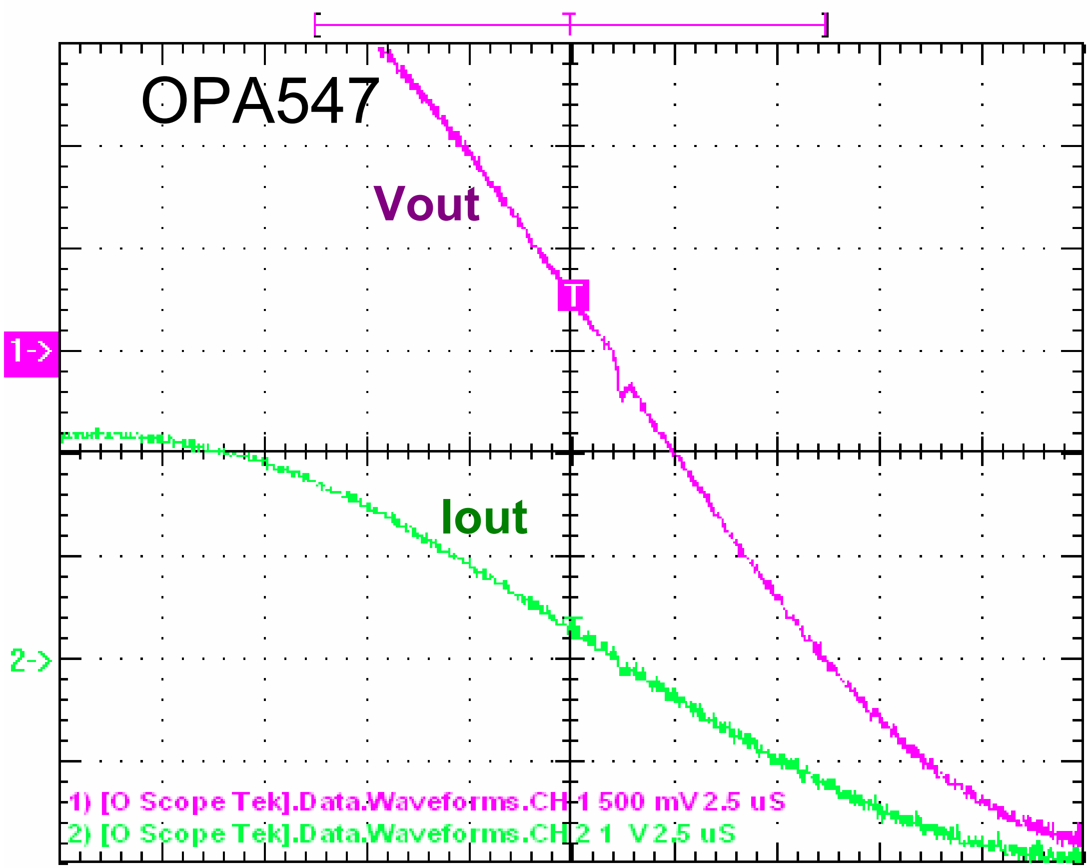

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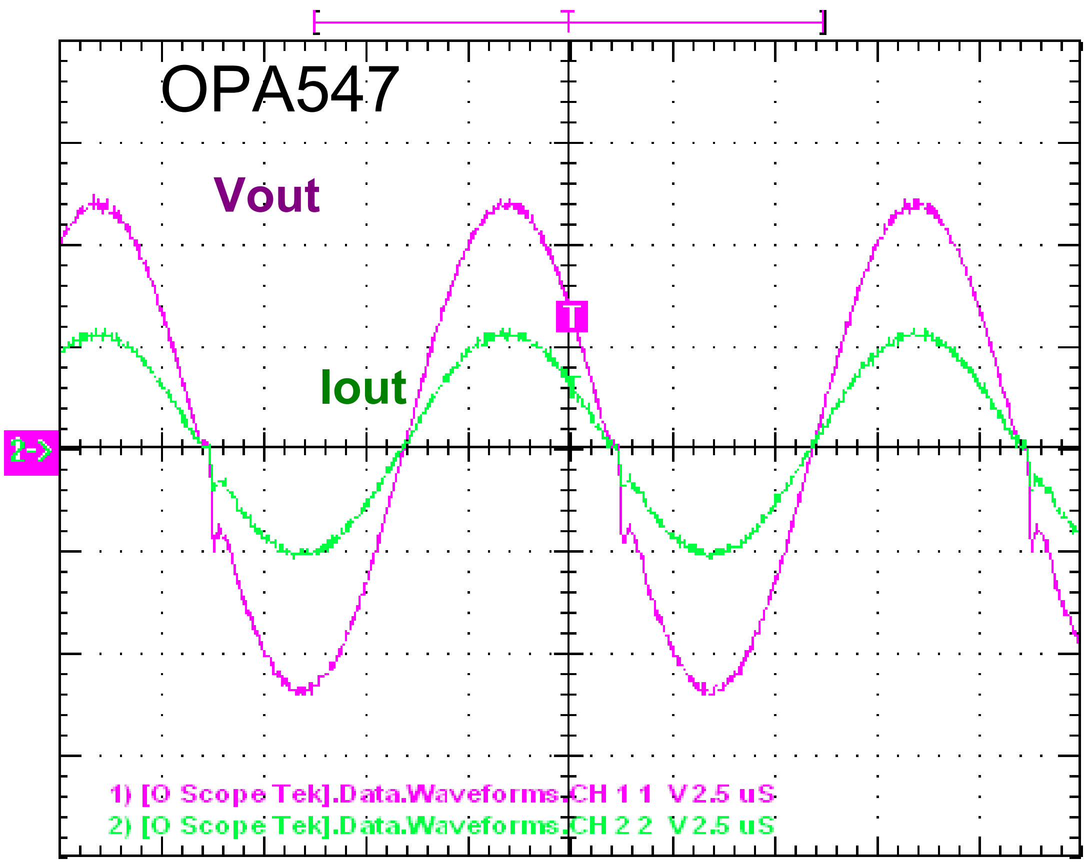
# OPA547
# Power Op Amp Measurement

RLoad = 31.25 ohms, Satisfactory Within OPA547 Bandwidth Limitation

**f = 100kHz**

Green Waveform

Notice output current is in phase with output voltage. The cross-over occurs at Iout = 0 amps, which is at Vout = 0V. The slew rate of 100kHz at 2.25V peak is 1.4V/us. Although this does not exceed the overall 6V/us in the OPA547 data sheet, negative slew condition causes cross-over. The OPA548 behaves similarly.



