Designing Microphone Preamplifiers

By Gary K. Hebert
129th AES Convention
San Francisco CA, November 2010

THAT Corporation

The Tutorial Overview

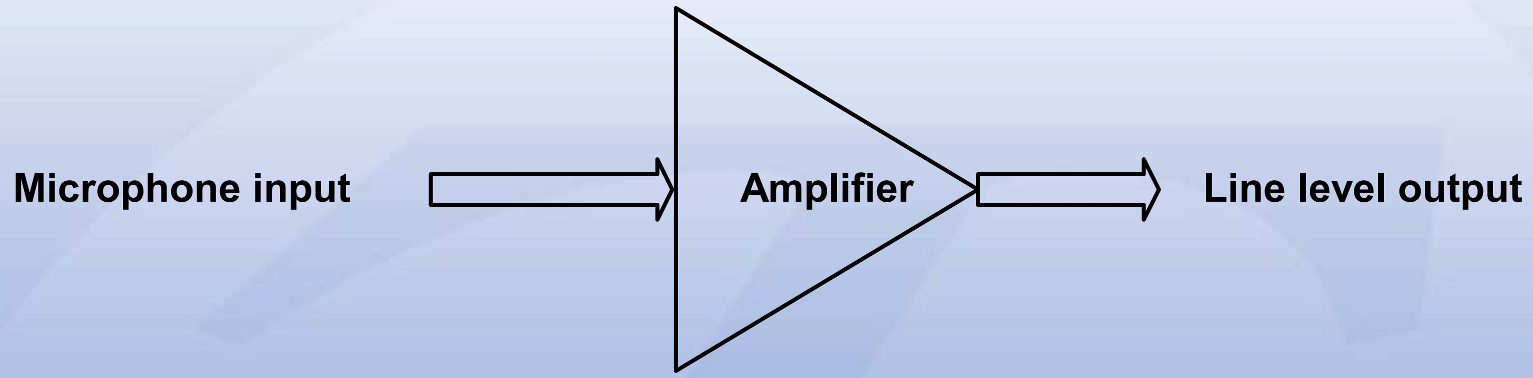
Section 1

Support Circuitry

Section 2

The Amplifier

Simple Block Diagram



Microphone signal levels vary widely due to:

- **Microphone sensitivity**
- **Source SPL**
- **Proximity to source**

Line level outputs are somewhat more constrained:

- **“Standard” maximum operating levels include 24, 18, 15 dBu**
- **A/D converter input levels are approximately 8 dBu or 2 Vrms differential**

Typical Requirements

Gain

- **Up to 40 dB covers the majority of close-mic'd applications**
- **Some situations require more than 70 dB**
- **Variability of input levels requires adjustable gain over a very wide range**

Phantom Power

- **Required for many microphones**
- **Standardized in IEC EN 61938**
  - **48 Volts +/- 4V at up to 10 mA per microphone**
- **On / off control**

Input Pad

- **Can allow higher input signal levels, at the expense of noise**
- **May be required depending on minimum gain and supply rails**
- **20 dB is common**

Resistant to common mode noise and RFI

Reliable

Preamplifier Technologies

Transformer-Coupled Vacuum Tube

- **Robust**
- **Colorful**
- **Costly**

Transformer-Coupled Solid State

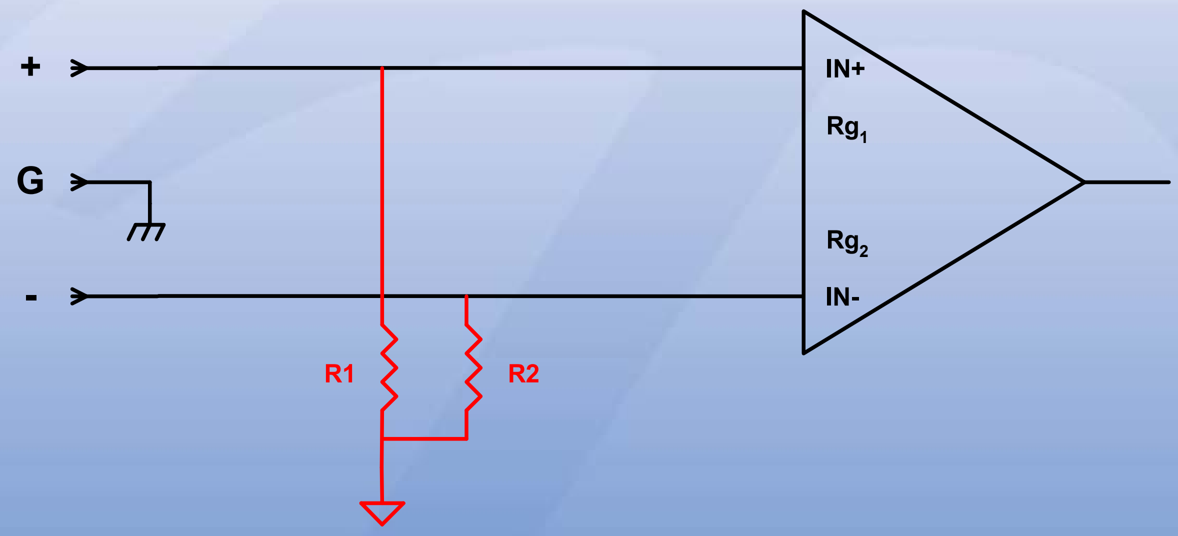
- **Also Robust**
- **Performance can be excellent**
- **Cost can be high**

Transformerless Solid State

- **More vulnerable**
- **Performance can be excellent**
- **Cost ranges from very low to high**

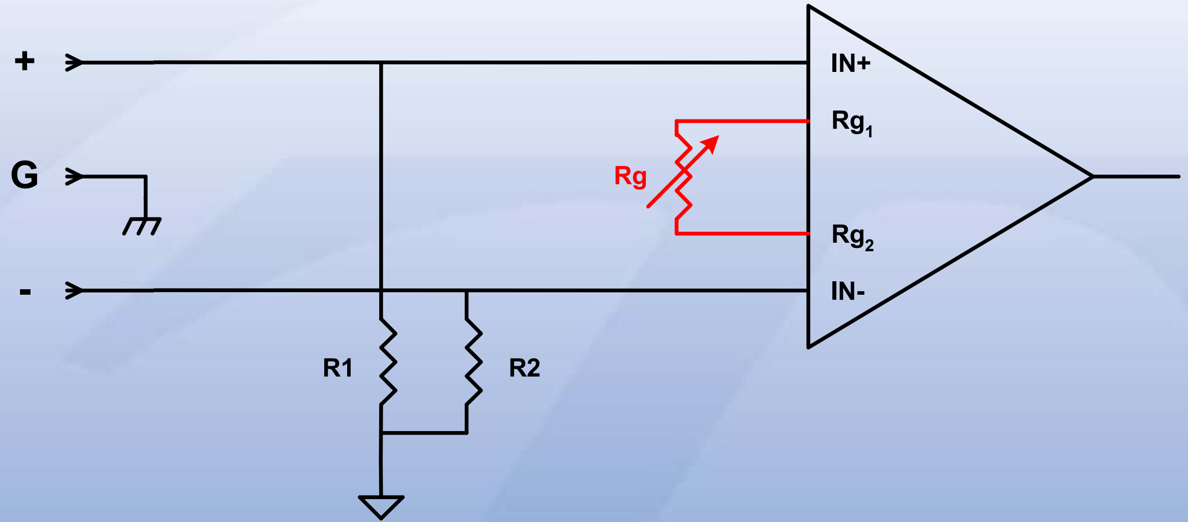
Transformerless solid state designs are the focus today

Amplifier Input Bias Current



Must provide a DC current path to supply the amplifier input bias current

Gain Control



The amplifier is often designed to vary gain using a single variable resistor (R_g)

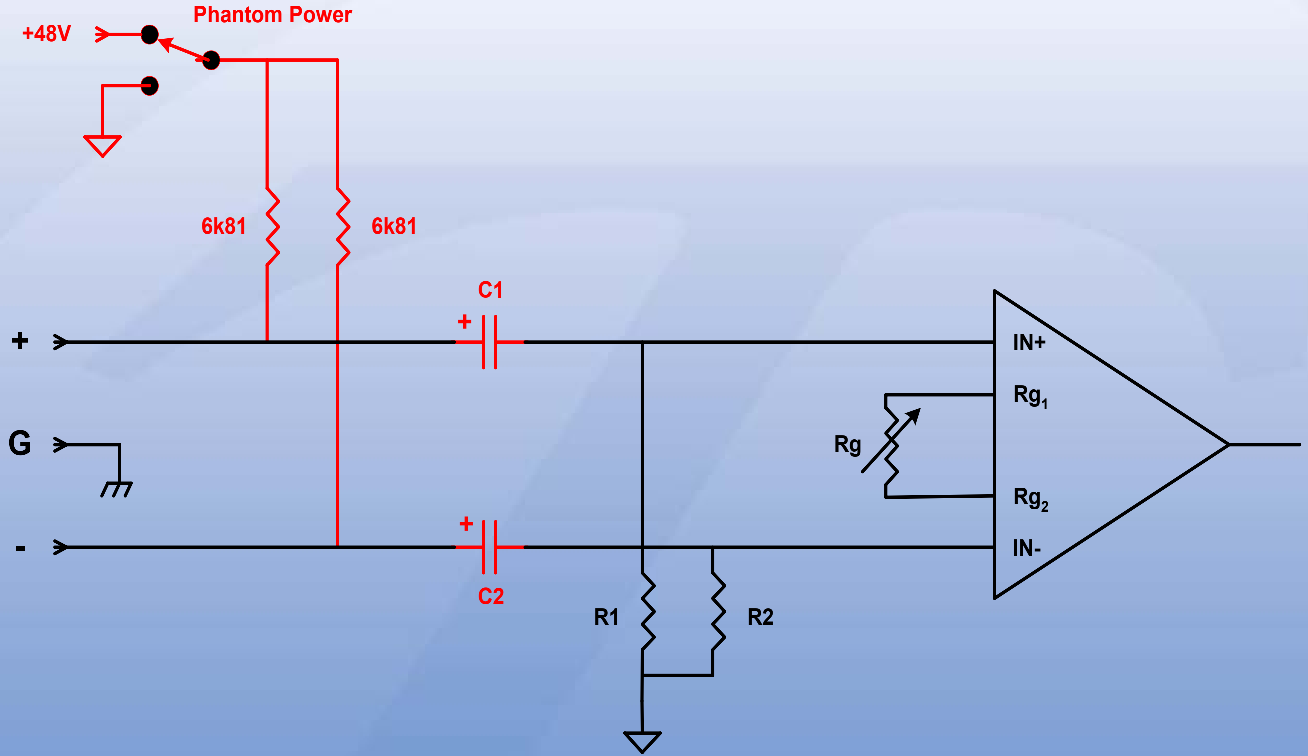
Manually controlled options

- Potentiometer with continuous control over a defined range
- Switched resistor network with a fixed number of steps and gain settings

Digitally controlled options

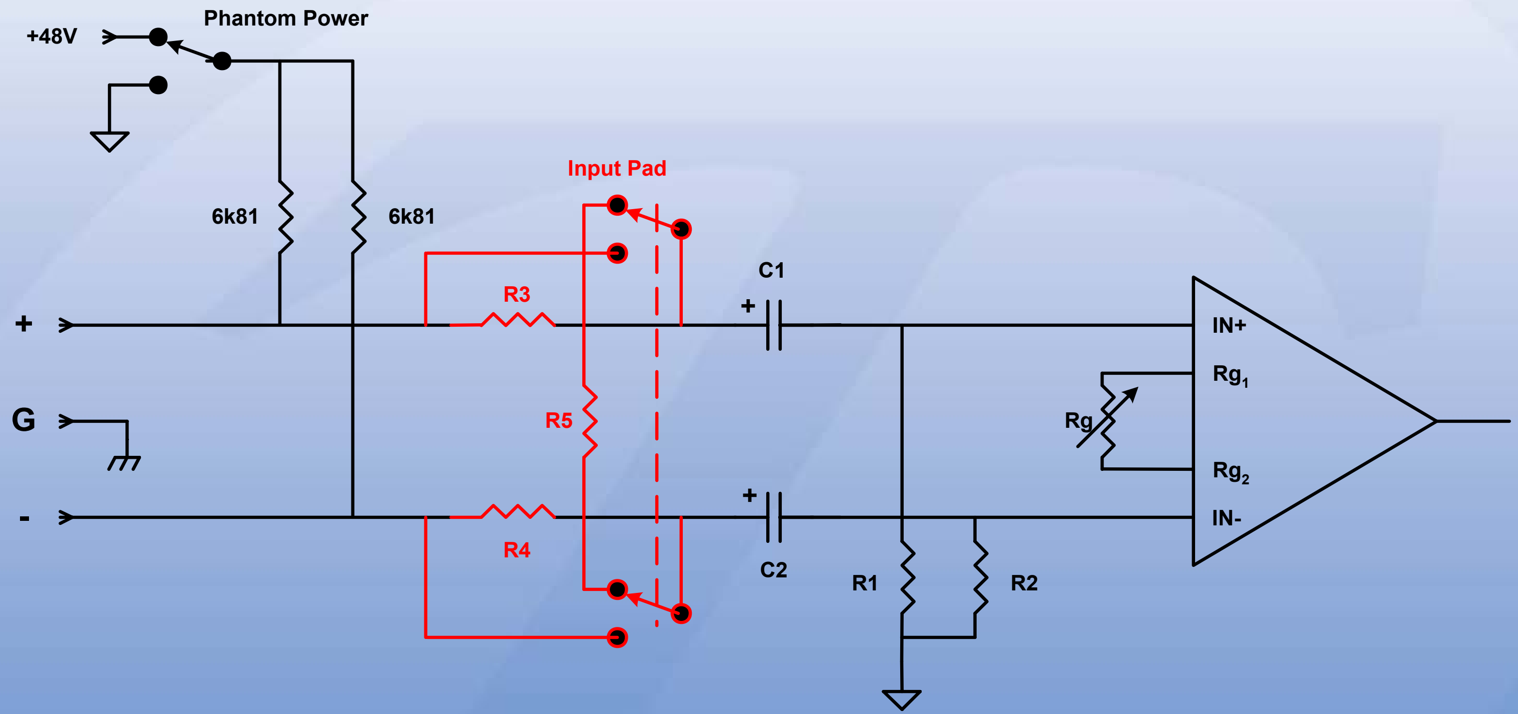
- Digitally switched resistor network with a predetermined number of steps
- Switches are either relays or silicon devices
- Both discrete and integrated circuit solutions are available

Phantom Power



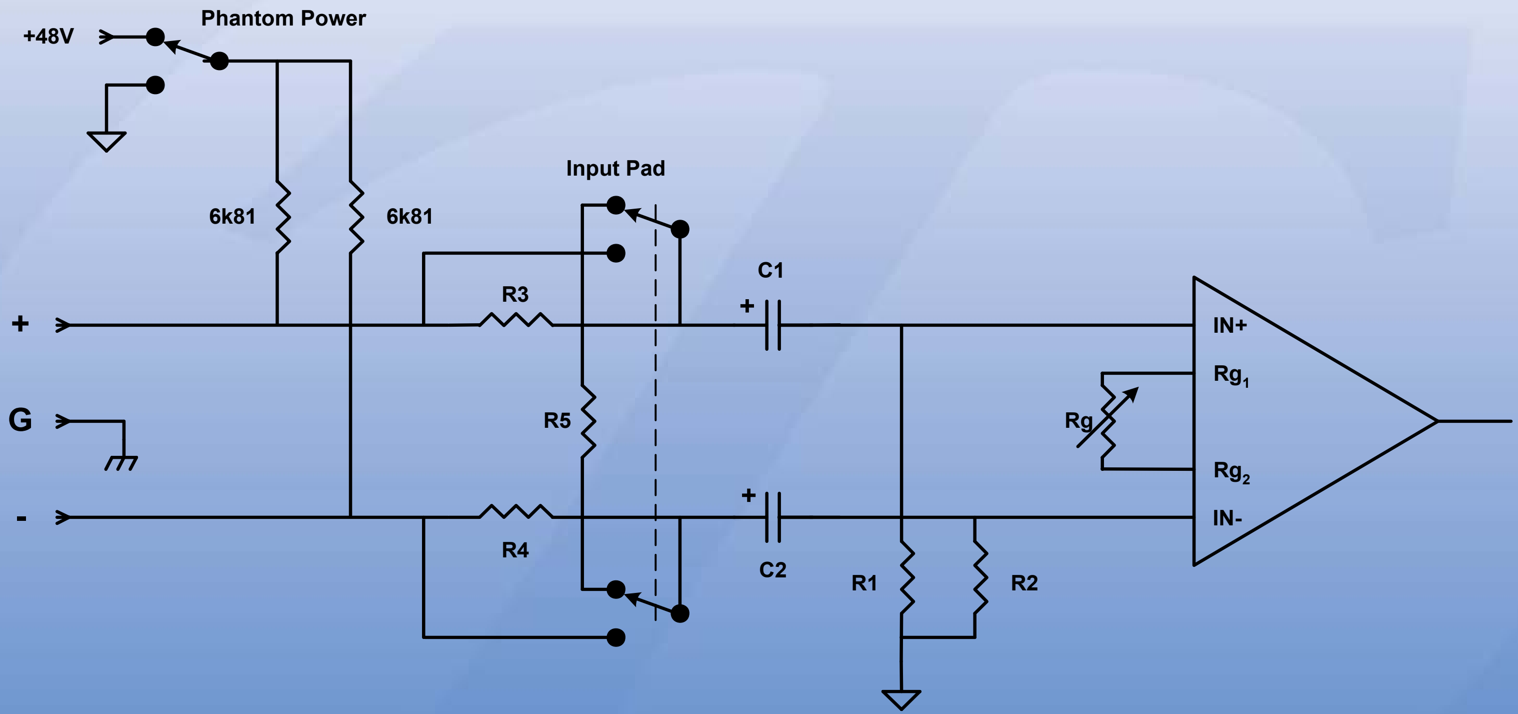
- C1 and C2 required to block the 48 V from the amplifier inputs
- 6.81k series resistors are specified in the standards for 48V phantom power
- On/Off is available via a
  - Simple mechanical switch in manual applications
  - Relay or silicon switch in digitally controlled systems

Input Pad



- Input pad is simply a signal attenuator prior to the amplifier
- This is a differential-only pad, it does not attenuate common-mode signals

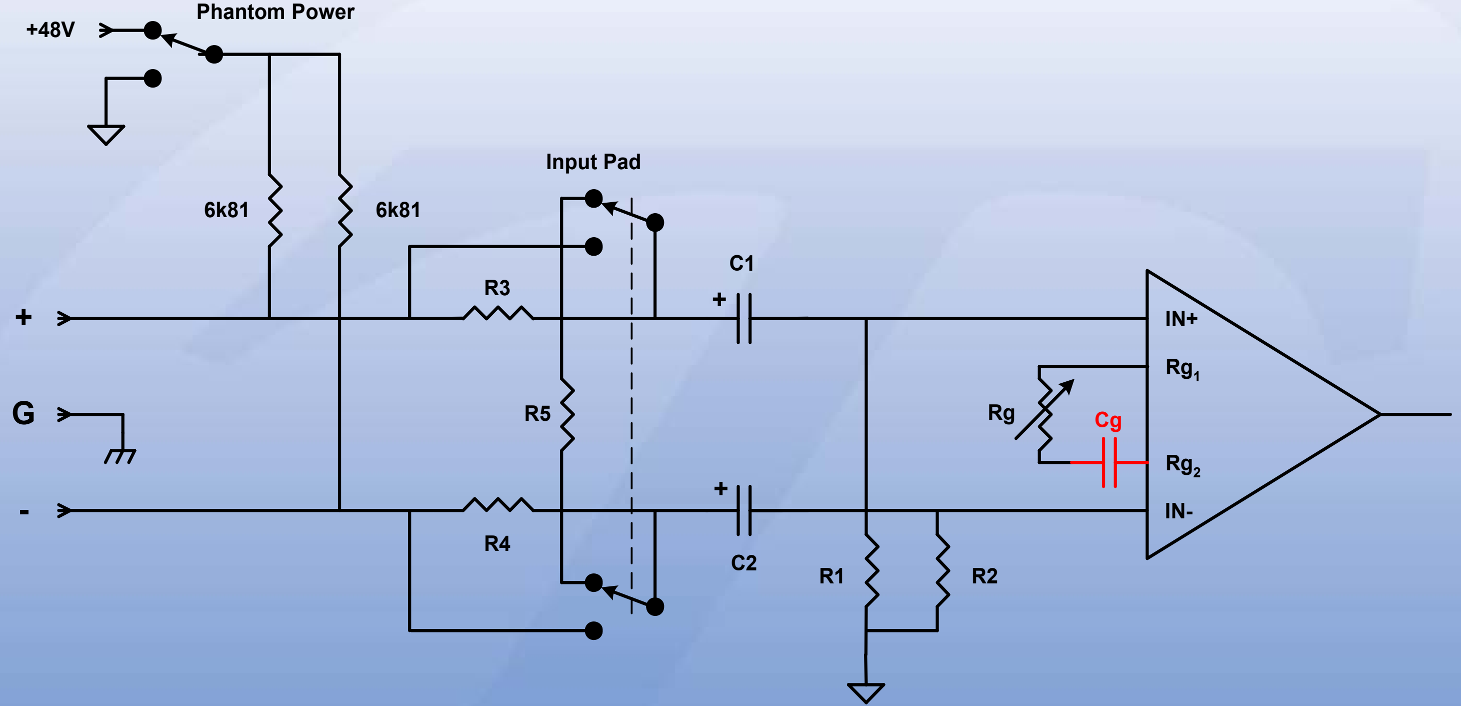
“Complete” Microphone Preamp



It would be nice to say "that's all there is" but………

there are gremlins are in the details!!