# OPA547
# Power Op Amp Measurement

RLoad = 31.25 ohms, Satisfactory Within OPA547 Bandwidth Limitation

**f = 100kHz**

Green Waveform

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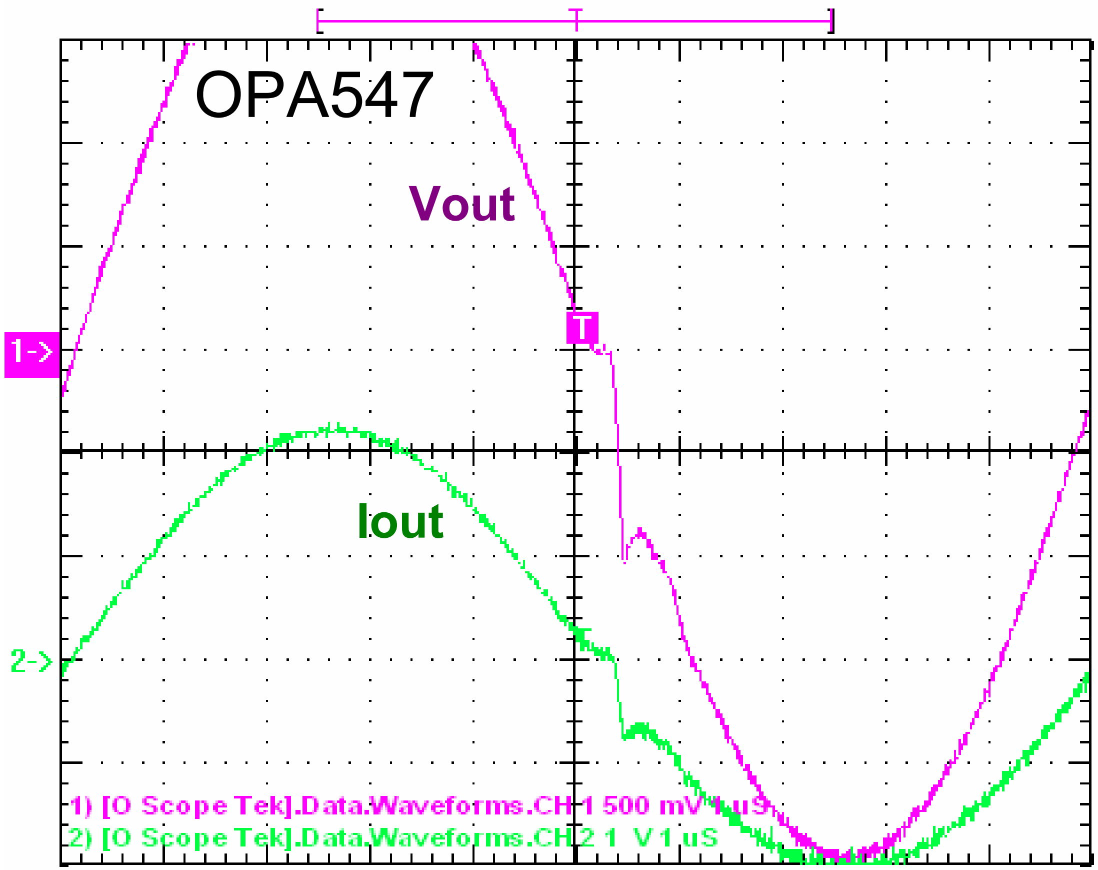
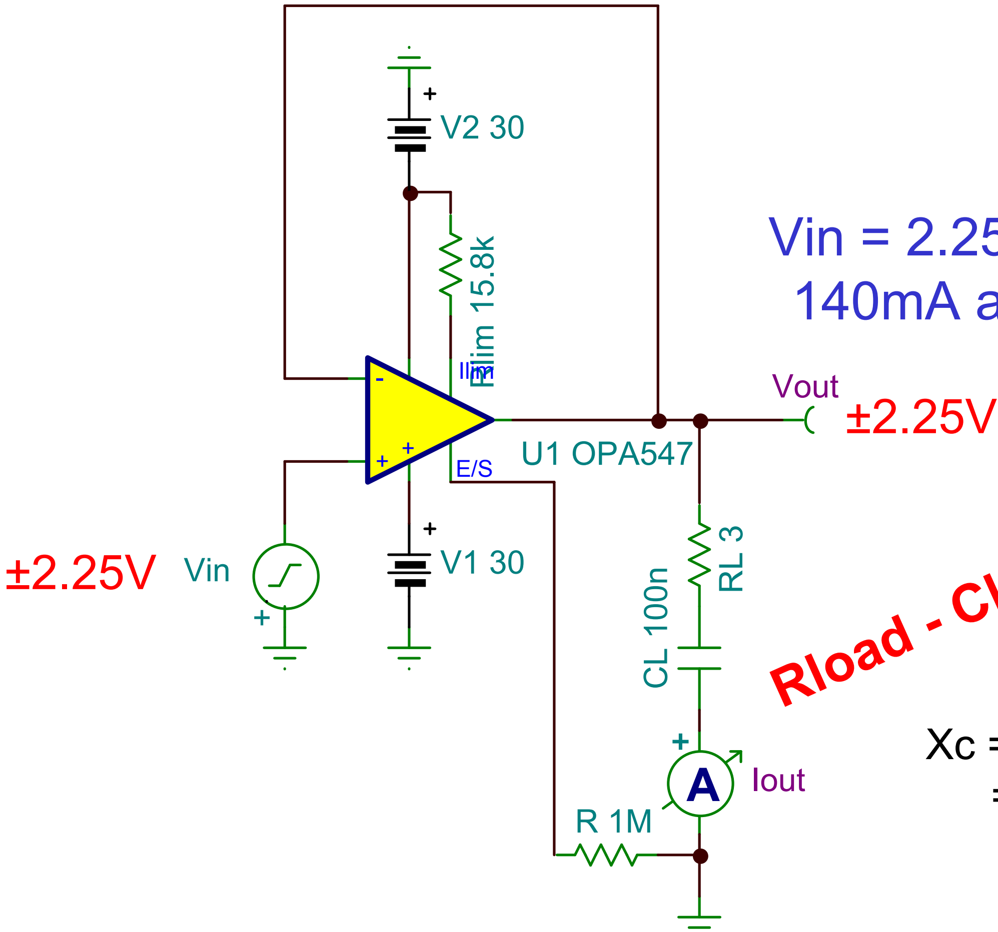


# OPA547
# Power Op Amp Measurement

## OPA547 RLoad = 3 ohms and 100nF

Vin = 2.25Vp, Iout = 140mA at 100kHz




Rload - Cload

Iout = 2.25V / 16.3 Ω
= 140mA ∠-73°

R = 3 Ω ∠0°

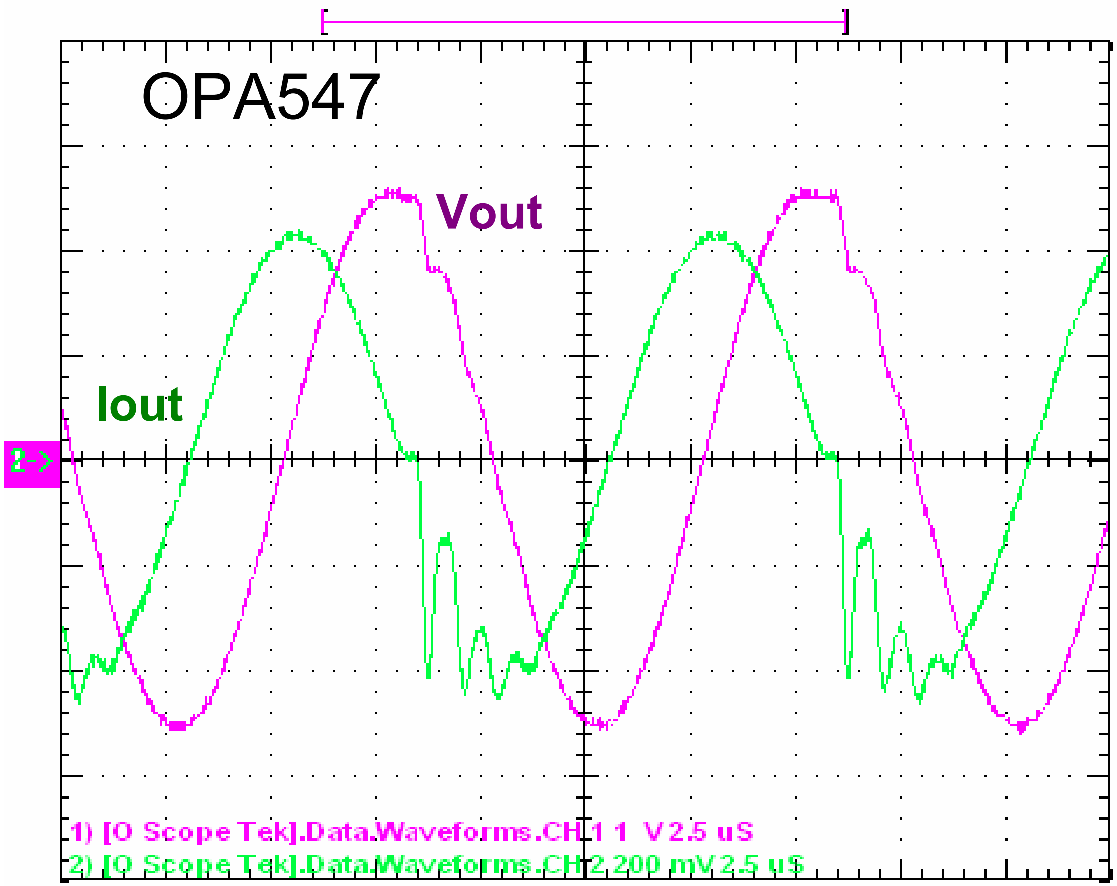
Xc = 1/(2πfC)
= 16 Ω ∠-90°

$Z = \sqrt{(3^2 + 16^2)}$
= 16.3Ω ∠-73°

# OPA547
# Power Op Amp Measurement

## CL = 100nF, Rseries = 3ohms, Heavy CLoad per OPA547 Data Sheet

With heavy capacitance load, beyond that specified in the data sheet, the OPA547 output does show some instability. This occurs during negative slewing in the OPA547. 3 ohms in series with 100nF (16 ohms at -90 degrees phase shift) results in a vectored load of about 16 ohms at 100kHz. Although the steady state vectored current of 140mA is within the OPA547 drive capability, the OPA547 will need an application circuit (shown in the following slides) to remain stable.



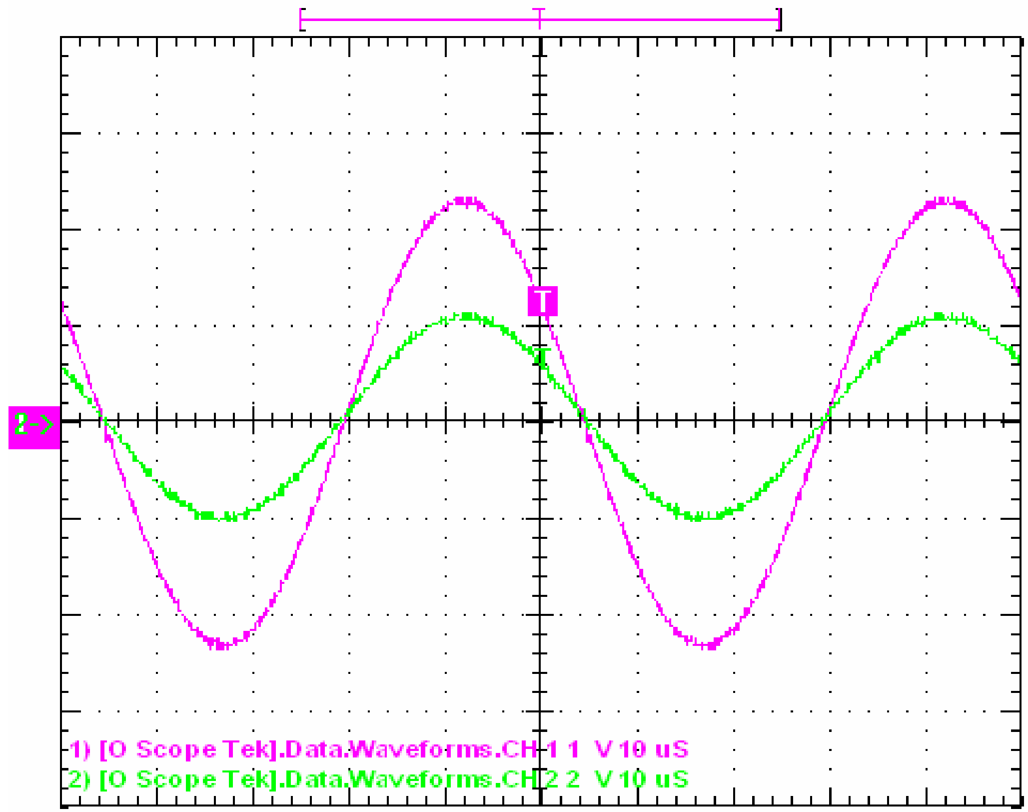

Green Waveform

i(t) = CdV/dt initially, then op amp recovery.

# Power Op Amps

## Crossover Distortion (COD) is dependent on:

1. **Highest Signal Frequency**
2. **Largest Signal Amplitude**
3. **Highest Slew Rate**
4. **Circuit Techniques**



# Power Op Amps

## Crossover Distortion (COD) can be improved by:

1. **Reducing input signal frequency**, given a constant amplitude
2. **Reducing input signal amplitude**, given a constant frequency
3. **Employing circuit techniques** - adding noise gain or using pull-down resistor
4. **Choosing a higher bandwidth amplifier** for signal frequency and amplitude

# Power Op Amps

## Crossover Distortion
## All NPN Power Output Stages

1. Can You Reduce It? – Somewhat.
   Mitigation Fix #1

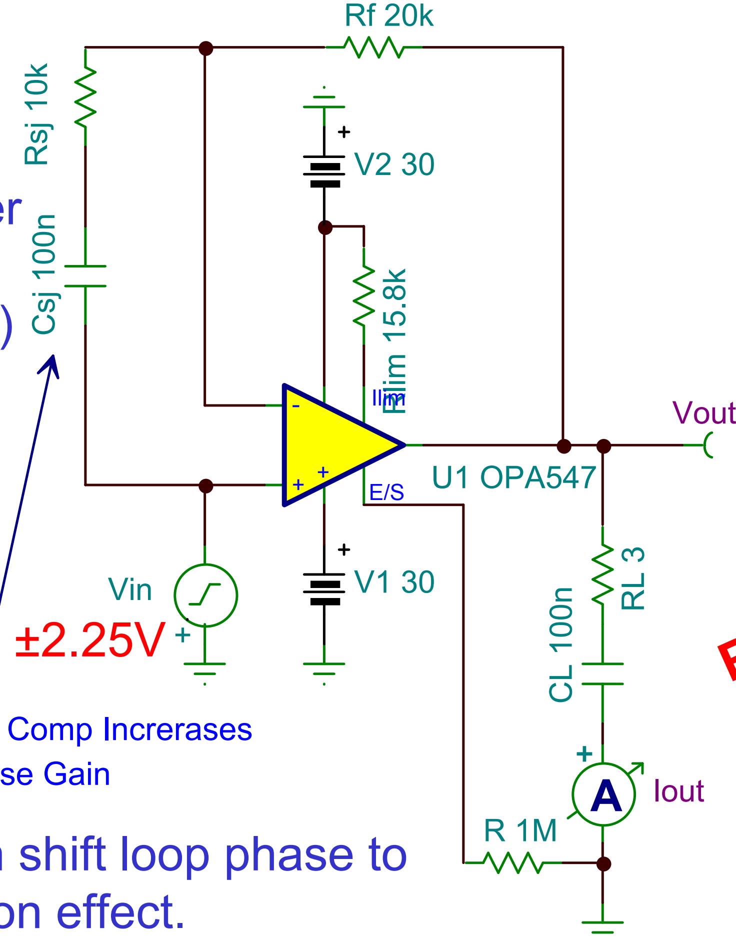
2. Can It Be Totally Fixed? – No, Without More Iq!
   But Yes, External Pull-Down Resistor.
   Application Fix #2

# OPA547
# Power Op Amp Measurement

**Mitigation Fix #1** CL = 100nF, Rseries = 3ohms, R-C Summing Junction to Vin

CL = 100nF, Rseries = 3ohms, Heavy CLoad per OPA547 Data Sheet

Noise gain = 3V/V at higher frequencies.
Gnoise = 3 = 1 + (20k/10k)




Reduces Ugliness but Increases Noise Gain, and Reduces BW

Rload - Cload

RC Comp Increrases Noise Gain

Rsj junction & Csj junction shift loop phase to reduce oscillation effect.

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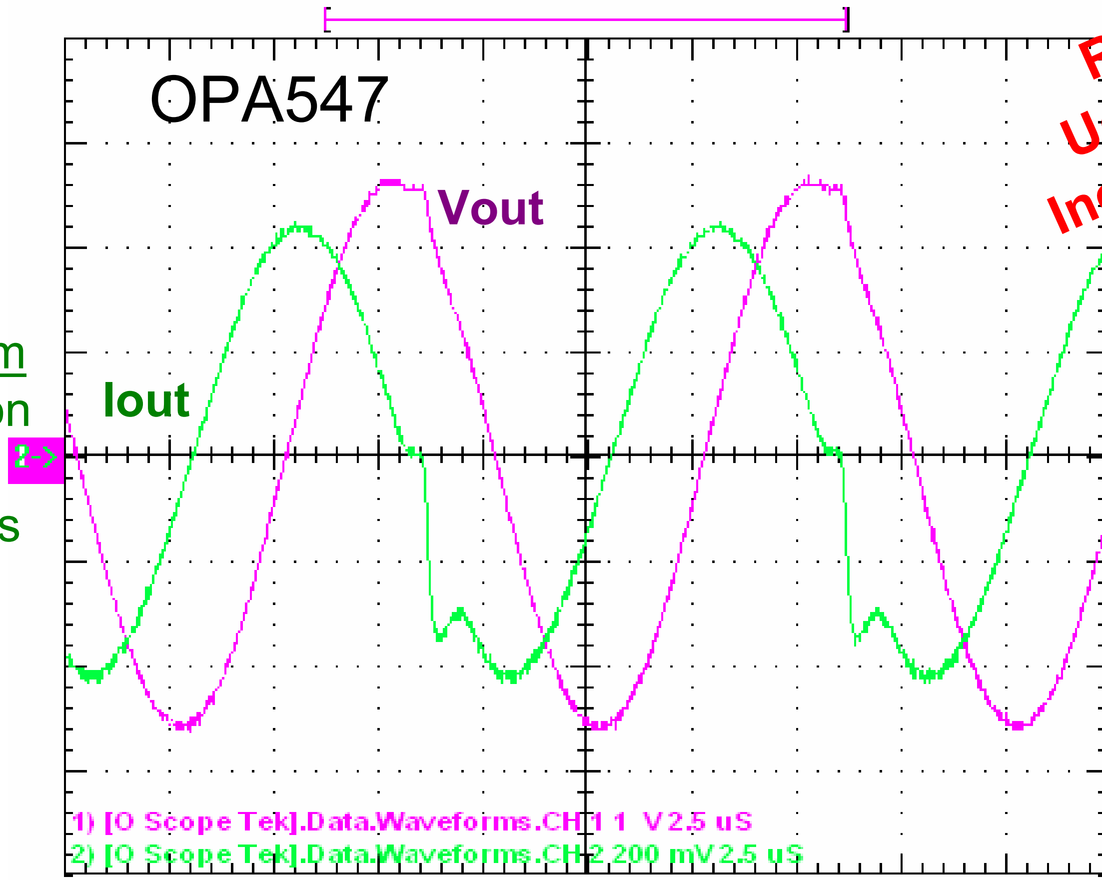
# OPA547
# Power Op Amp Measurement

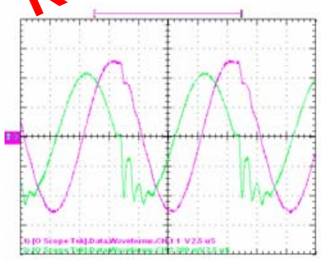
**Mitigation Fix #1** CL = 100nF, Rseries = 3ohms, R-C Summing Junction to Vin

CL = 100nF, Rseries = 3ohms, Heavy CLoad per OPA547 Data Sheet

Green Waveform
Compensation on Summing Junction, Cleans Up Output Waveform Somewhat.