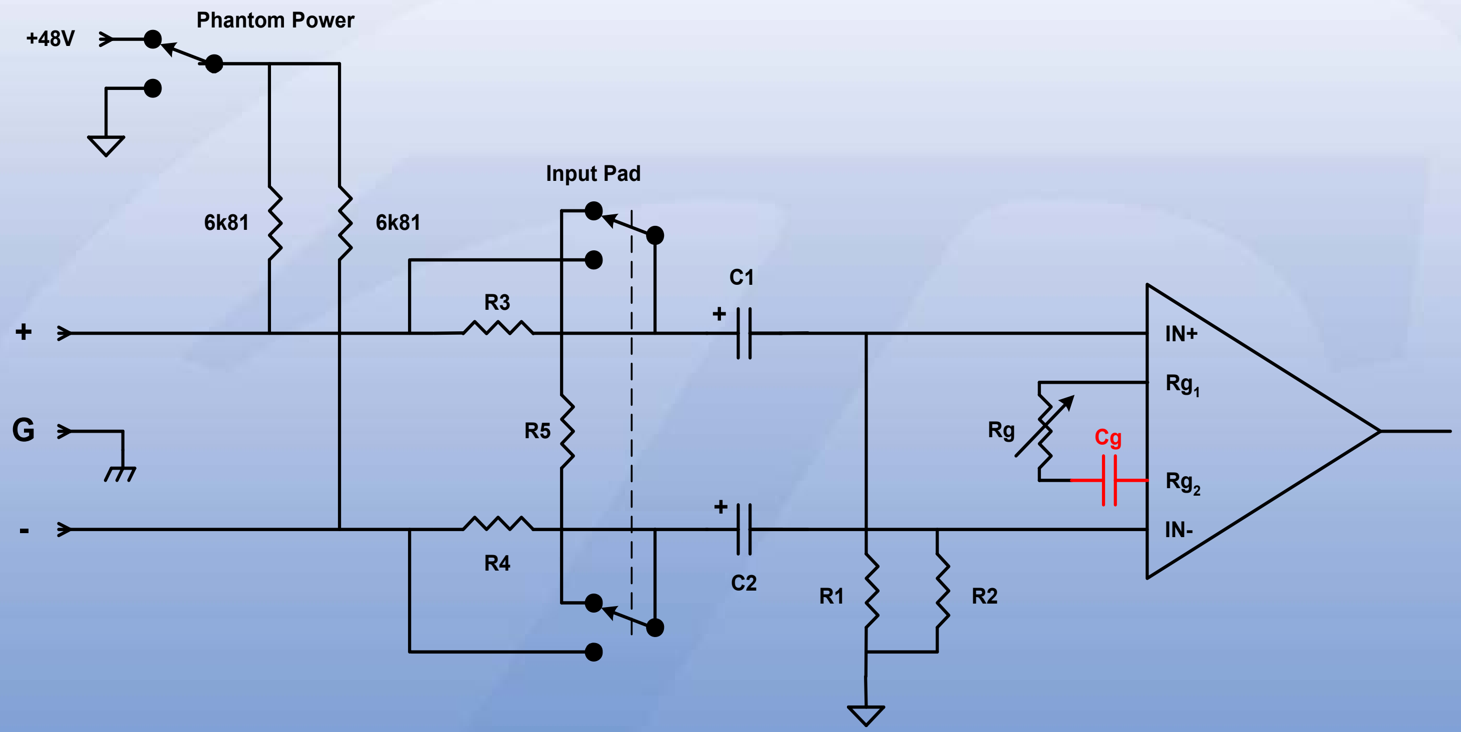
DC Offset Changes



- Changes in gain can result in the DC offset changes at the output of the amplifier

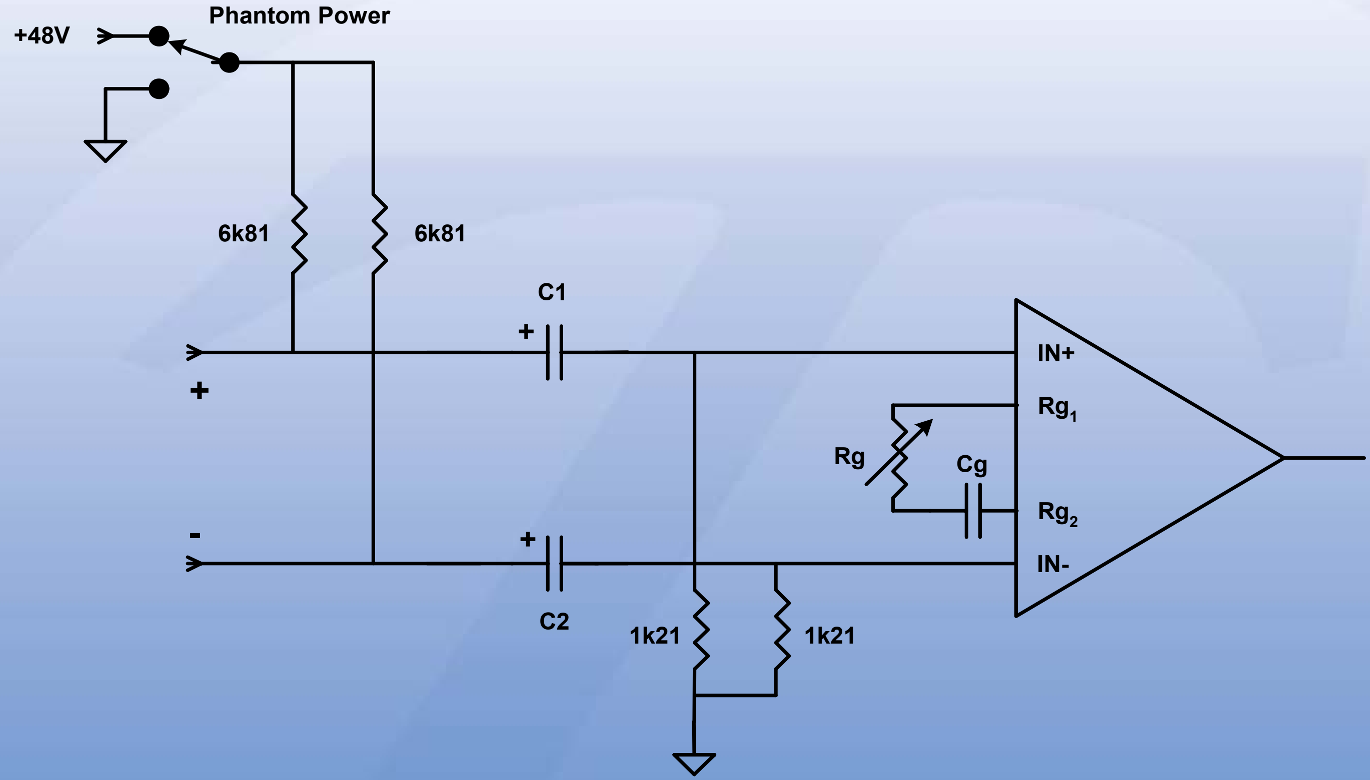
- 2 solutions are available
  - Adding a capacitor (Cg) sets the DC gain to a fixed value and avoids these offset changes
  - A servo-amplifier can also be effective, but we don't have time to discuss them today

Trade-offs with Cg



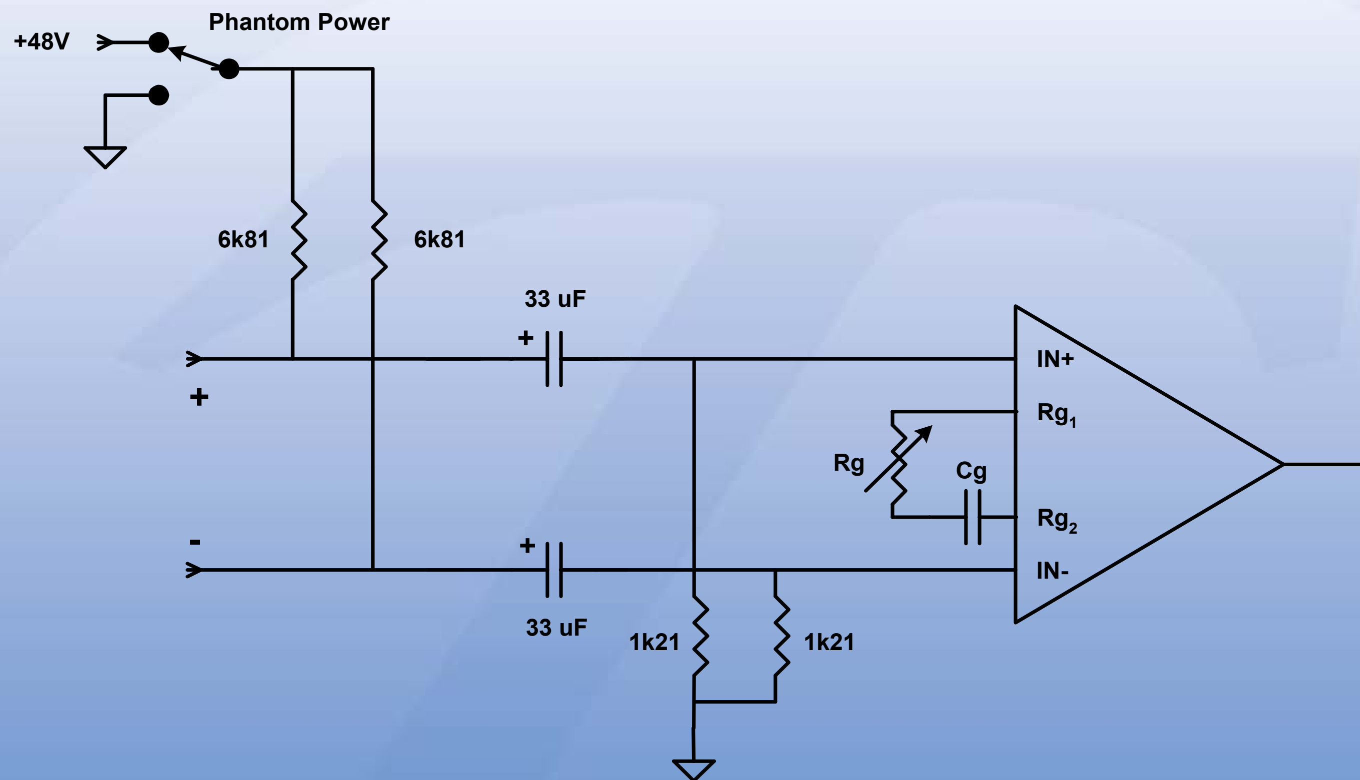
- Rg and Cg create a high-pass filter in the signal path
- Rg can vary from <5 to >10k ohms
- Cg must have a very large capacitance to avoid low frequency audio attenuation
  - Worst at highest gain

Resistor Value Selection



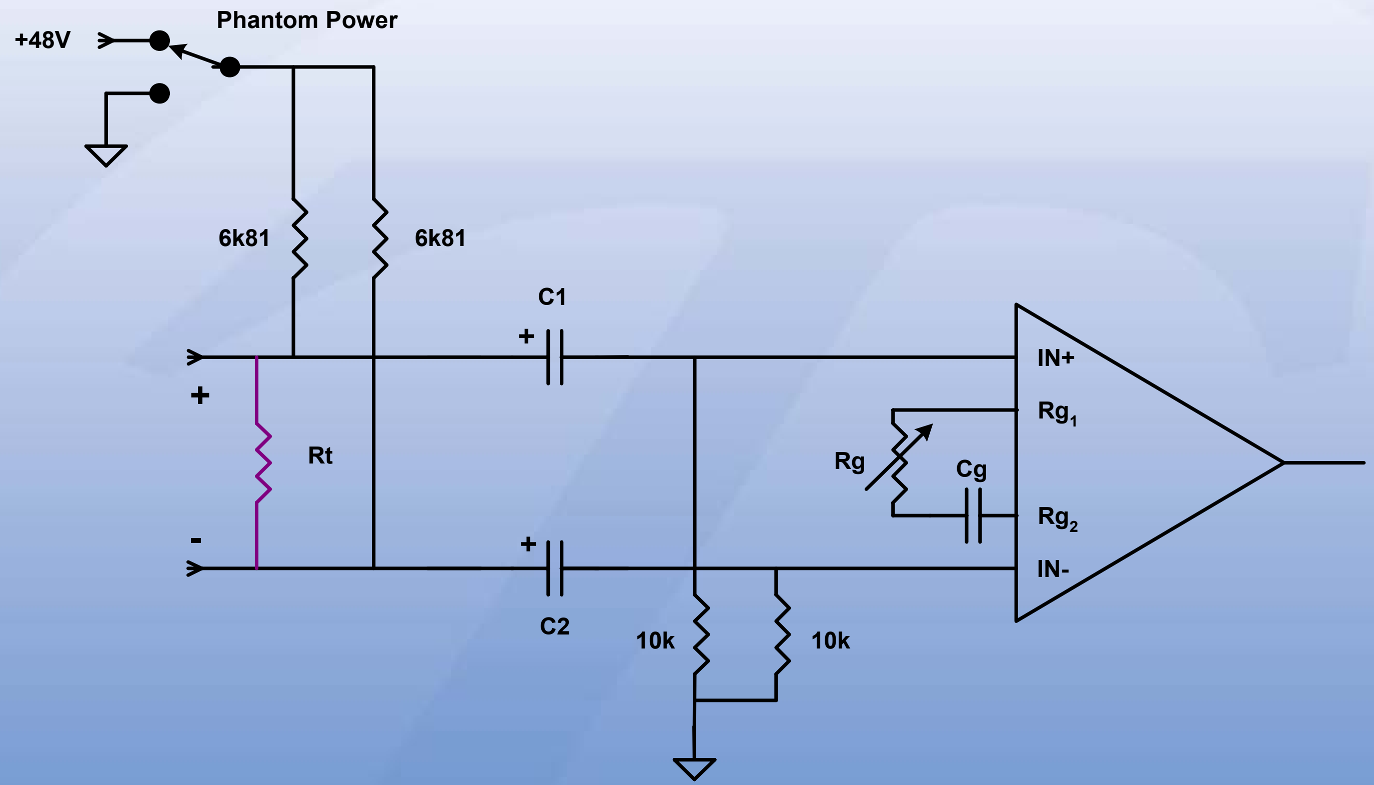
- Microphone are commonly specified for 2 to 3 kohm loads
- Differential input impedance is (R1 II 6.81k) + (R2 II 6.81k)
- Therefore, suitable values for R1 & R2 are between 1172 and 1924 ohms