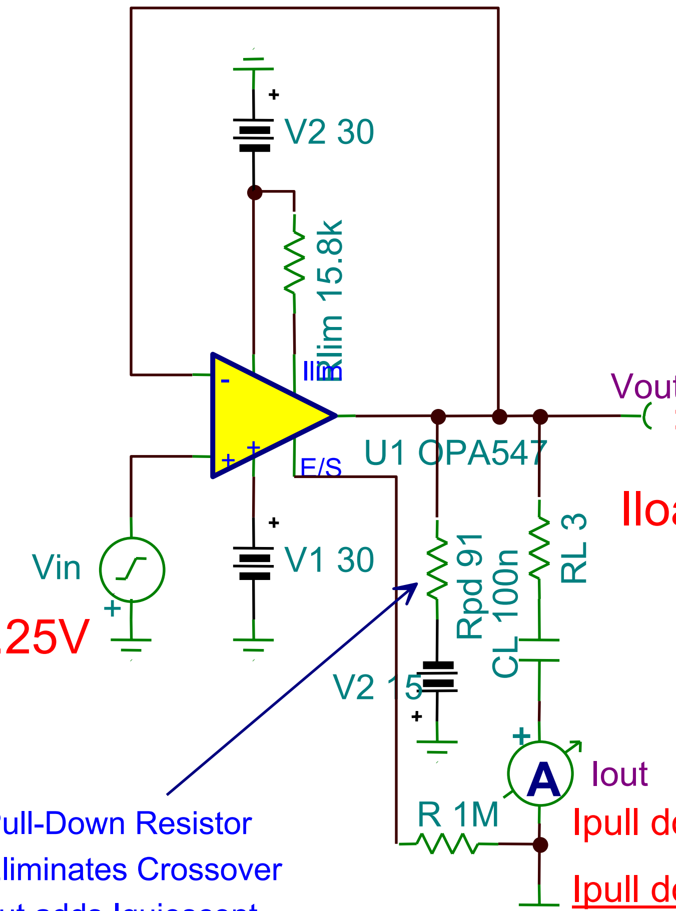

Reduces Ugliness but Increases Noise Gain, and Reduces BW



# OPA547
# Power Op Amp Measurement

**Application Fix #2** CL = 100nF, Rseries = 3ohms, 91 ohms connected to -15V

CL = 100nF, Rseries = 3ohms, Heavy CLoad per OPA547 Data Sheet




Pull Down Resistor Makes All Clean, but adds Iquies

±2.25V

Iload = ±140mA

Rload - Cload

Ipull down = about 190mA, which keeps the upper output power transistor always turned on.

±2.25V

Pull-Down Resistor Eliminates Crossover but adds Iquiescent

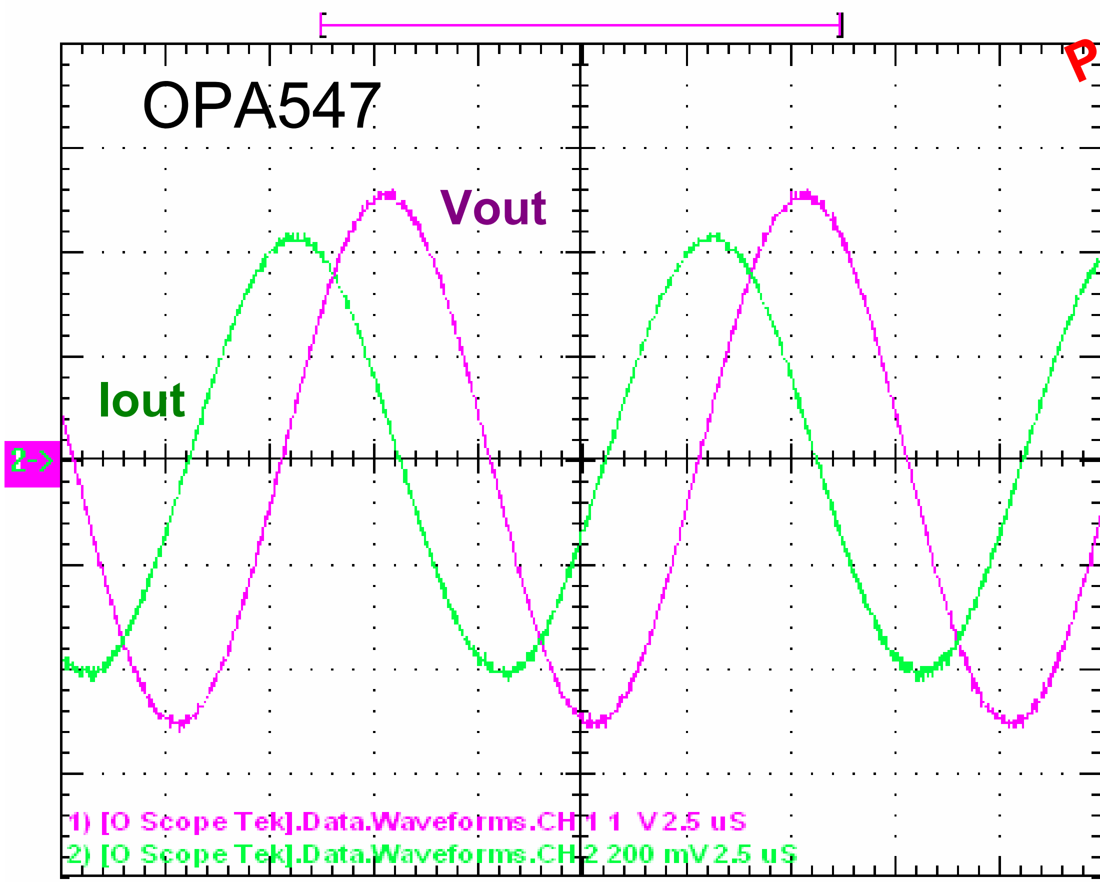
Ipull down + = (15V+2.25V) / 91Ω = +190mA

Ipull down - = (15V-2.25V) / 91Ω = -140mA

# OPA547
# Power Op Amp Measurement

**Application Fix #2** CL = 100nF, Rseries = 3ohms, 91 ohms connected to -15V

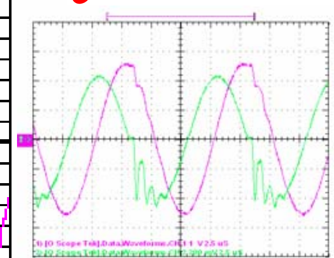
CL = 100nF, Rseries = 3ohms, Heavy CLoad per OPA547 Data Sheet




Green Waveform

Negative Pull Down Keeps Upper Output Power Transistor Turned On, Which Provides a Clean Output Waveform.

Pull Down Resistor Makes All Clean, but adds Iquies



# Power Op Amps

## Crossover Distortion

## Time and Frequency Domain

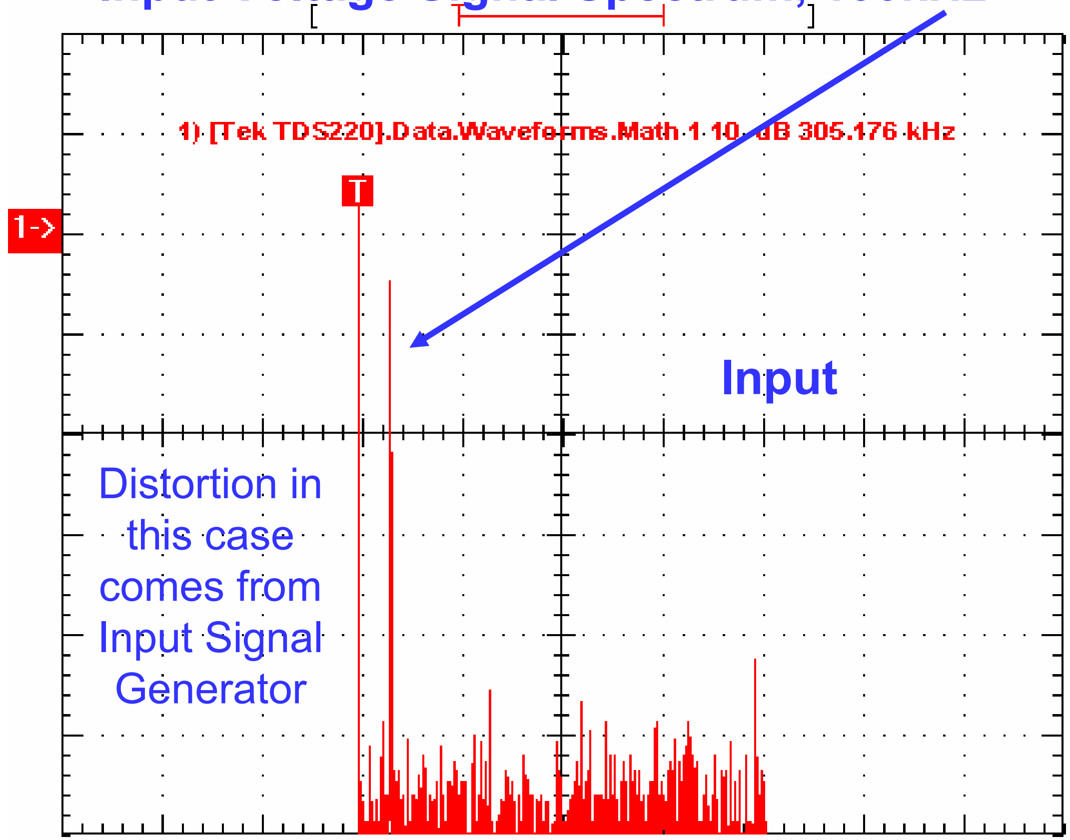
For Pull Down Resistor Application fix

# OPA547
# Power Op Amp Measurement

**Application Fix #1** CL = 100nF, Rseries = 3ohms, 91 ohms connected to -15V

CL = 100nF, Rseries = 3ohms, Heavy CLoad per OPA547 Data Sheet

**Input Voltage Signal Spectrum, 100kHz**




Pull Down Resistor Makes All Clean, but adds Iquies

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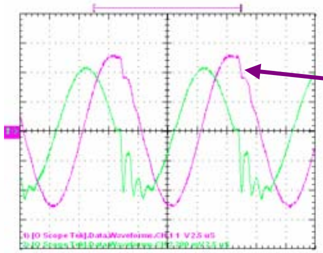