Capacitor Value Selection



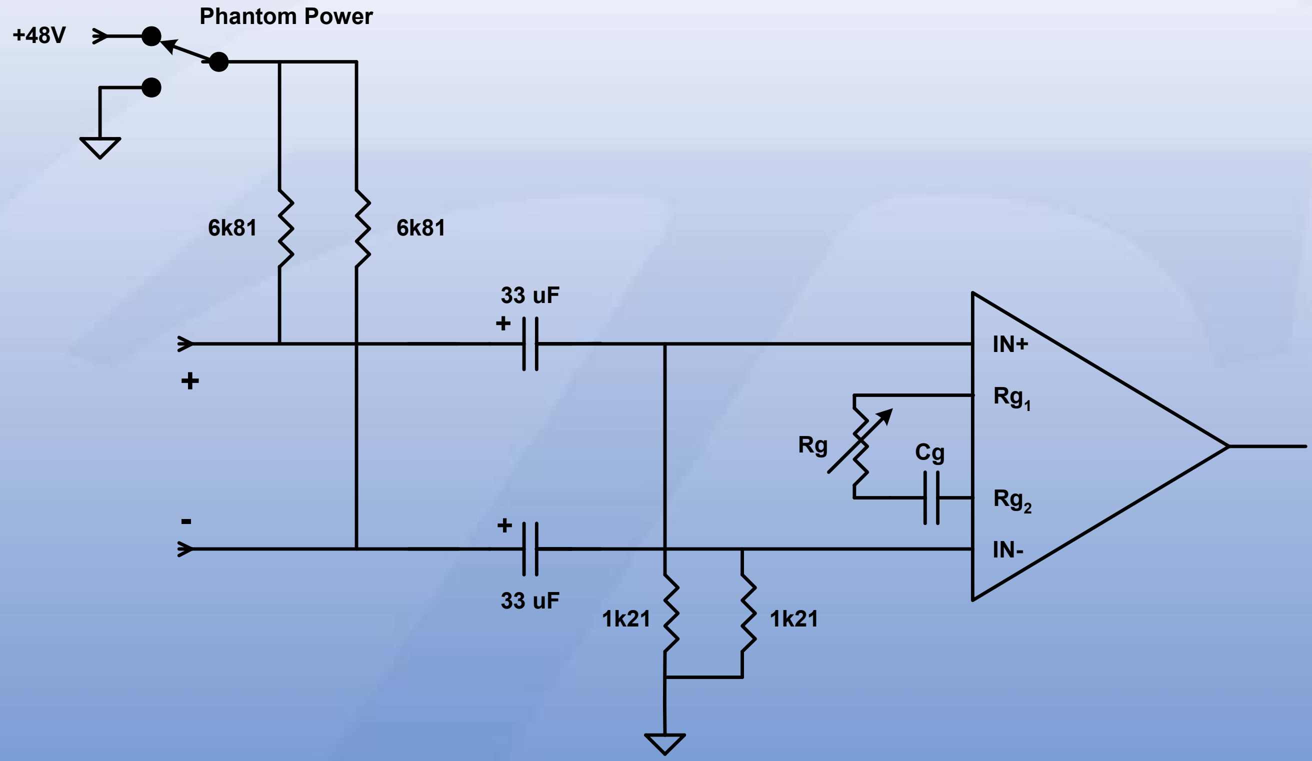
- High-pass filter corner frequency is set by the blocking capacitor and bias resistor and is equal to 1 / (2 x pi x R x C)
- For a 5 Hz corner frequency, the minimum values for C1 & C2 are 26 uF
- The next largest standard value is 33 uF
- Results in a nominal corner frequency of about 4 Hz

Alternative Resistor-Capacitor Value Selection



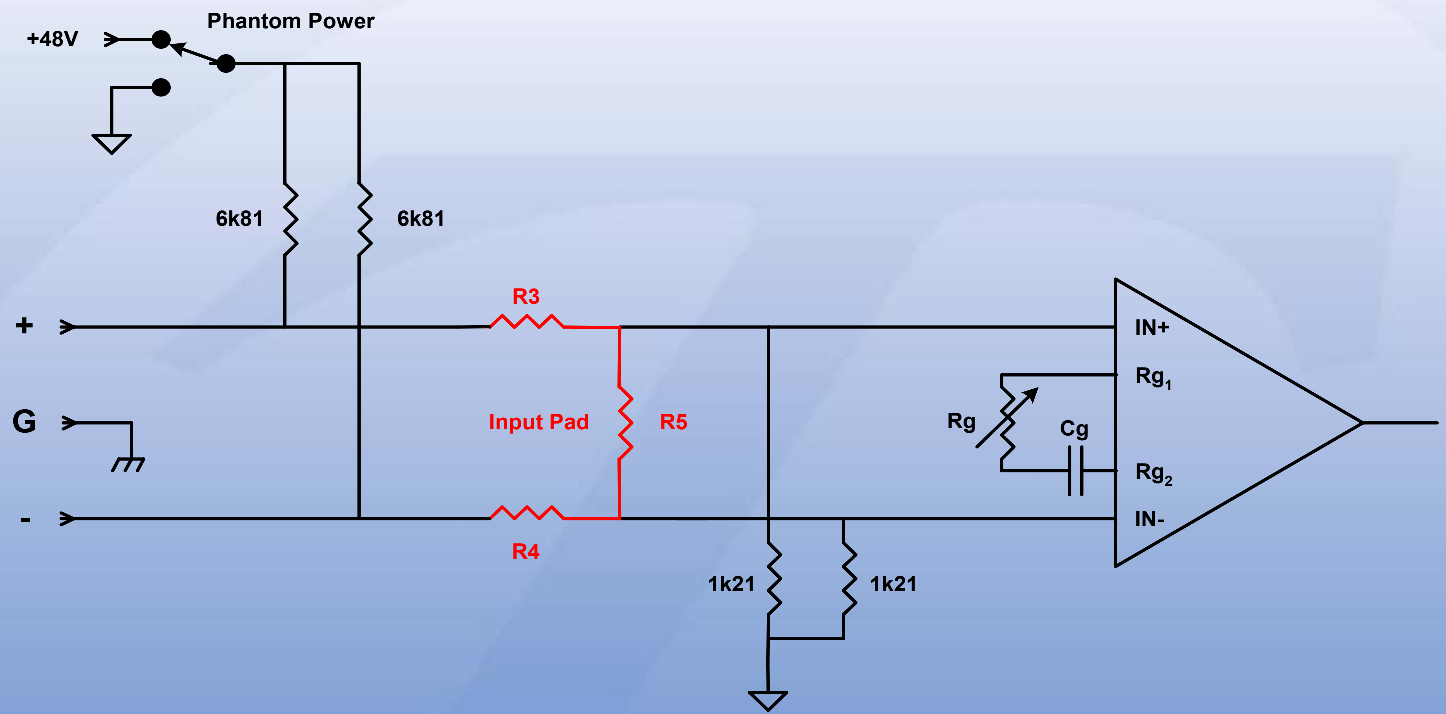
– **C1 and C2 can be made smaller if bias resistors are made larger**
– **Rin is defined by Rt**
– **However, C1 and C2 convert 1/f noise to 1/f^2 noise**
– **10k resistors contribute thermal noise and current noise*R**

Common Mode Rejection (CMRR)



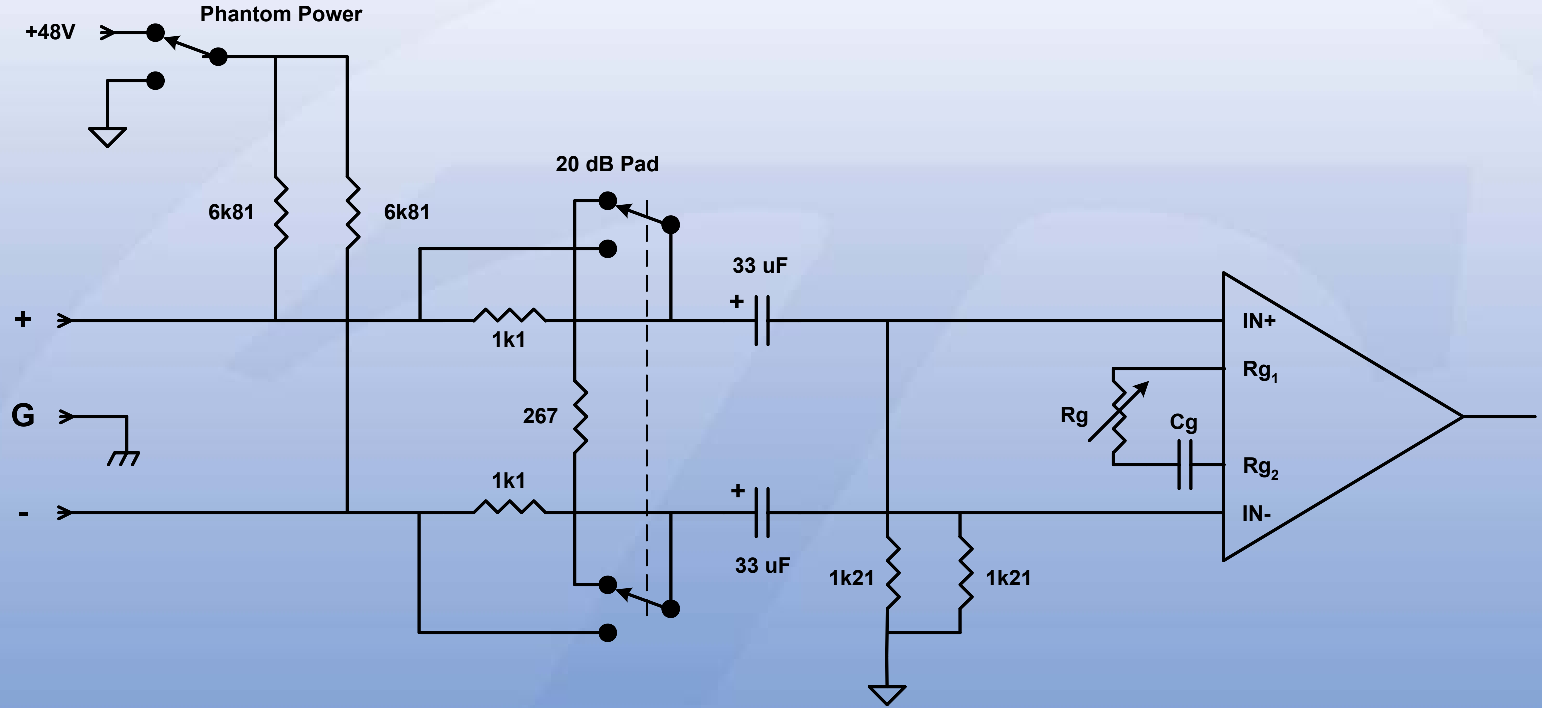
- Common-mode to differential conversion results from mismatches in:
  - 6.81 k resistors
  - 1.21 k resistors
- Low frequency CMRR affected by capacitor mismatch

U-Pad Attenuator



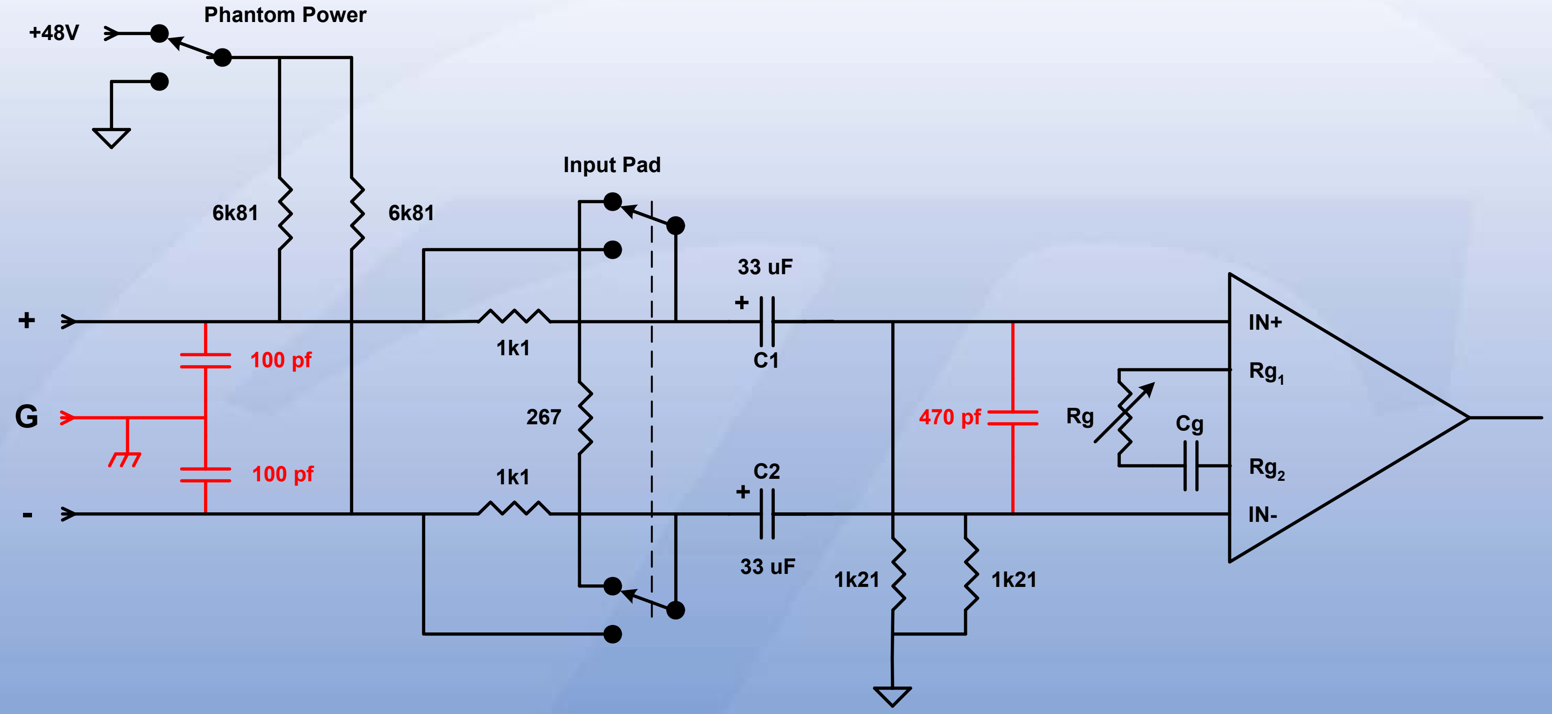
- Z_{IN} with and without pad can be closely matched
- Can be designed for any attenuation
  - 20dB is typical
- Noise performance is degraded
- Better noise, less headroom with less attenuation

Example -20 dB Input Pad



- Z_{IN} with and without pad is approximately 2k
- 20 dB Attenuation
- Pad output impedance is approximately 240 ohms
- See THAT Design Note DN-140 for details and alternatives

RFI Protection

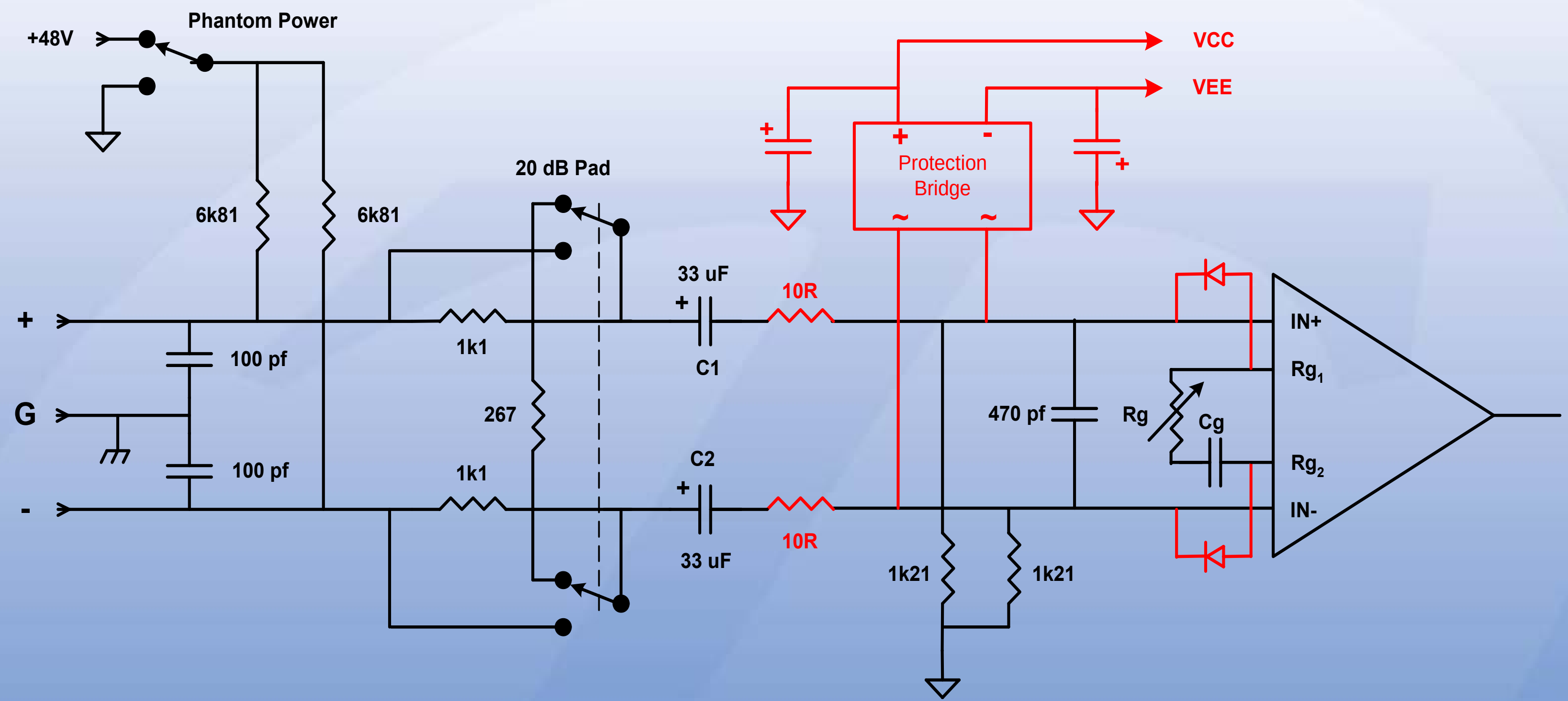


- RFI protection is required in any practical design
- 100 pf caps at the input connector attenuate differential and common-mode RFI
- 470 pf cap at amplifier input pins reduces differential high frequencies from both internal and external sources

Phantom Power Faults

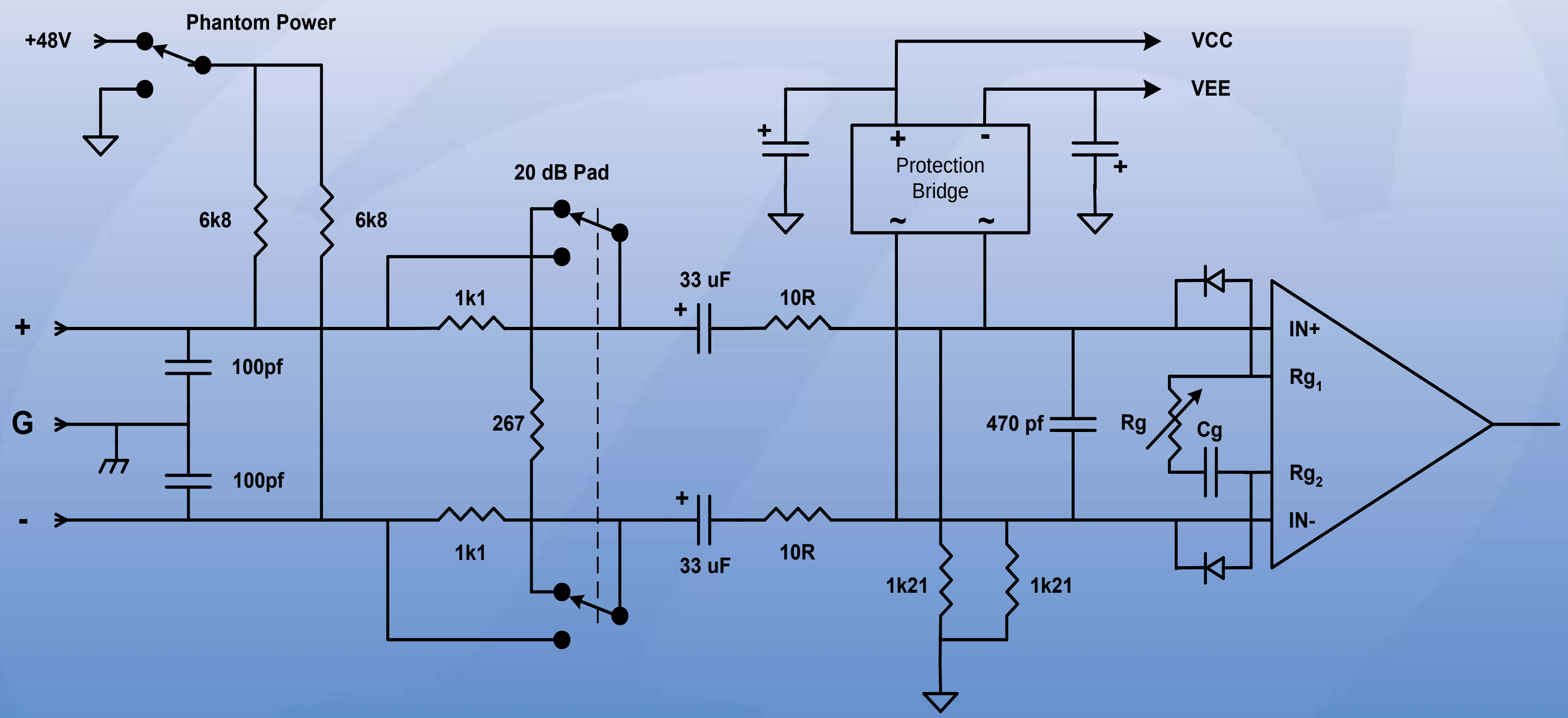
- **Shorting input pins to ground with phantom turned on**
  - **33uF coupling caps C1 & C2 start charged to 48V**
  - **Positive end of C1, C2 connect to ground**
  - **Negative end of C1, C2 driven to -48V!**
- **The shorting sequence can vary**
  - **"Single-ended": One input to ground**
  - **"Common-mode": both inputs to ground simultaneously**
  - **"Differential": One input to ground, then the other**
  - **Differential is worst**
- **Big currents flow as C1, C2 discharge**
  - **Currents over 3 *amperes* flow in the capacitors**

Phantom Fault Protection



- Limit the current with small value resistors
- Direct fault currents away from the amplifier inputs
  - Input diodes provide a conduction path which bypasses the amplifier
  - This current varies with gain setting
- Diode bridge directs fault current to rails
  - Consider impact on supply rails
  - Minimize supply transient with capacitance

Complete Microphone Preamp



THAT Corporation

References and Additional Information

- THAT Corp ***"THAT 1510/1512"*** data sheet
- THAT Corp ***"THAT 1570 & 5171"*** data sheets,
- THAT Corp ***"Design Note 140"***
- THAT Corp ***"Design Note 138"***
- THAT Corp ***"Analog Secrets Your Mother Never Told You"***
- THAT Corp ***"More Analog Secrets Your Mother Never Told You"***
- ***"The 48 Volt Phantom Menace Returns"*** **Audio Engineering Society Preprint from the 127^{th} AES Convention, Oct 2009**
- ***"The 48 Volt Phantom Menace"*** **Audio Engineering Society Preprint from the 110^{th} AES Convention, May 2001**

All THAT Corp references are available at thatcorp.com

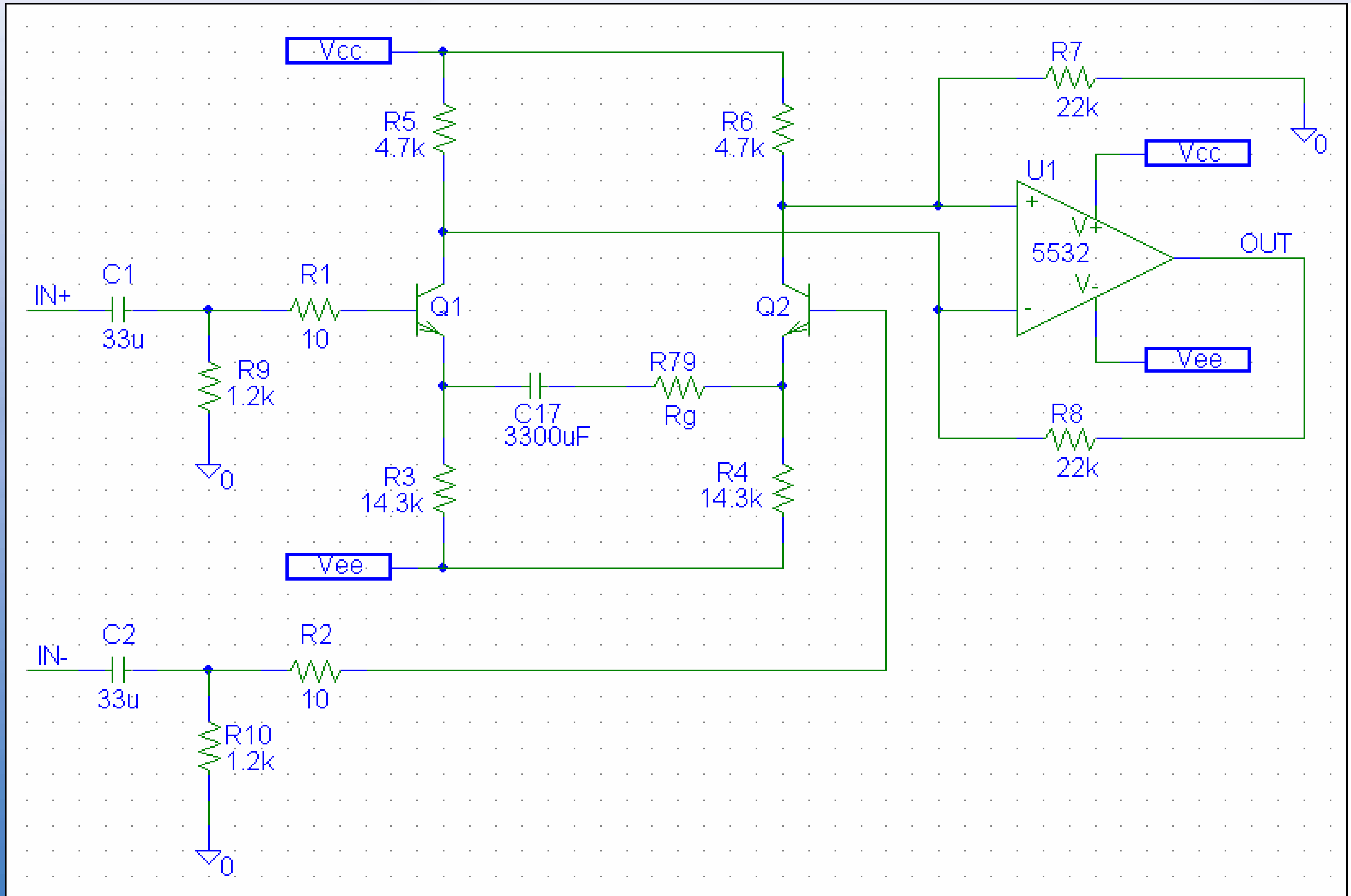
Amplifier Topologies

What's inside the triangle?

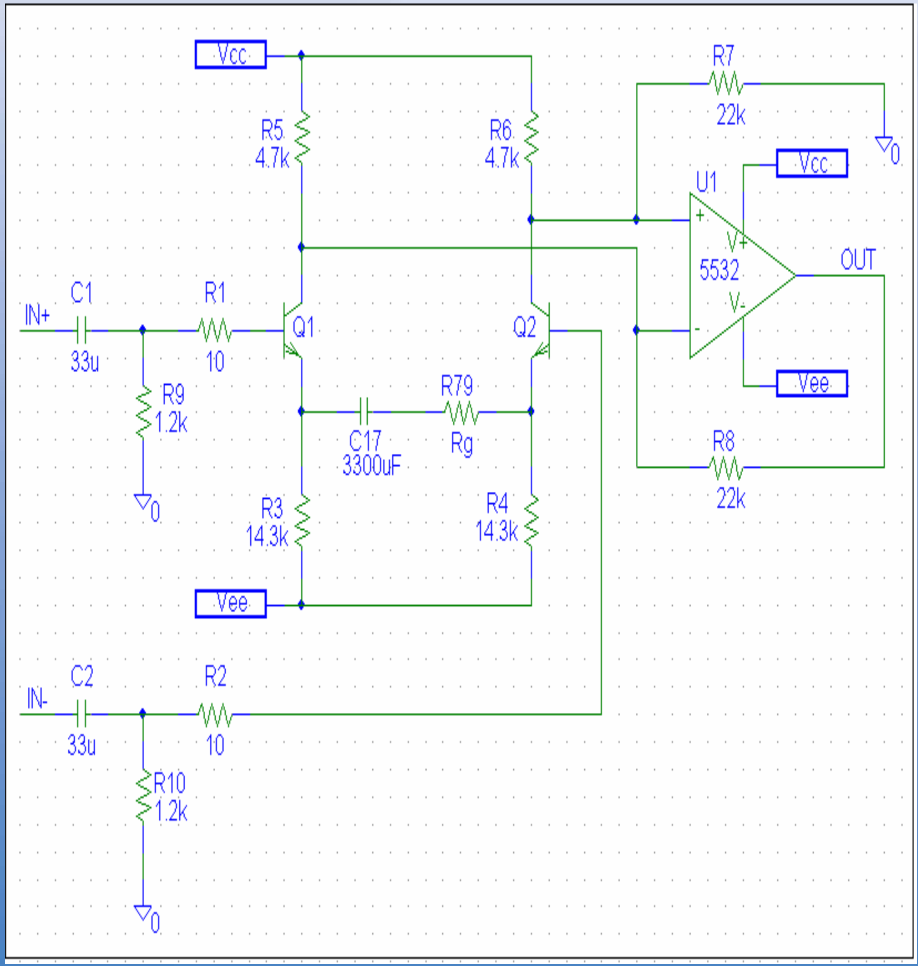
Scope

- We will concentrate on topologies that allow a wide range of gain with a single control.
- The goal is to balance the requirements for low distortion and low noise at both ends of the gain range.

Simple Mic Preamp Schematic



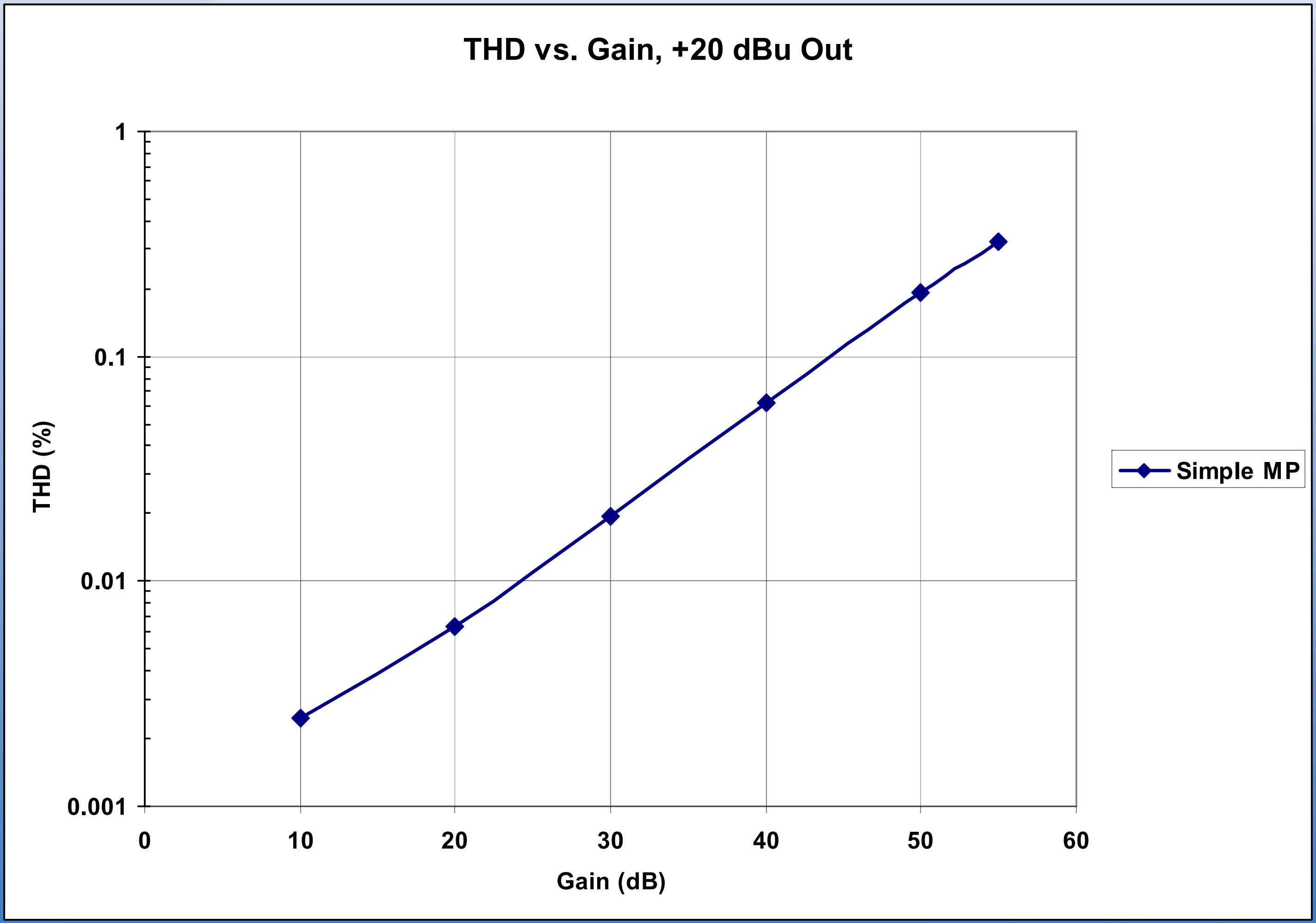
Simple Mic Preamp



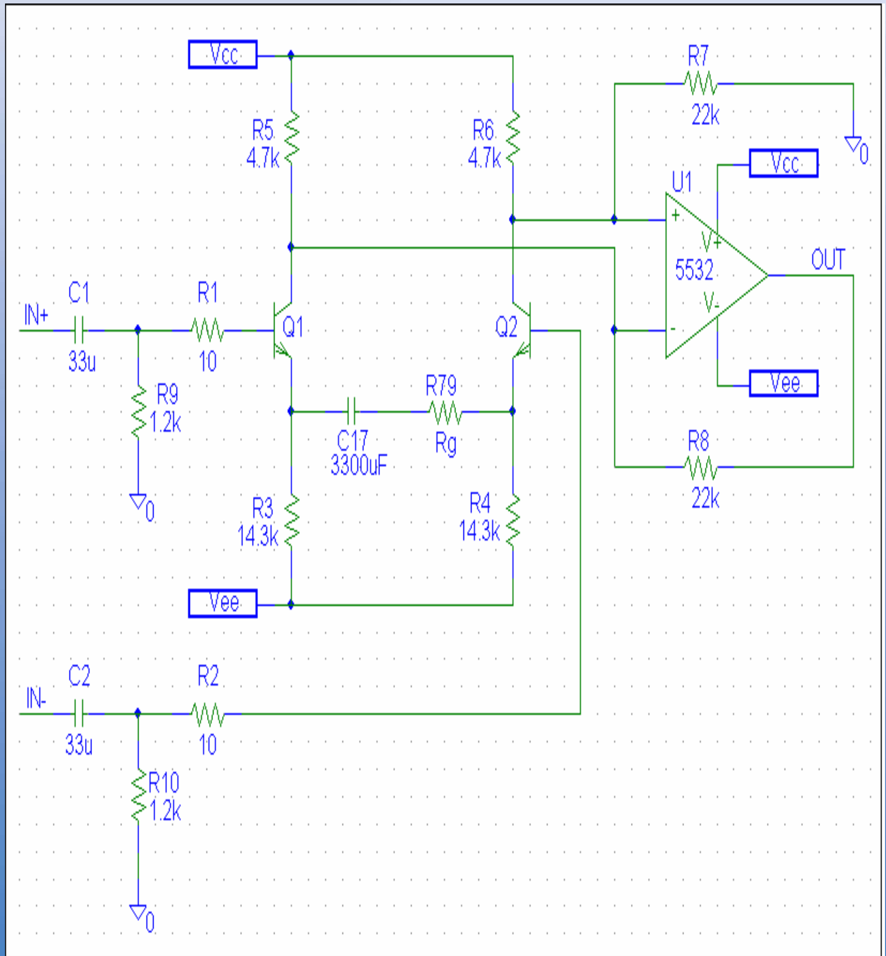
- Ic = 1 mA per input transistor, set by ($|V_{EE}|$ - V_{BE})/14.3k
- Diff Gain = 22k/(r_e + R_g/2||14.3k)
- where $r_e = 1/g_m = KT/qI_C$ = 26 ohms
- But – "r_e" is current dependent!
- Minimum gain = 22k/14.3k = 3.7 dB