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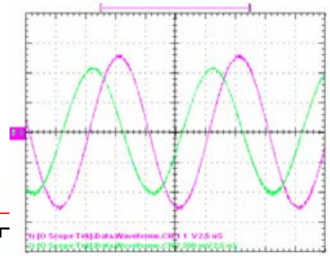
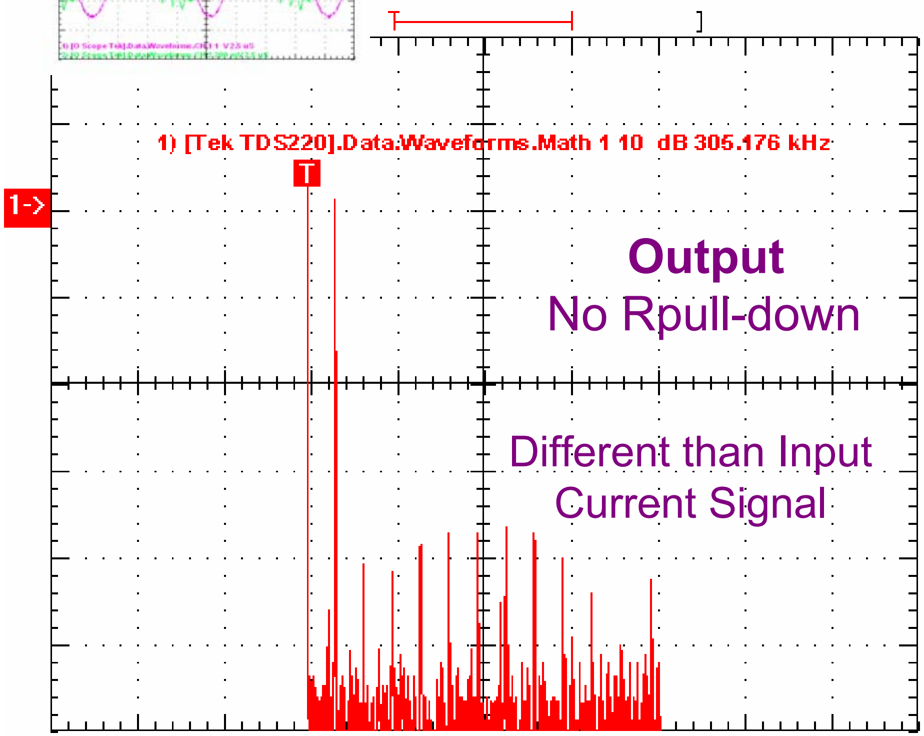
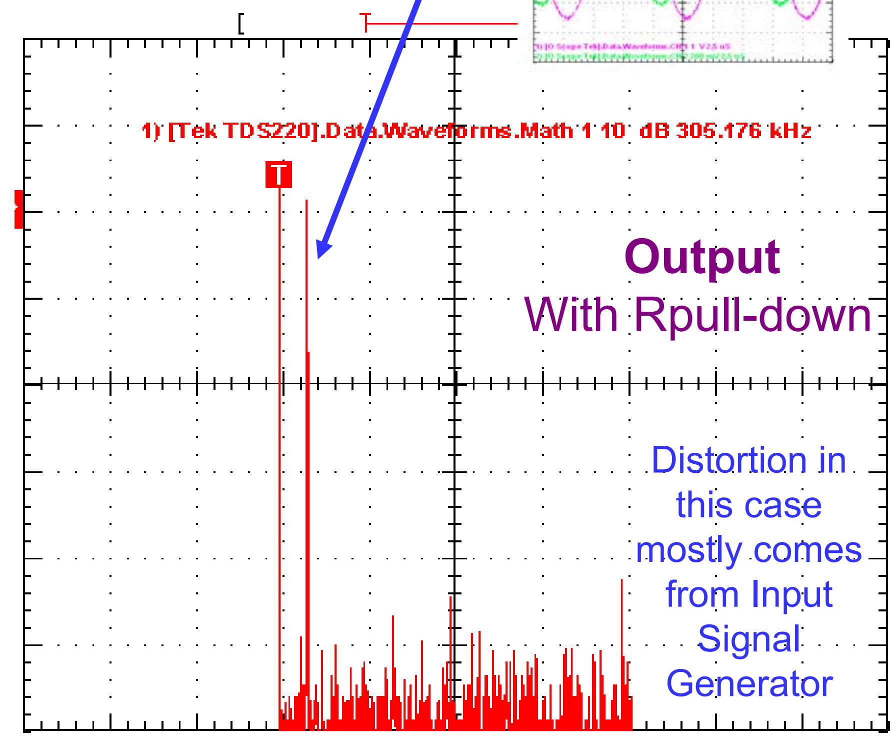
Output **VOLTAGE** Signal Spectrum, 100kHz





High-Performance Analog

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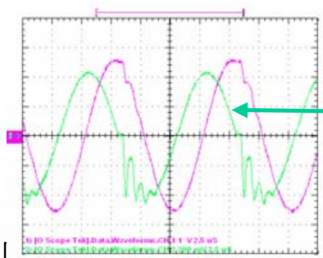
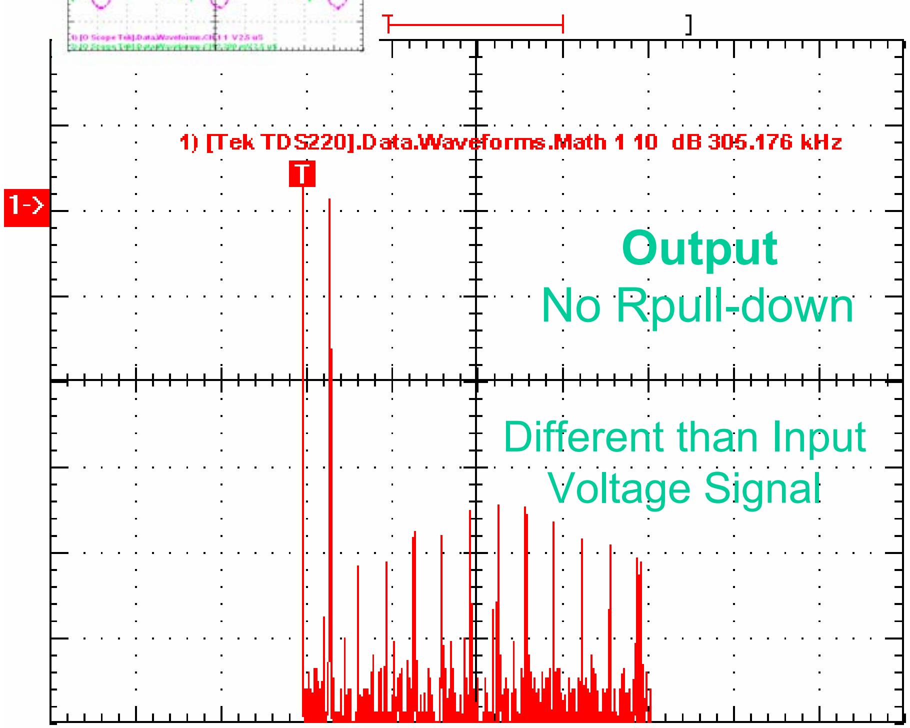
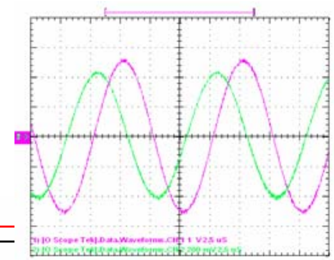
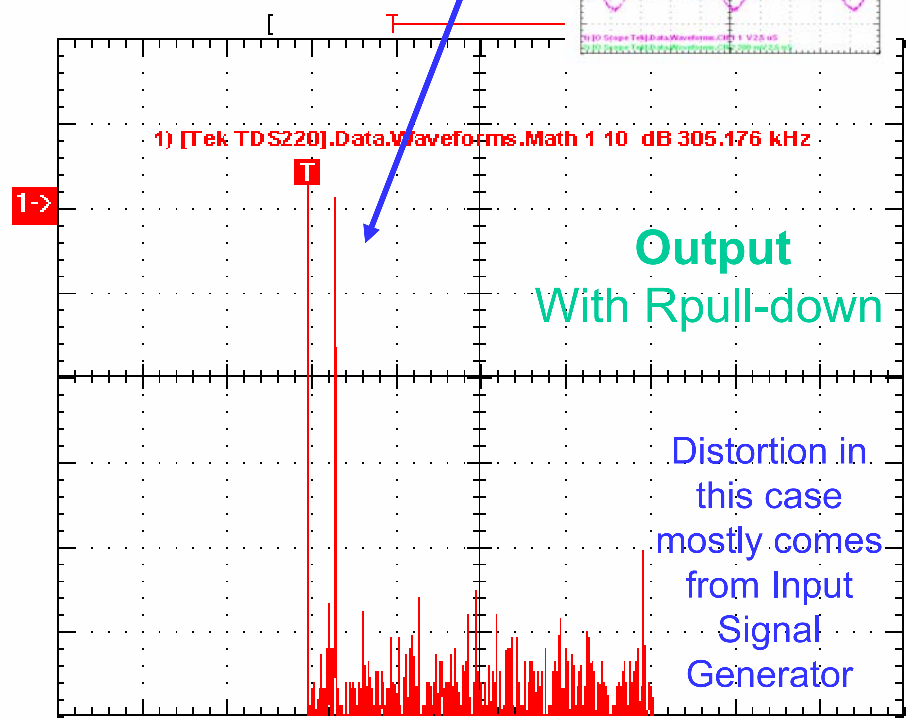
Output **CURRENT** Signal Spectrum, 100kHz