Simple Mic Pre THD Performance

THD vs. Gain, 1 kHz, +20 dBu Out

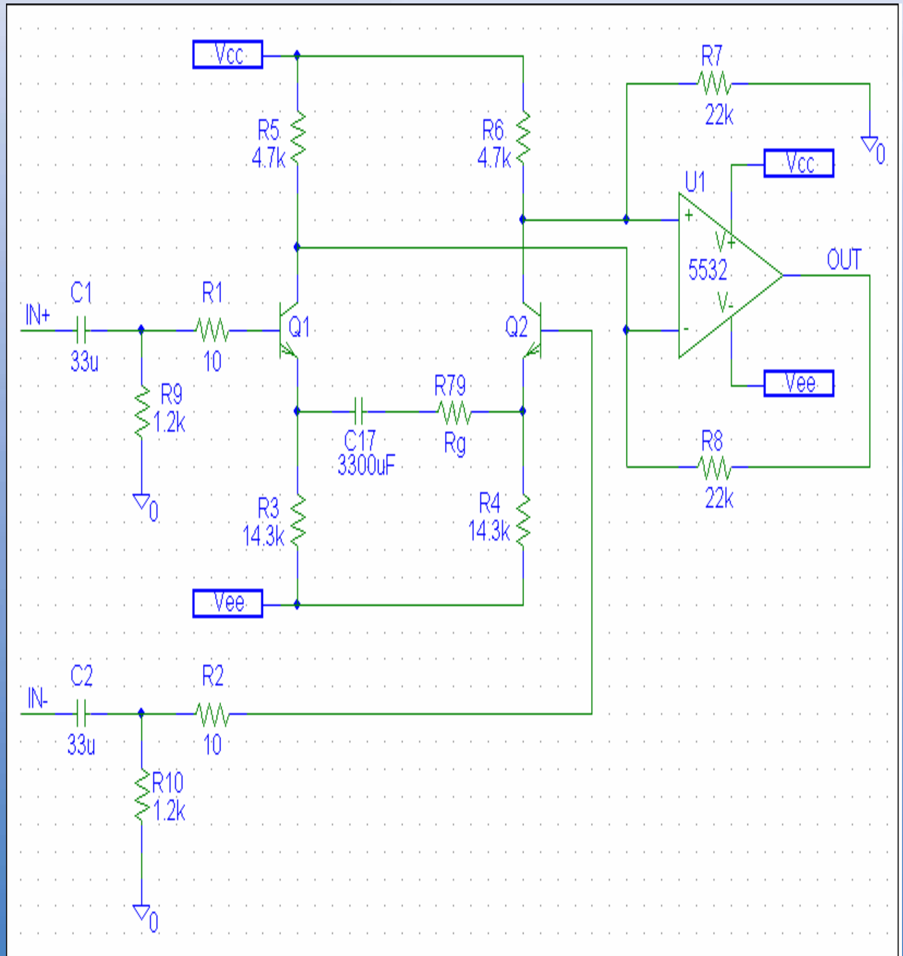


High-Gain Noise Sources of Simple Mic Preamp



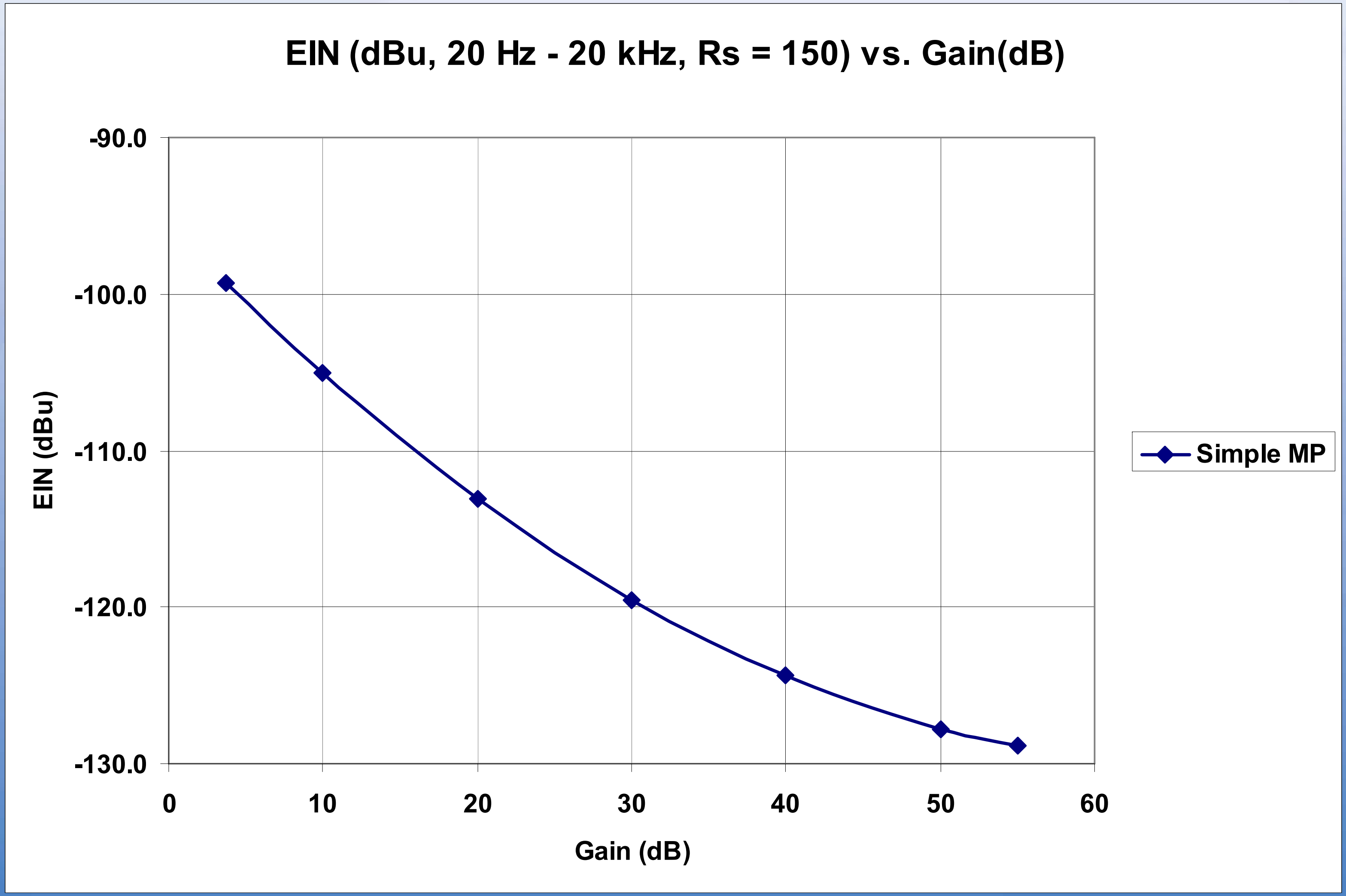
- Input noise at high gains dominated by:
- Q_1, Q_2 I_C Shot Noise (RTI) = $\frac{2\sqrt{qI_C}}{g_m} = \sqrt{4kTr_e}$
- Q_1, Q_2 r_b Thermal Noise = $\sqrt{8kTr_b}$
- R_1, R_2, R_g Thermal Noise = $\sqrt{4kT(R_1+R_2+R_g)}$

Low-Gain Noise Sources of Simple Mic Preamp

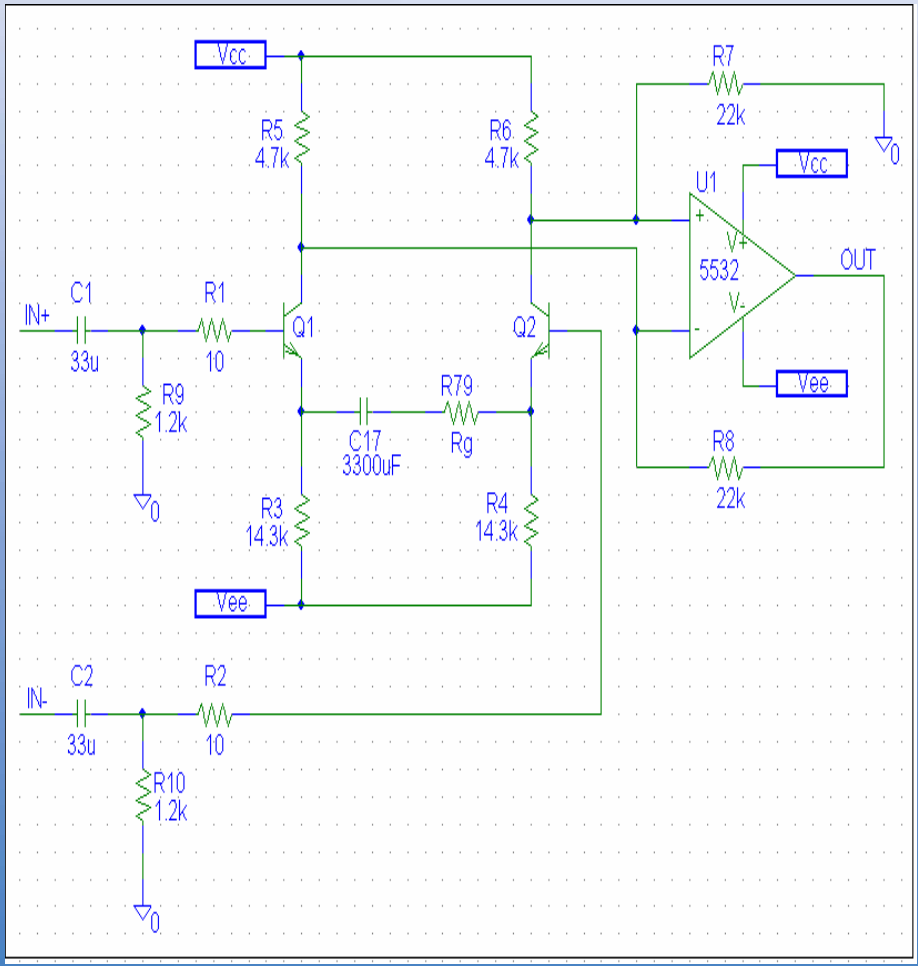


- Input noise at low gains dominated by:
- Thermal Noise of R_5 and R_6
- Thermal Noise of: $R_g \| (R_3 + R_4)$
- Q_1,Q_2 I_B shot noise across $\frac{R_g \| (R_3 + R_4)}{2}$
- EIN of U1

Noise Performance of Simple Mic Preamp



CMRR Performance of Simple Mic Preamp

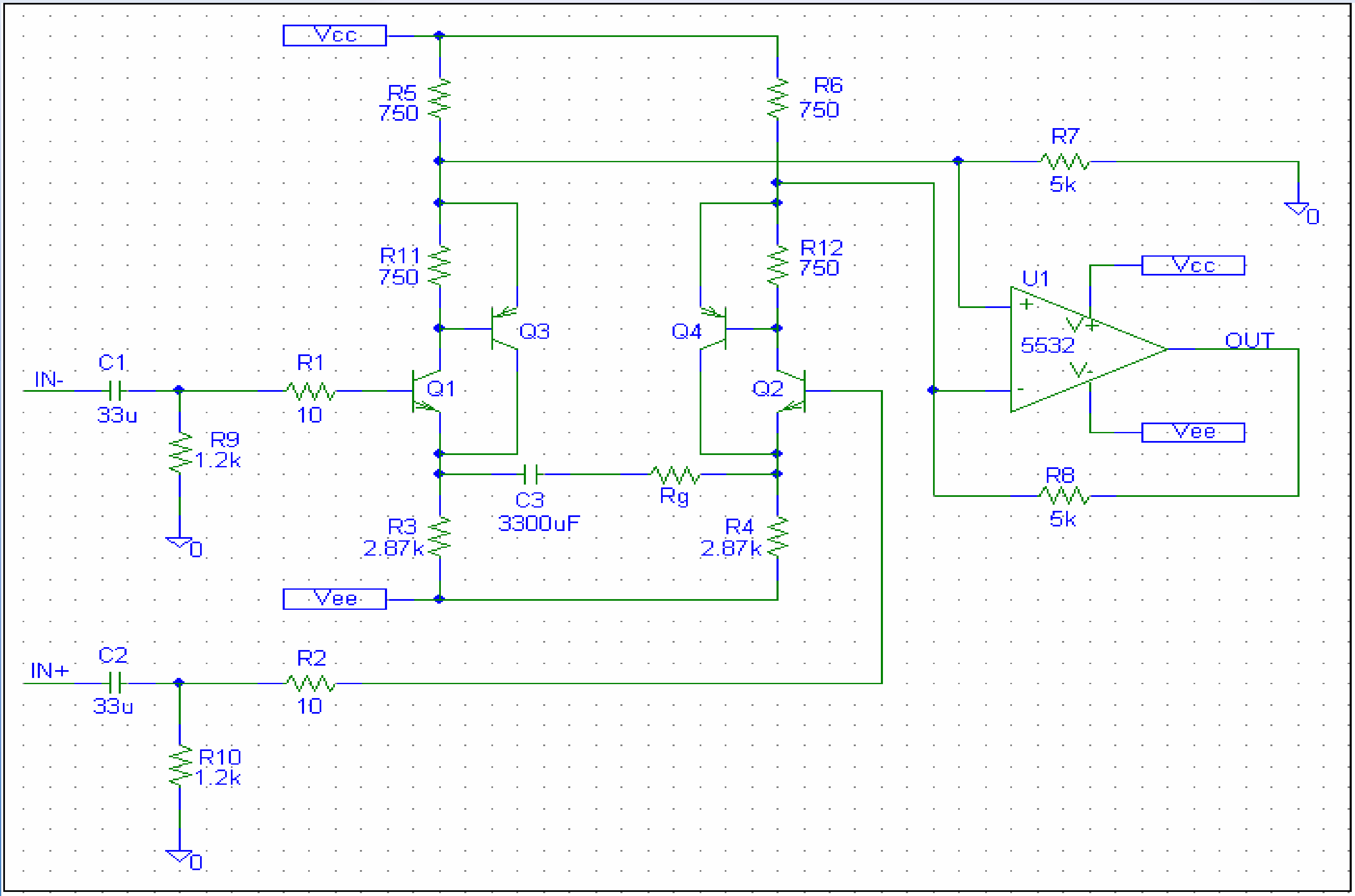


- CM to differential conversion can occur due to mismatches in:
- R_3 and R_4
- R_5 and R_6
- R_7 and R_8
- R_9 and R_{10}
- Q_1 and Q_2

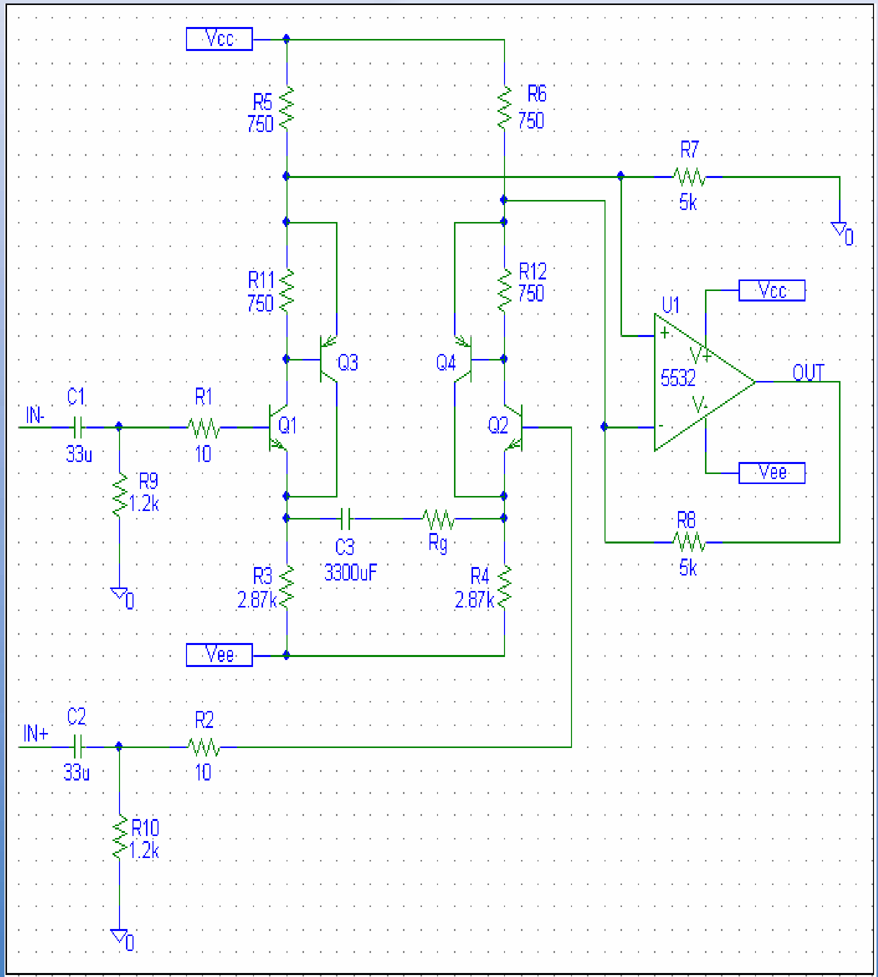
Simple Mic Preamp

- 2 Transistors and 1 Opamp
- Very Low Cost
- Marginal Performance

Complementary Feedback Pair Mic Preamp

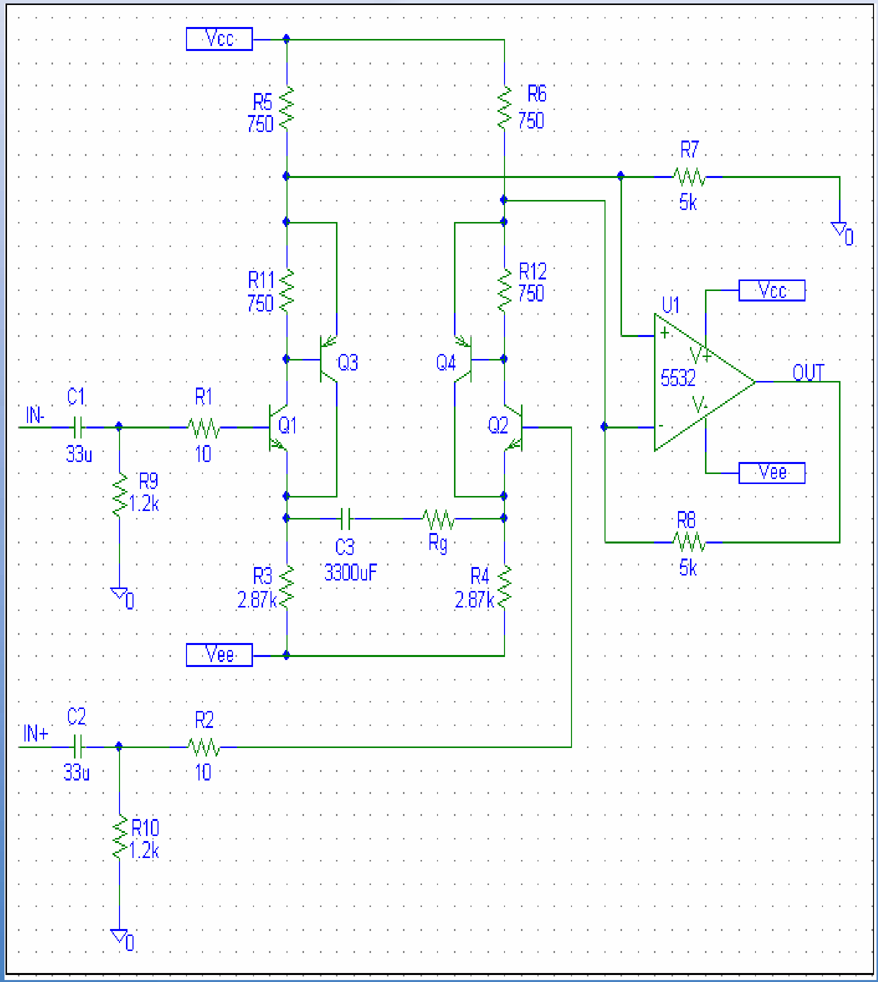


CFP Mic Preamp



- Input devices are each a compound transistor (Complementary Feedback Pair)
- NPN Input Ic set by Vbe/750 ohms (1 mA each)
- NPN Ic + PNP Ic set by (|Vee|-Vbe)/2k87 (5 mA per side)