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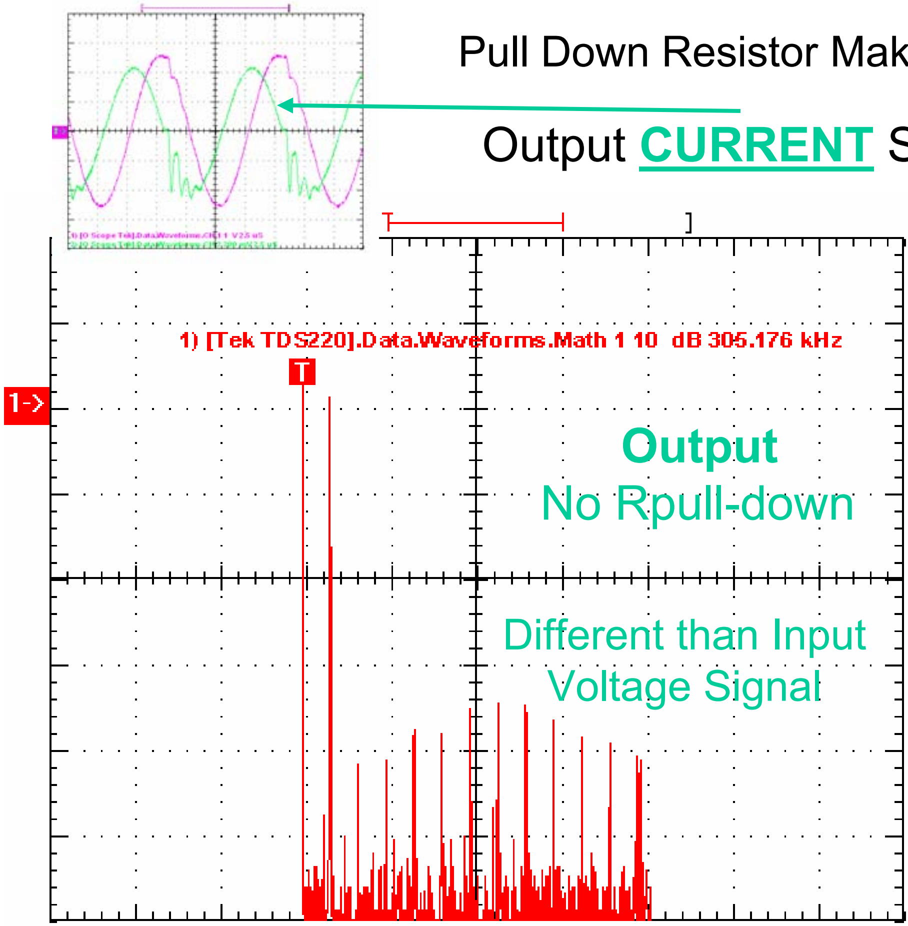
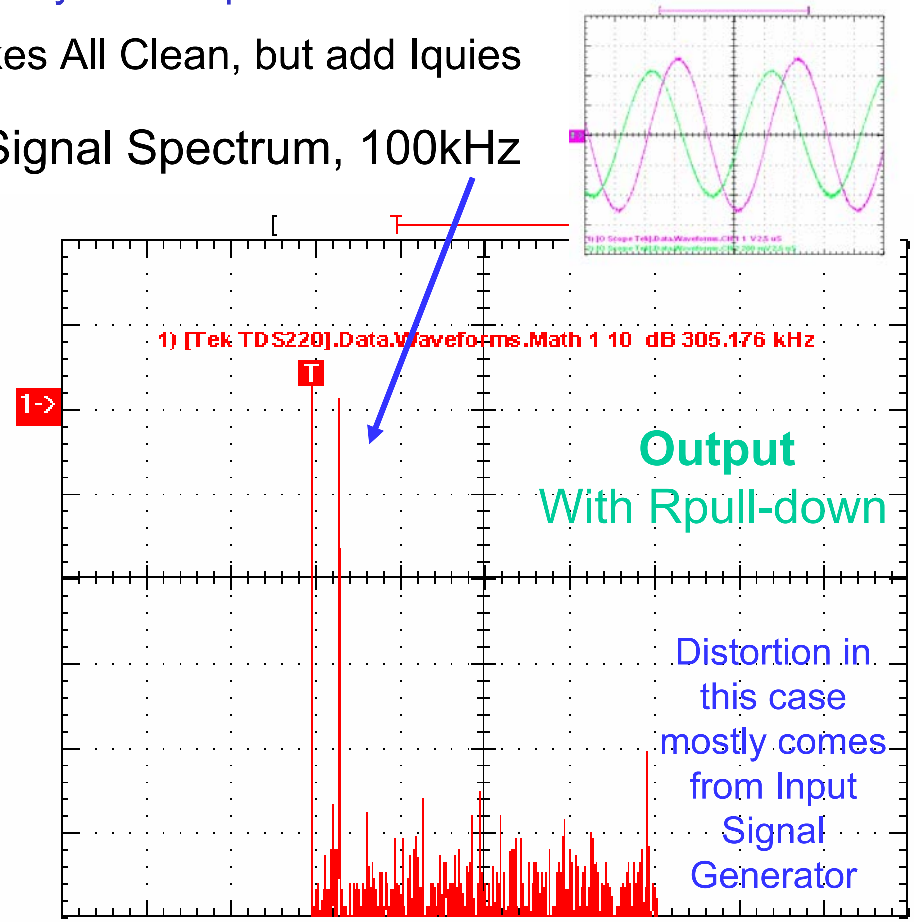


# Power Op Amps

**<u>The Real Fix For Reducing Crossover Distortion</u>**

**No Matter How You Look At It,**

**The Circuit Requires More Quiescent Current,**

**Especially in the Output Stage.**

# Power Op Amps

## Swing to the Output Rail

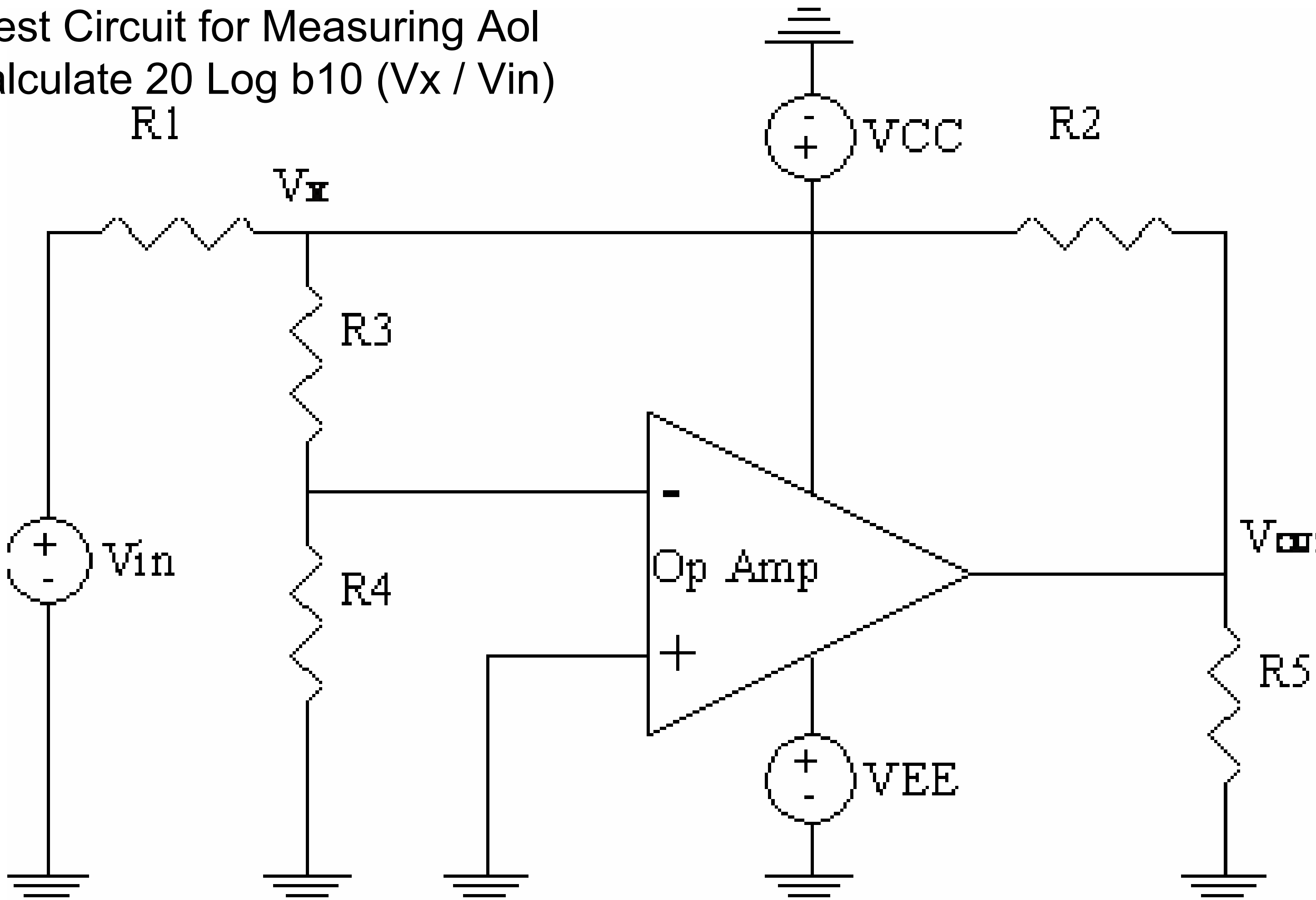
*It's Based on Linearity in Both Cases*

1. Maintaining Aol
2. Keeping THD Below Some Level

# Power Op Amps

## Swing to Output Rail with good linearity is dependent on Aol

Test Circuit for Measuring Aol
Calculate 20 Log b10 (Vx / Vin)