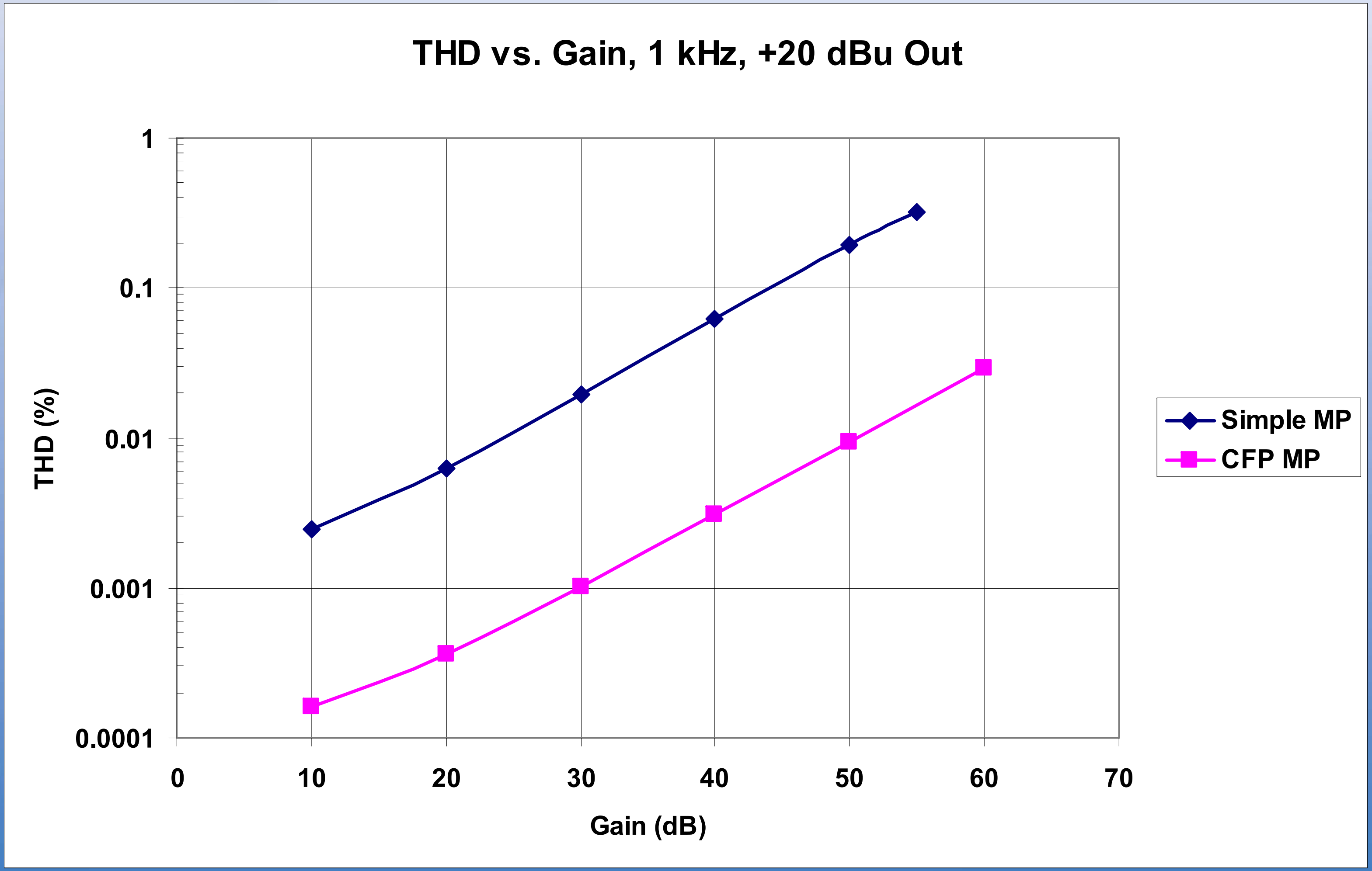
CFP Mic Preamp



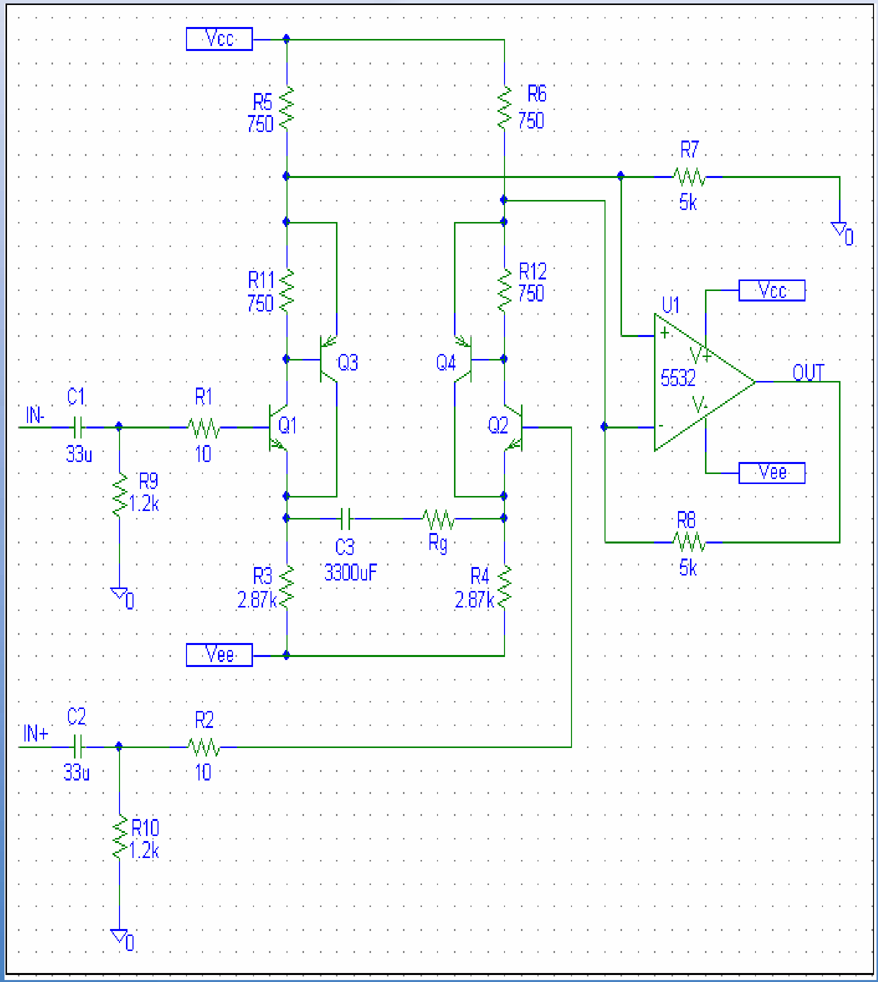
- Output impedance at NPN emitters is now: $r_o = \dfrac{1}{g_m(1+\beta_{PNP} \bullet \dfrac{R_{11}}{r_{\pi PNP}+R_{11}})}$
- Still current dependent, but much lower
- Gain = 5k/(r_e/74 + Rg/2||2.87k)
- Minimum Gain = 5k/2.87k = 4.8 dB

THD Performance of CFP Mic Preamp

THD vs. Gain, 1 kHz, +20 dBu Out

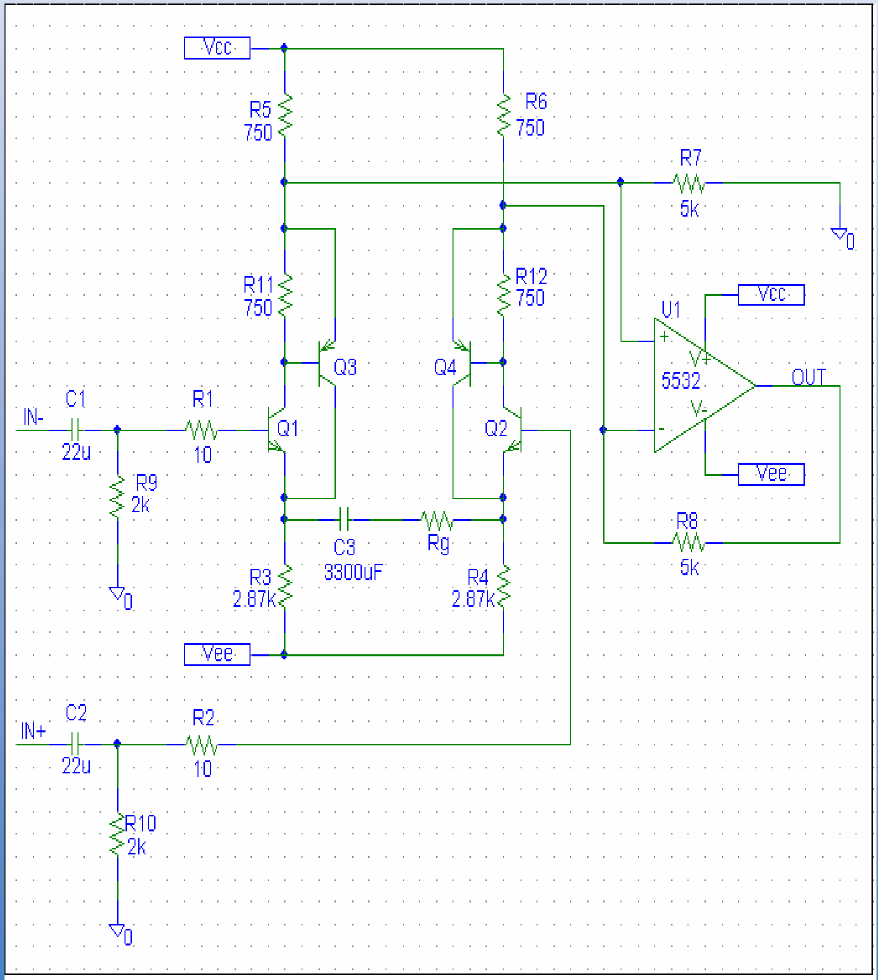


High-Gain Noise Sources of CFP Mic Preamp



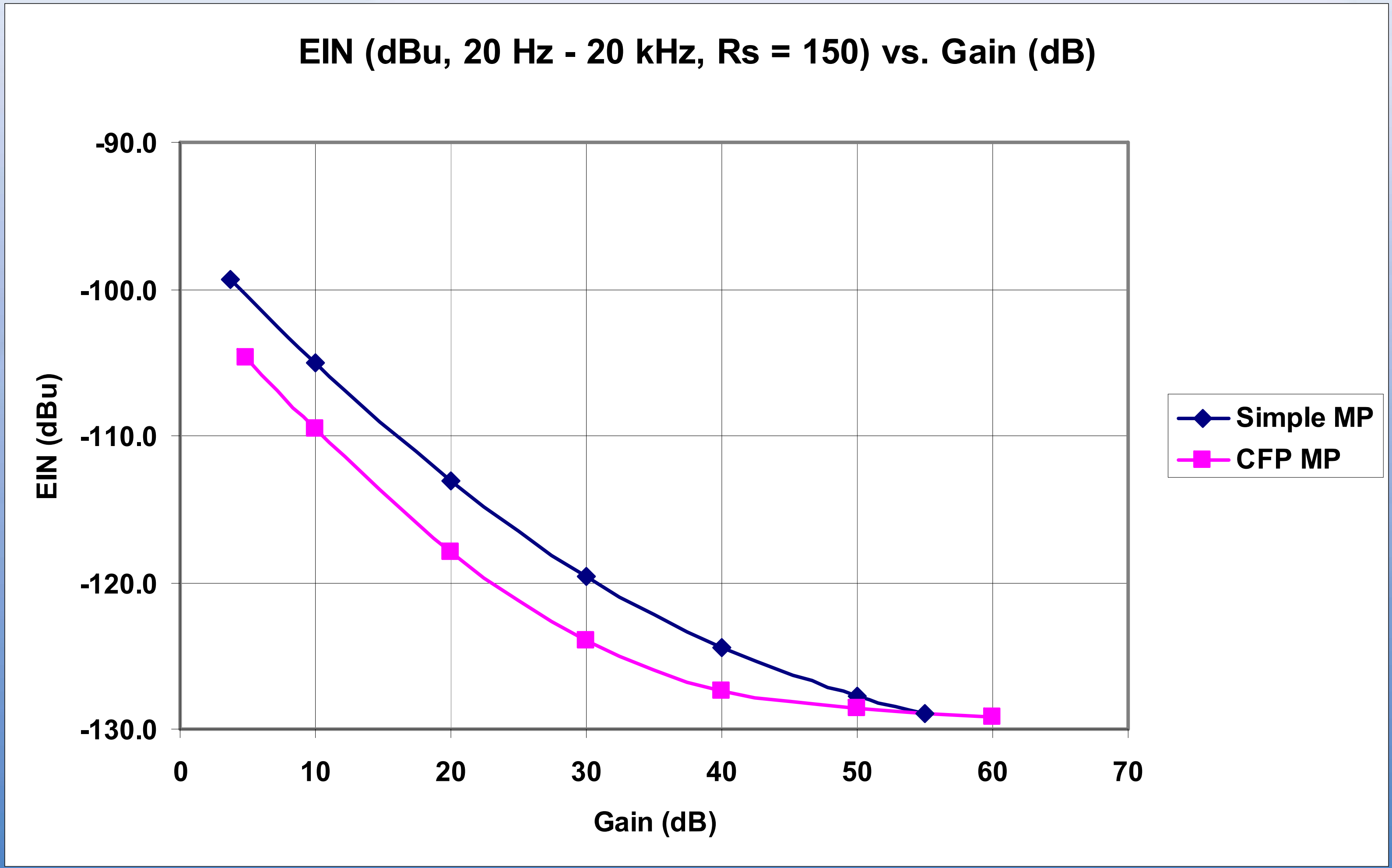
- Input noise at high gains dominated by:
- Q_1, Q_2 I_C Shot Noise (RTI) = $\frac{2\sqrt{qI_C}}{g_m} = \sqrt{4kTr_e}$
- Q_1, Q_2 r_b Thermal Noise = $\sqrt{8kTr_b}$
- R_1, R_2, R_g Thermal Noise = $\sqrt{4kT(R_1+R_2+R_g)}$

Low-Gain Noise Sources of CFP Mic Preamp

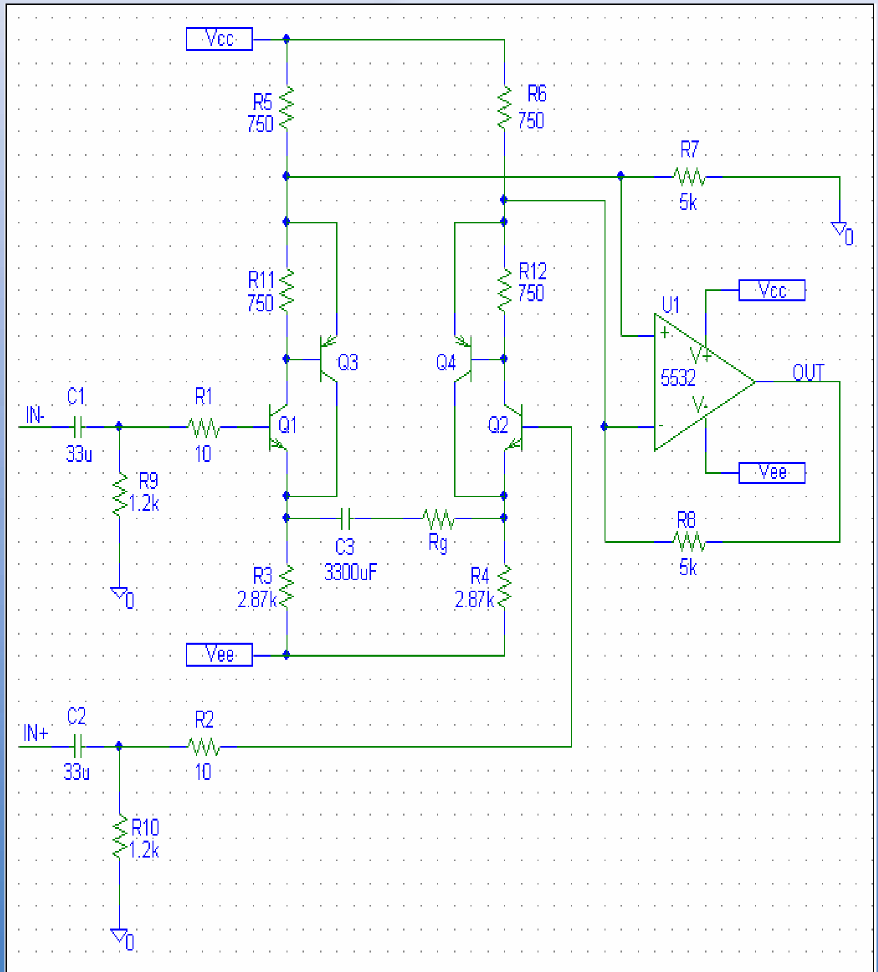


- Input noise at low gains dominated by:
- Thermal Noise of R_5 and R_6
- EIN of U1
- Thermal Noise of $R_g \| (R_3 + R_4)$
- Q_1,Q_2 I_B shot noise across $\frac{R_g \| (R_3 + R_4)}{2}$

Noise Performance of CFP Mic Preamp



CMRR Performance of CFP Mic Preamp



- CM to Diff conversion can occur due to mismatches in:
- R_3 and R_4
- R_5 and R_6
- R_7 and R_8
- R_9 and R_{10}
- R_{11} and R_{12}

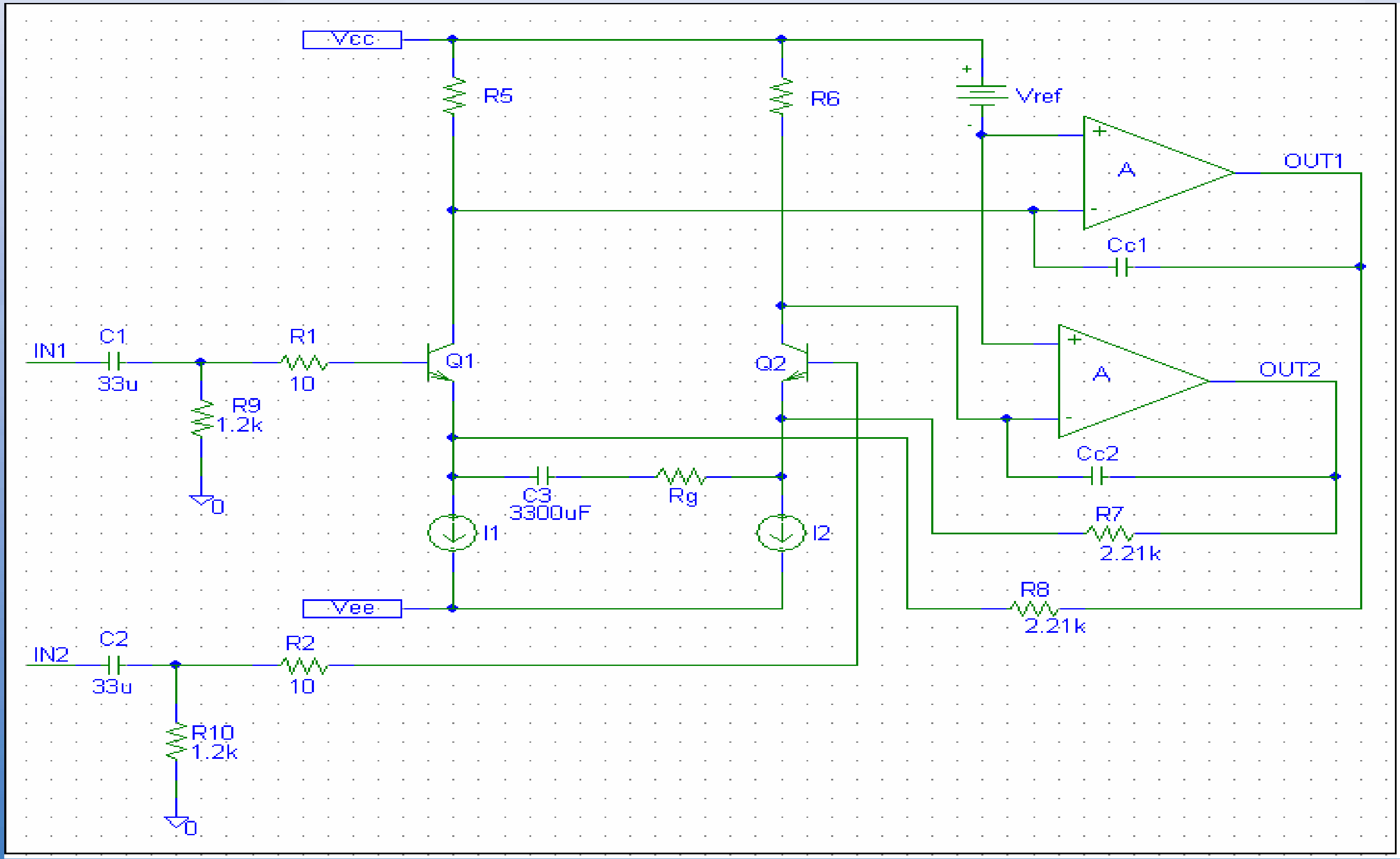
CFP Mic Preamp

- Performance is improved over Simple Mic Preamp
- Distortion performance still not terrific at high gains
- Power consumption is high to get that performance
- Cost is modest