# Power Op Amps, OPA547

## Swing to Output Rail With Good Signal Purity is dependent on Slew Rate

At the Zero Crossing

SR = 2π * Vp * BWfp

Example #1

SR = 2π * 2.25V * 100kHz

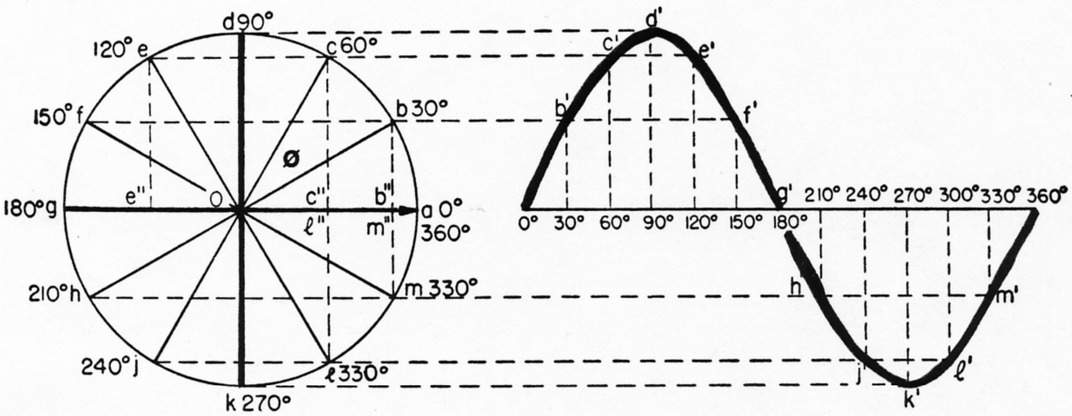
= 1.4V/us

Example #2

SR = 2π * 27Vp max * 35kHz

= 6V/µs min

Construction of a Sine Curve




Showing how a sine curve may be constructed from the vertical projections of the rotating radius, *oa*.

**ELECTRONICS**

$$v(t) = V_{MAX} \sin(2\pi f t)$$

angular frequency, w = 2πft

angle, ø = wt

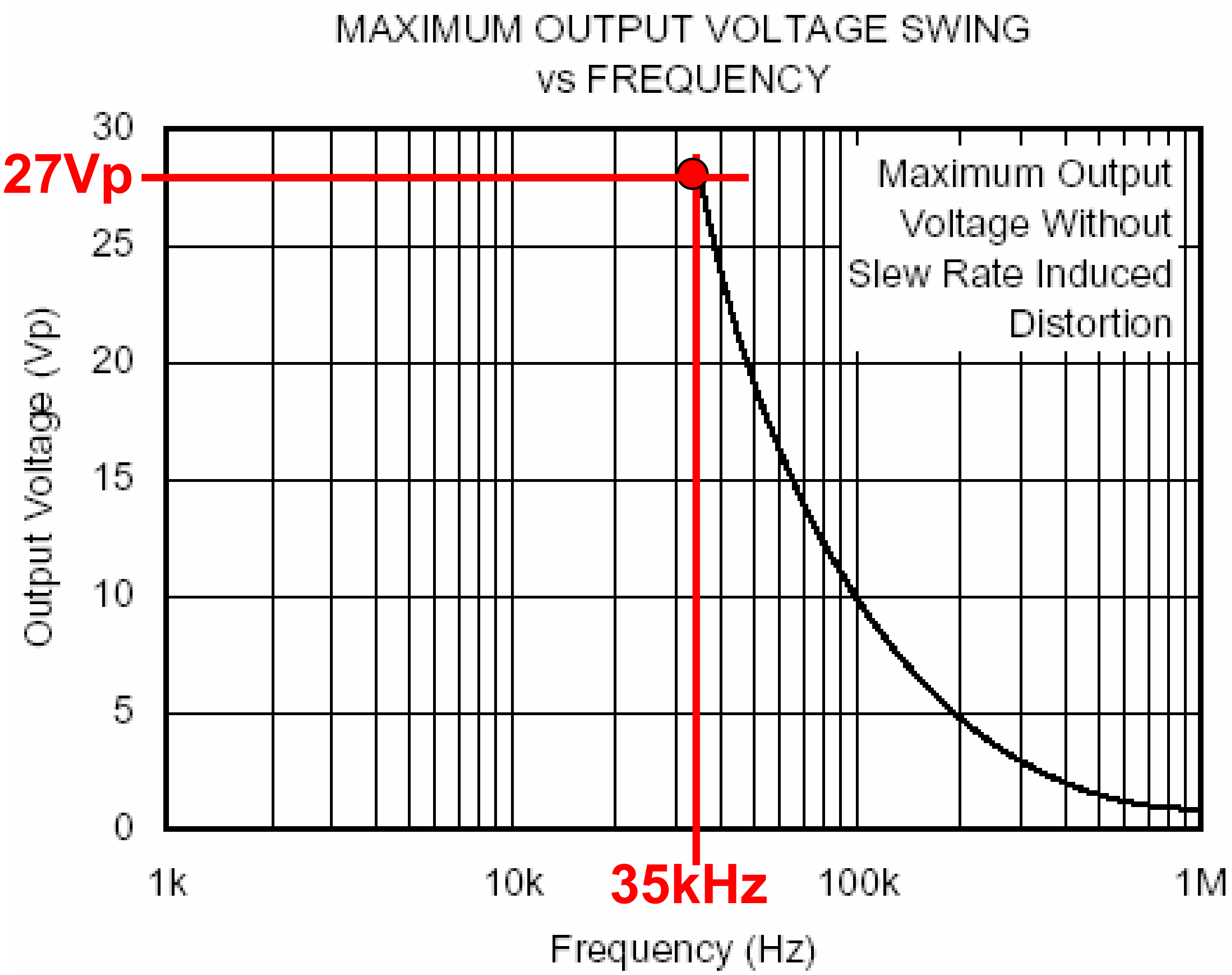
# Power Op Amps

## What affects Crossover Distortion (COD)?

1. **Output Swing is a Function of Frequency**
2. **Distortion is a Function of Frequency**
3. **Distortion or Fidelity is a Function of Open Loop Gain, Aol**
4. **Overshoot or Ringing is a Function of Load Capacitance**

# Power Op Amps, OPA547

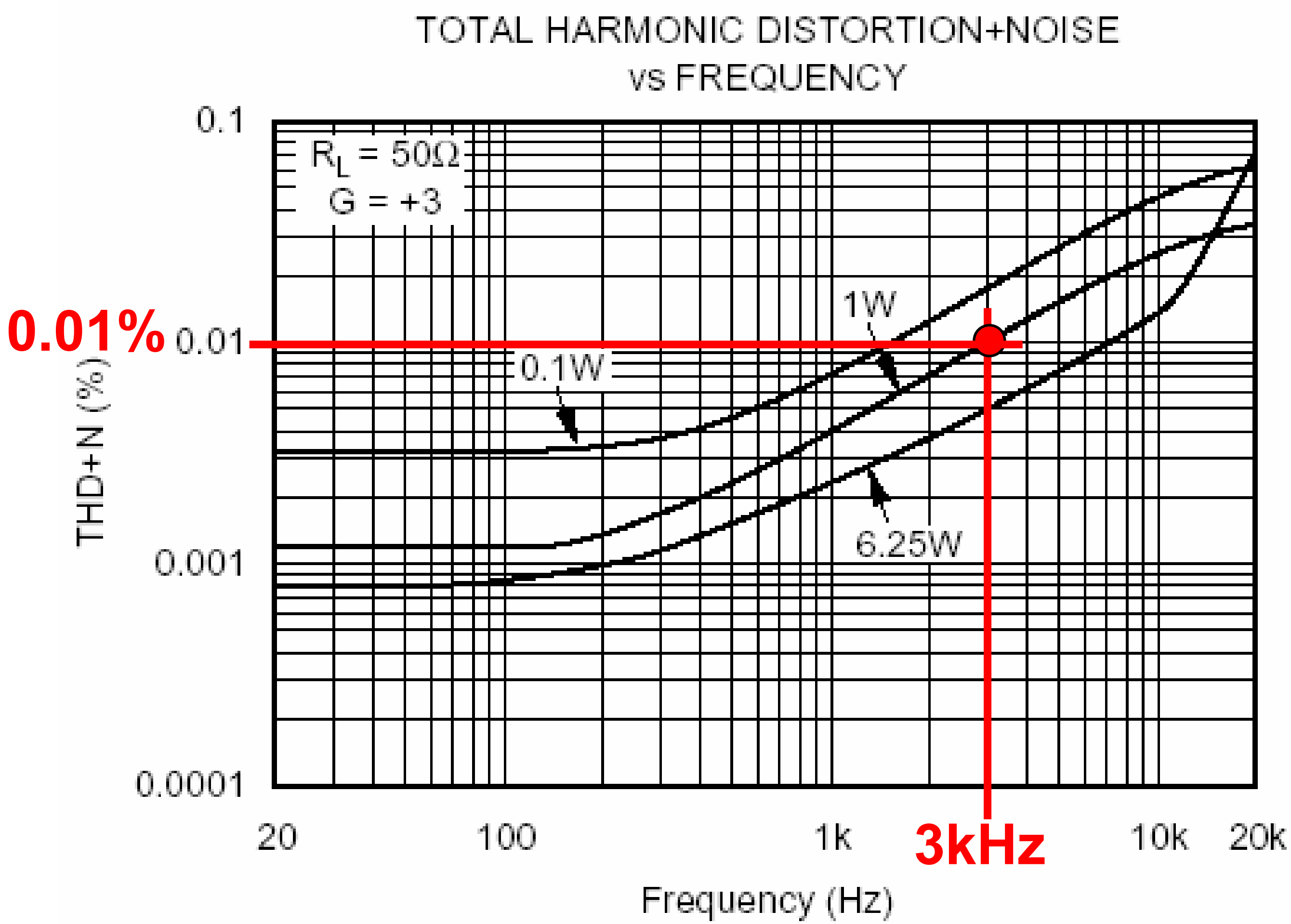
## Output Swing is a Function of Frequency



# Power Op Amps, OPA547

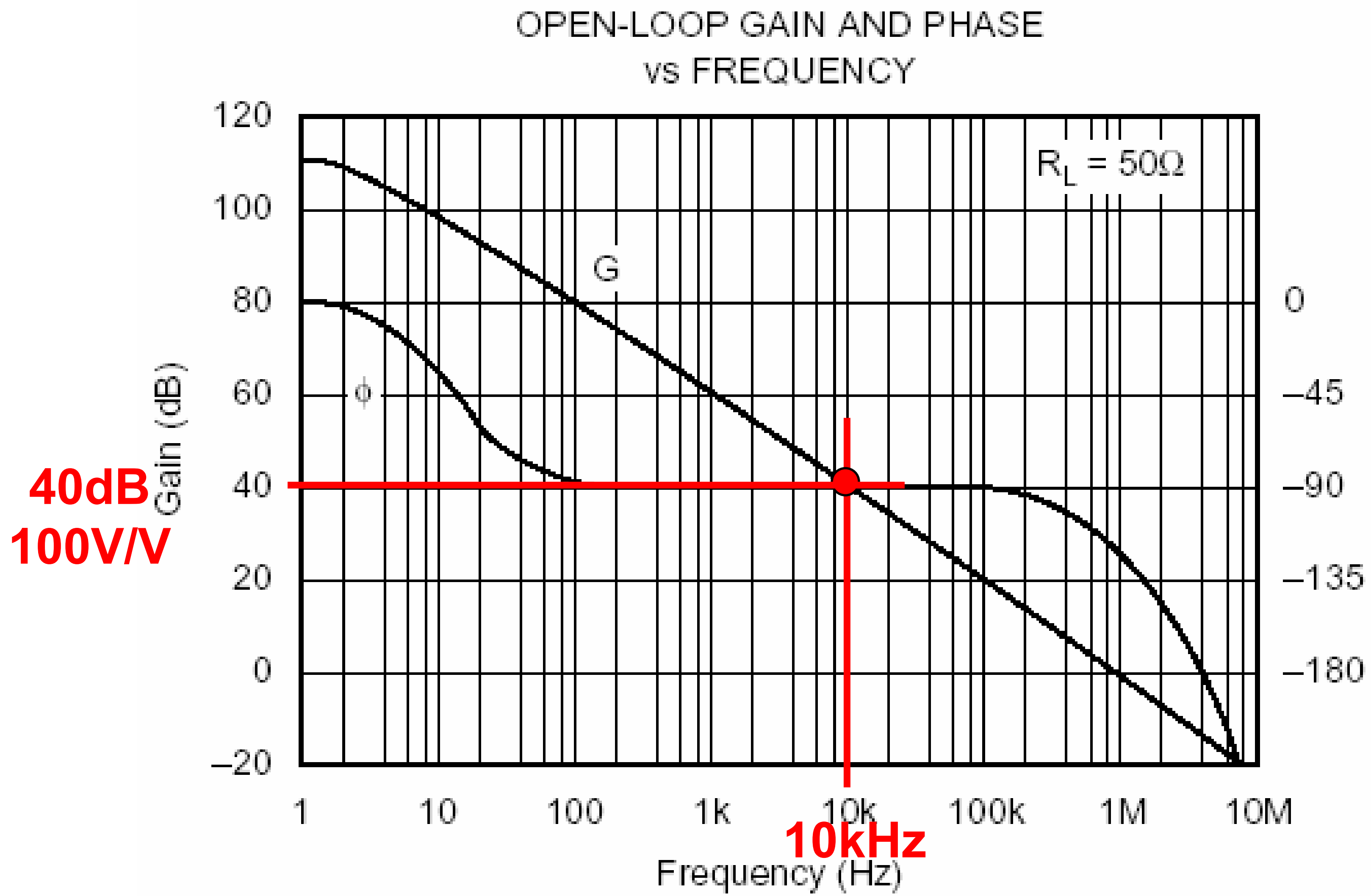
## Distortion is a Function of Frequency

At the Zero Crossing, SR = 2π * Vp * BWfp



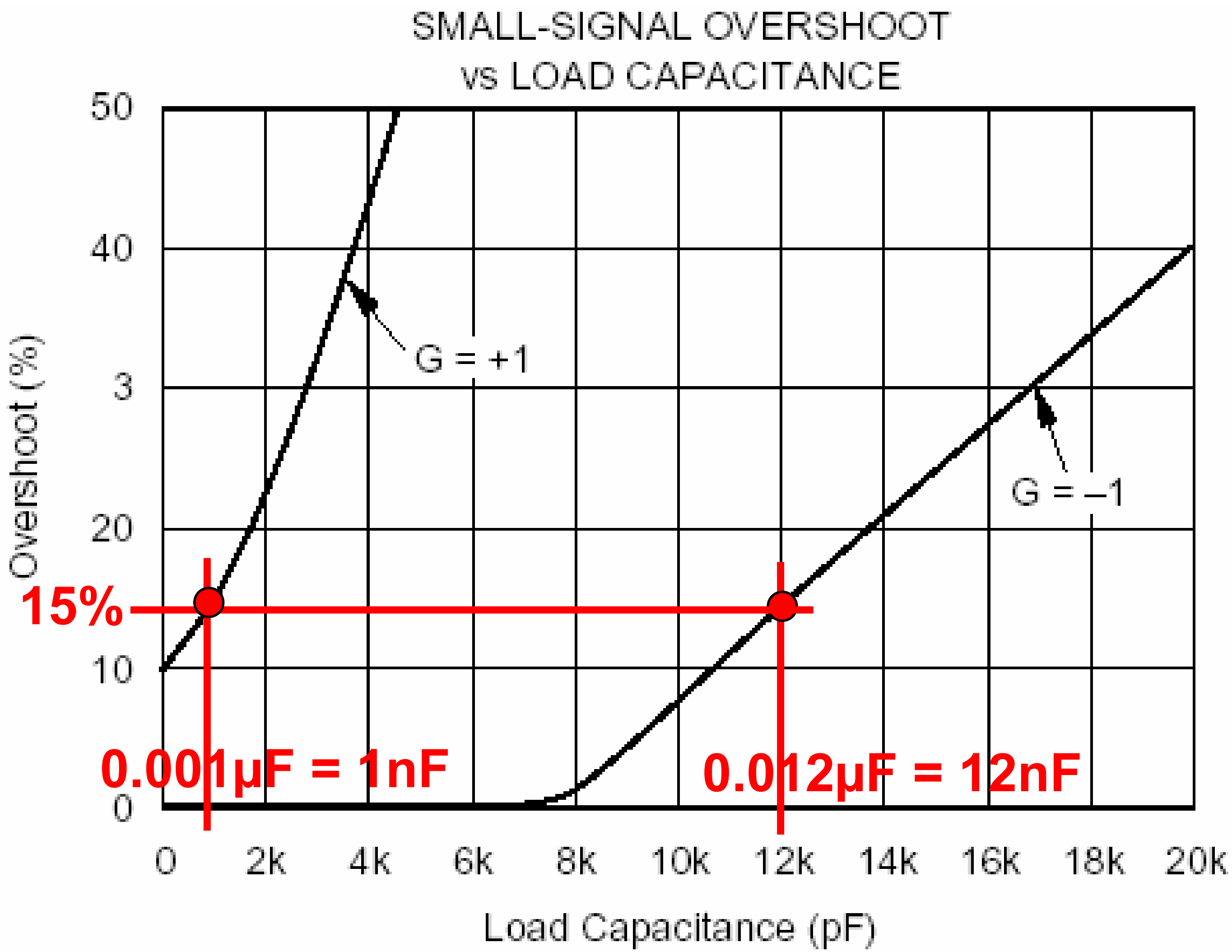
# Power Op Amps, OPA547

## Distortion or Fidelity is a Function of Aol



# Power Op Amps, OPA547

## Overshoot or Ringing is a function of Load Capacitance



# Power Op Amps

## Happy Crossover Distortion

## Thank You For Your Participation

John Brown