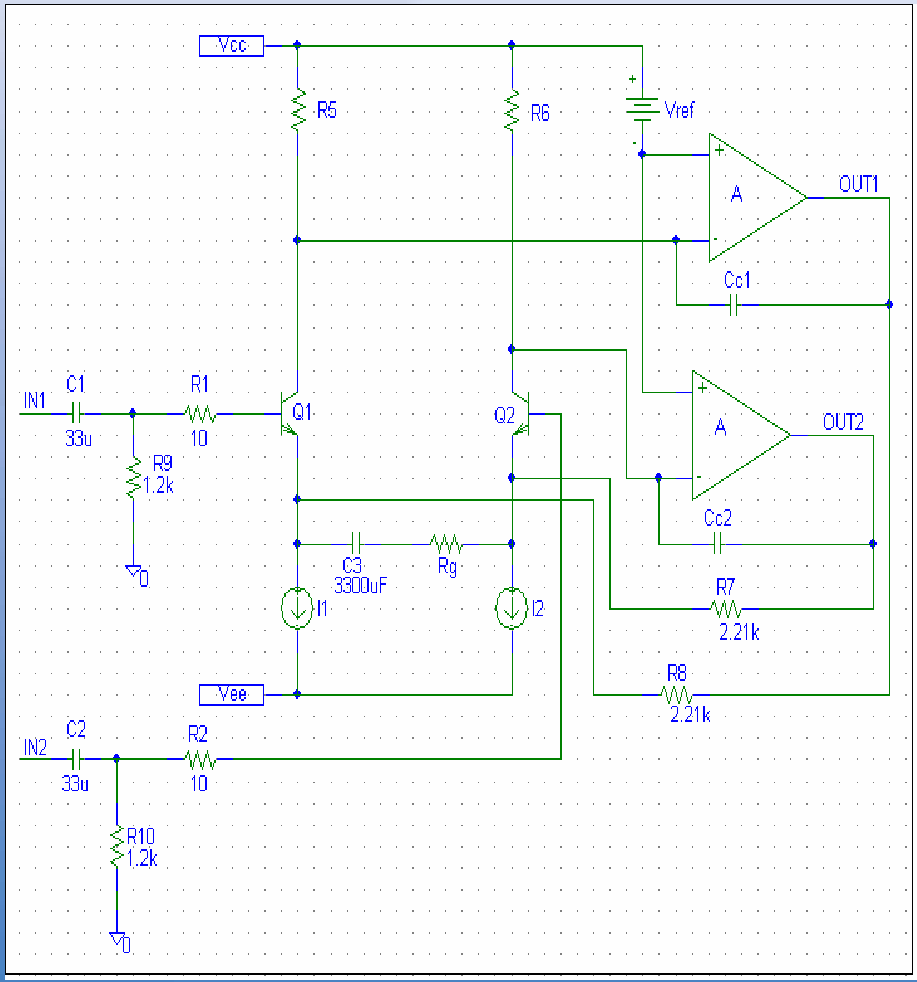
Current Feedback Instrumentation Amp

- Topology used in most integrated mic preamp ICs including ADI - SSM2019, TI - INA103, INA163, INA217, THAT – 1510,1512, 1570 and possibly others
- Scott Wurcer – AD524 IEEE Paper 12/82
- Graeme Cohen AES Paper – “Double Balanced Microphone Amplifier” 9/84

Basic CFIA Mic Preamp Schematic

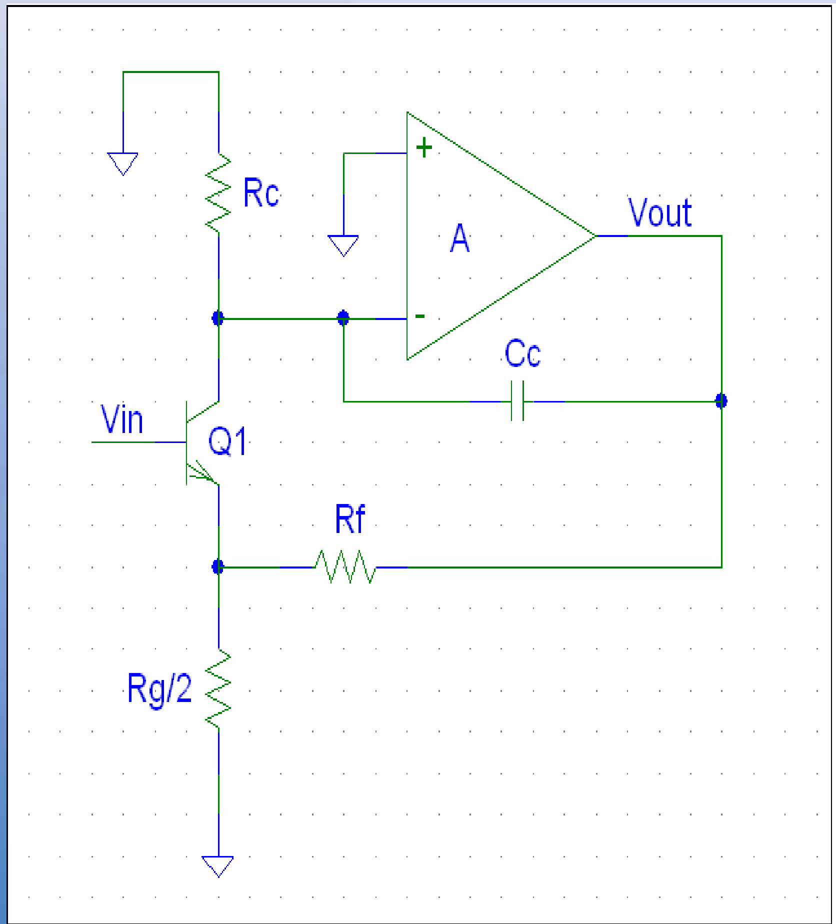


Basic CFIA Mic Preamp



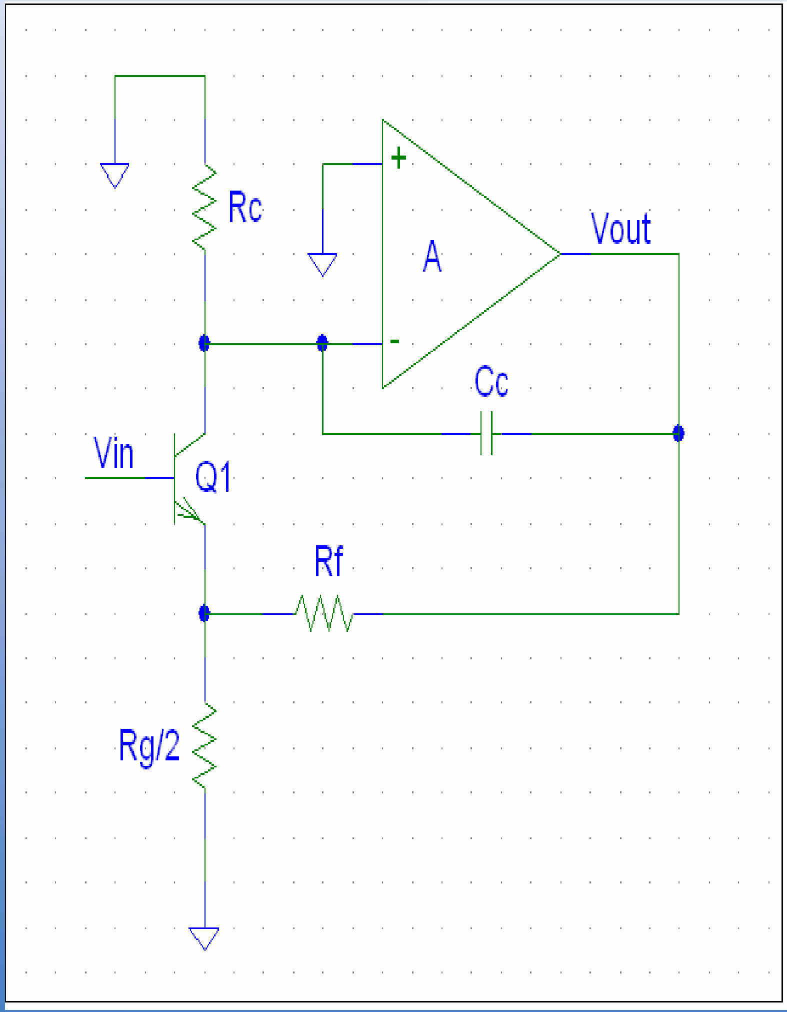
- Input Transistor Ic = Vref/R_5
- Current Sources I_1 and I_2 are for "bias current cancellation" only
- Gain = $1 + (2R_7/R_g)$
- Min. gain = 0 dB

What's "Current Feedback"?



- Closed loop bandwidth stays substantially constant with closed loop gain until r_e becomes a significant factor
- Cc charging current is not limited

"Half Circuit" of CFIA



$$\frac{V_{out}}{V_{in}} = \frac{\dfrac{R_C \bullet A}{\left[r_e + (R_F \| R_G/2)\right](R_C C_M S + 1)}}{1 + \dfrac{R_C \bullet A}{\left[r_e + (R_F \| R_G/2)\right](R_C C_M S + 1)} \bullet \dfrac{R_G}{2R_F + R_G}} = \frac{A}{1 + A\beta}$$

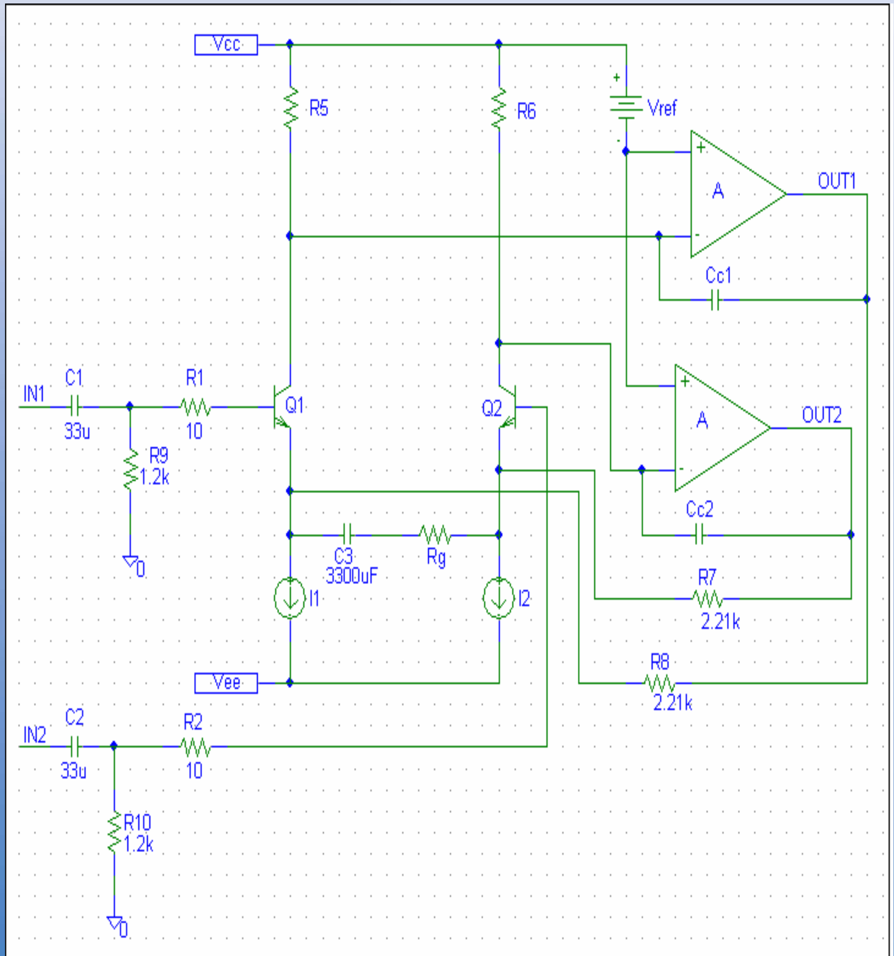
Where $C_M = C_C(A+1)$, $r_e = 1/gm$

For $r_e \ll (R_F \| R_G/2)$:

$$\frac{V_{out}}{V_{in}} = \frac{\dfrac{R_C \bullet A}{(R_F \| R_G/2)(R_C C_M S + 1)}}{1 + \dfrac{R_C \bullet A}{R_F(R_C C_M S + 1)}} = \frac{A}{1 + A\beta}$$

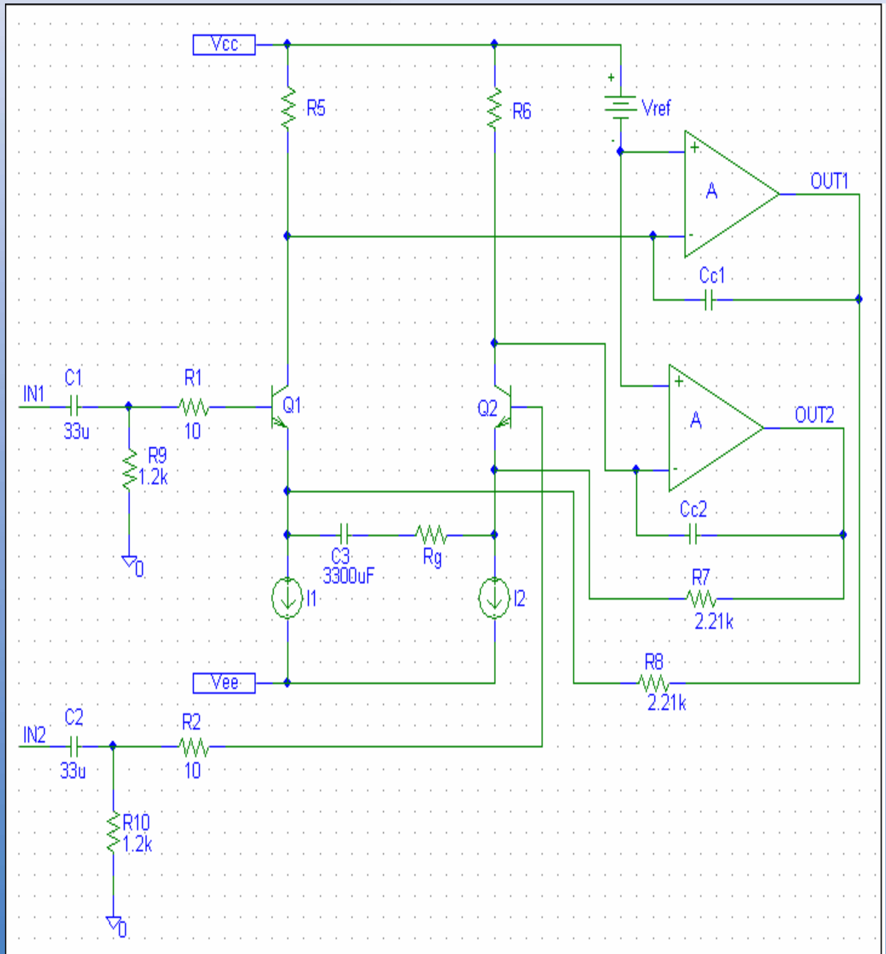
Note that the loop transmission $A\beta$ is independent of the closed loop gain if r_e is much less than the feedback network impedance

High-Gain Noise Sources of CFIA Mic Preamp



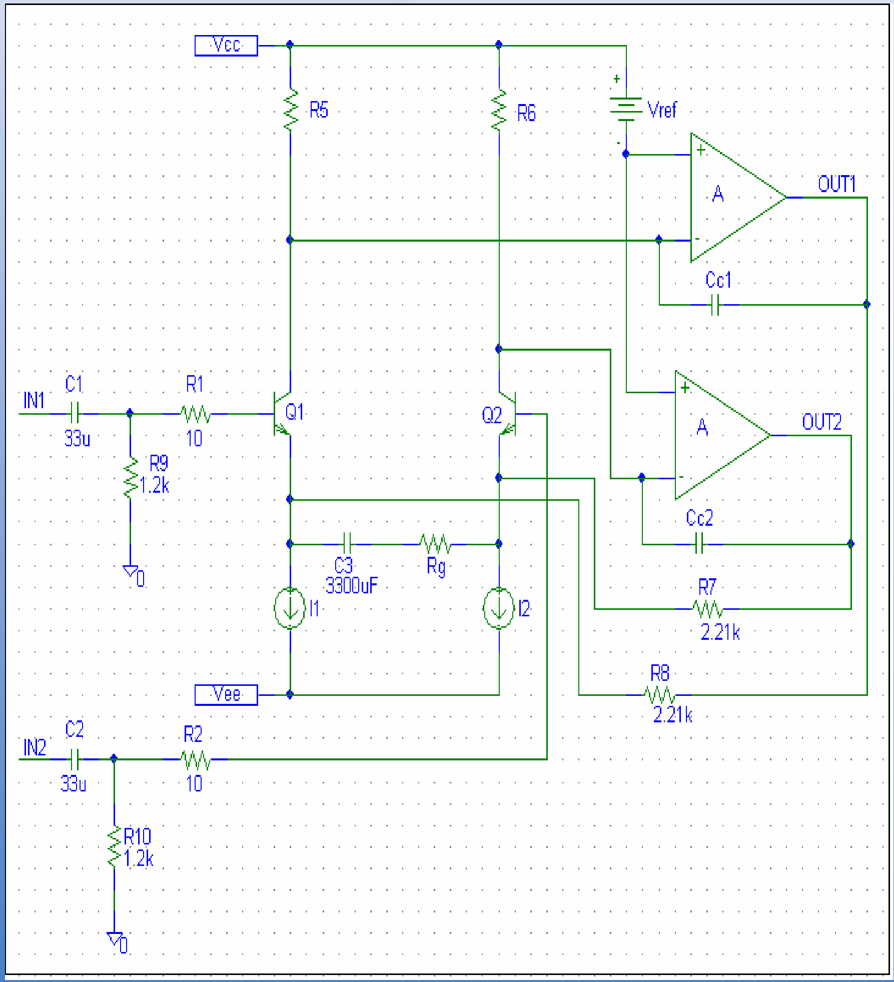
- Input noise at high gains dominated by:
- Q_1, Q_2 I_C Shot Noise (RTI) = $\frac{2\sqrt{qI_C}}{g_m} = \sqrt{4kTr_e}$
- Q_1, Q_2 r_b Thermal Noise = $\sqrt{8kTr_b}$
- R_1, R_2, R_g Thermal Noise = $\sqrt{4kT(R_1+R_2+R_g)}$

Low-Gain Noise Sources of CFIA Mic Preamp



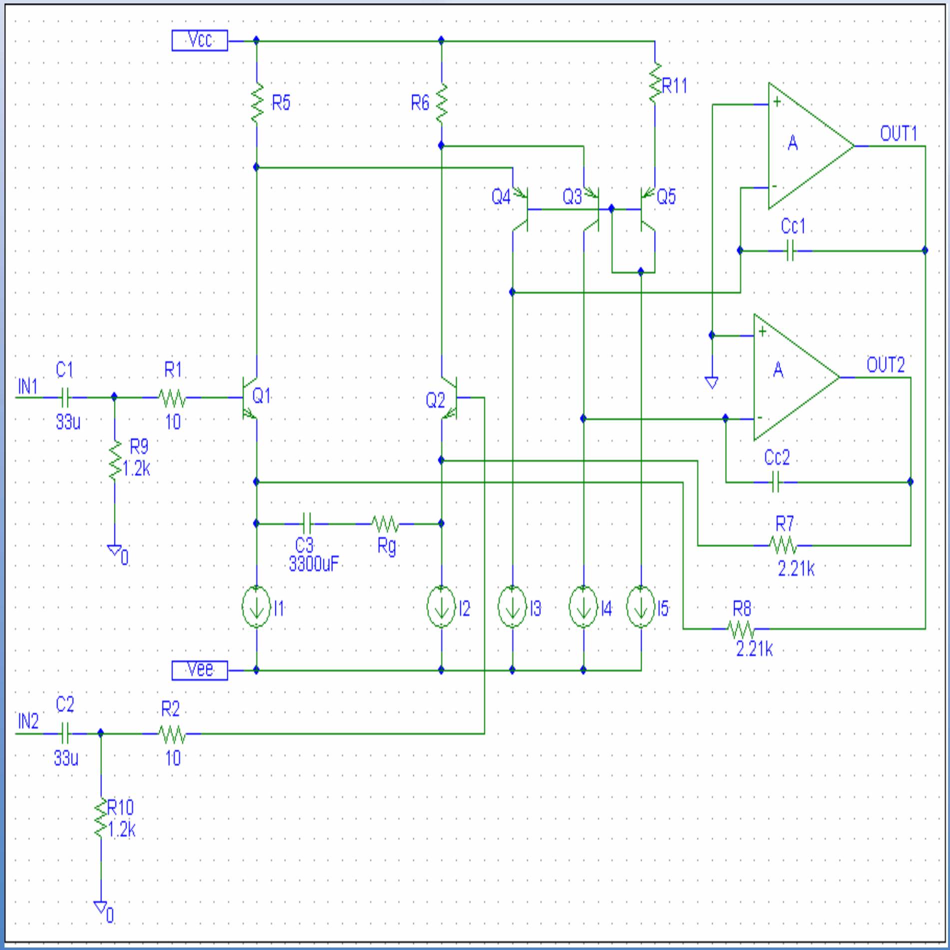
- Input noise at low gains dominated by:
- Thermal Noise of R_5, R_6
- Noise of I_1, I_2
- Thermal Noise of $R_g \| (R_7 + R_8)$
- Q_1,Q_2 I_B shot noise across $\frac{R_g \| (R_7 + R_8)}{2}$
- EIN of U1, U2

CMRR Performance of CFIA Mic Preamp



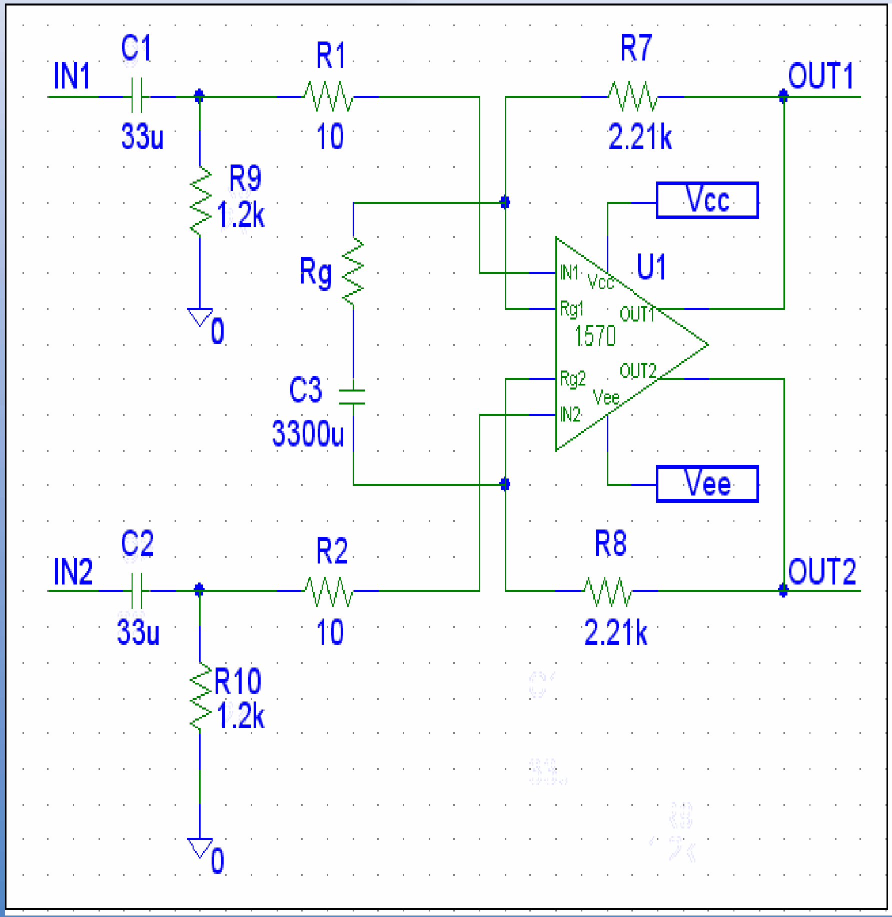
- Unity CM Gain to OUT1 – OUT2
- CMRR = Differential Gain
- CM to Diff conversion can occur due to mismatches in transistors

Refinements to the CFIA



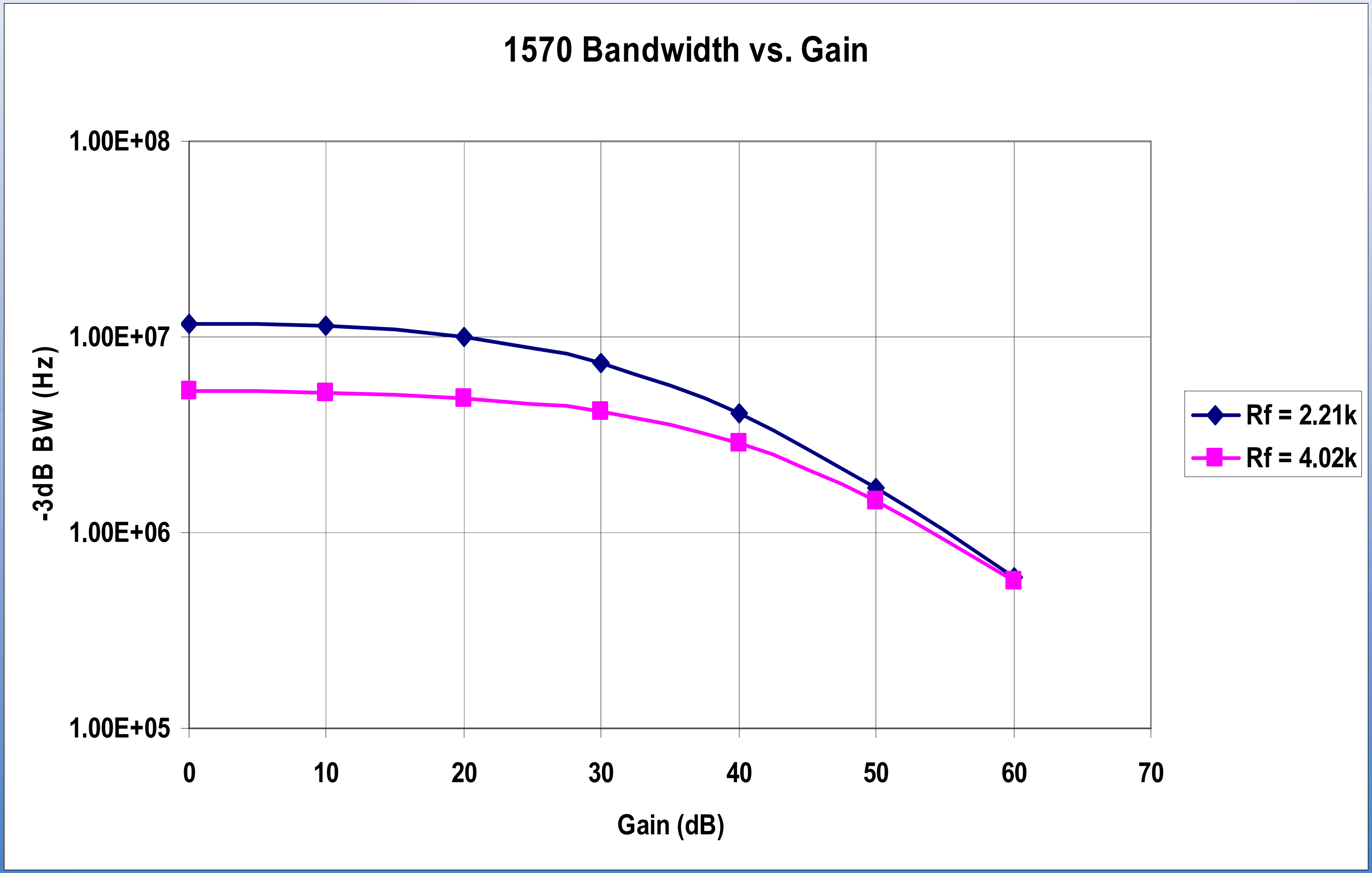
- **Early effect and Ccb mismatch in the current source transistors can also contribute to THD at low gains**
- **Cascoding helps here at the expense of some input CM range**
- **A Folded Cascode can minimize the noise contribution of the integrator stages and R_5 and R_6 while minimizing the impact on input CM range**
- **At this level of complexity an IC makes sense and the good device matching helps performance**

A Real Example THAT's 1570 CFIA



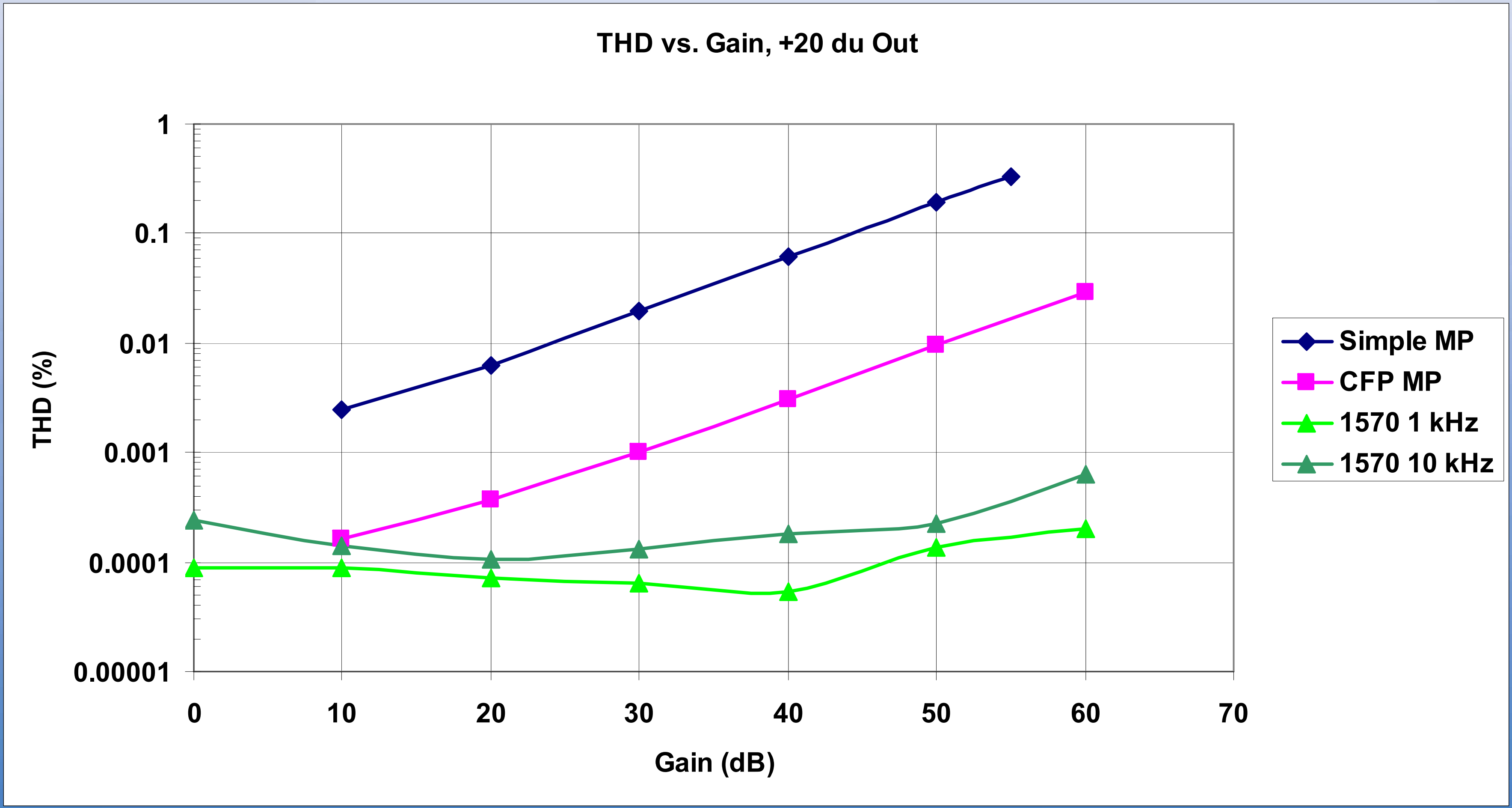
- An integrated circuit current-feedback instrumentation amplifier front end
- Utilizes the techniques described on the previous slide.
- Compensated for R_F values down to 2 kohm

1570 Bandwidth vs. Gain

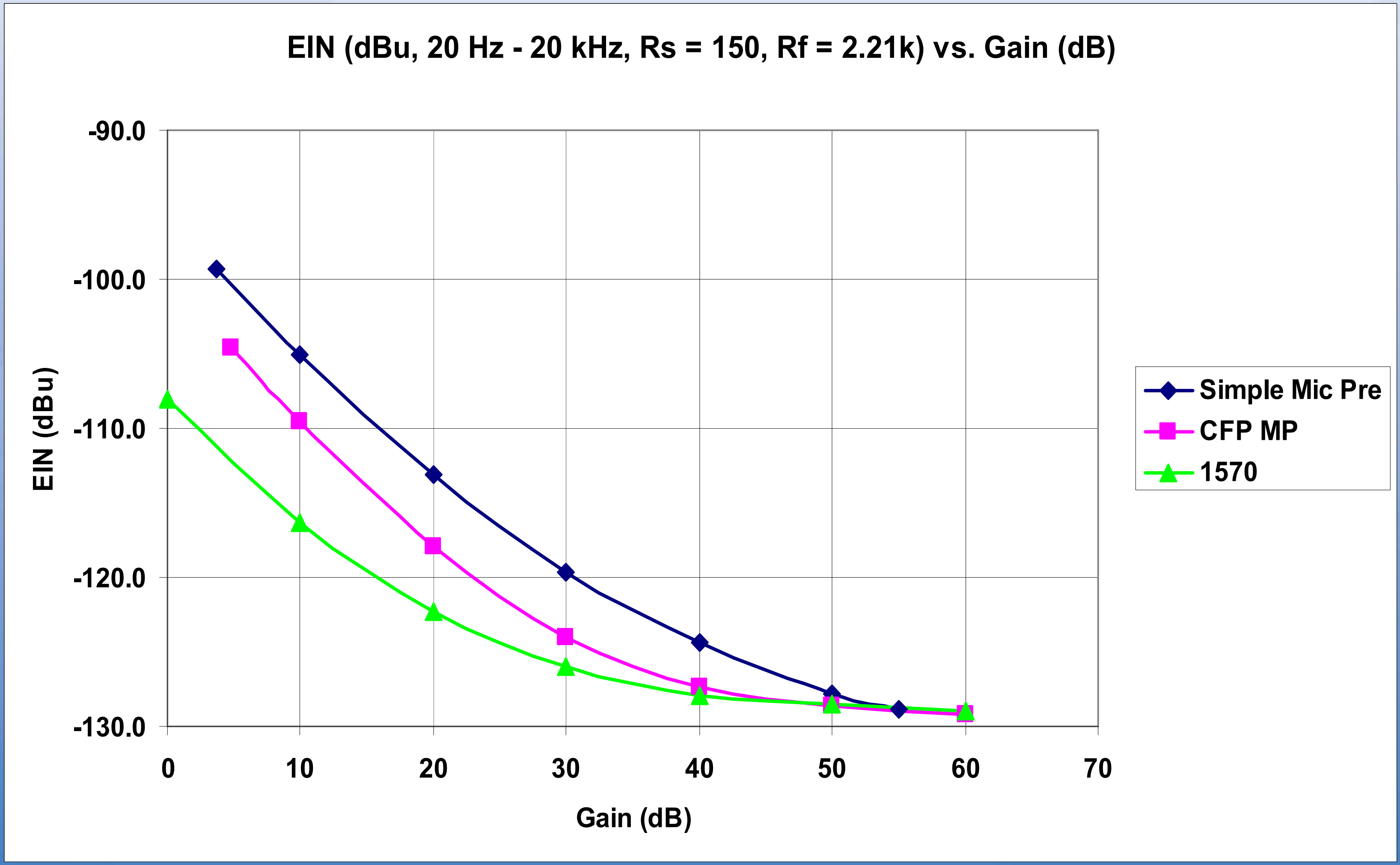


THD Performance of 1570 Mic Preamp

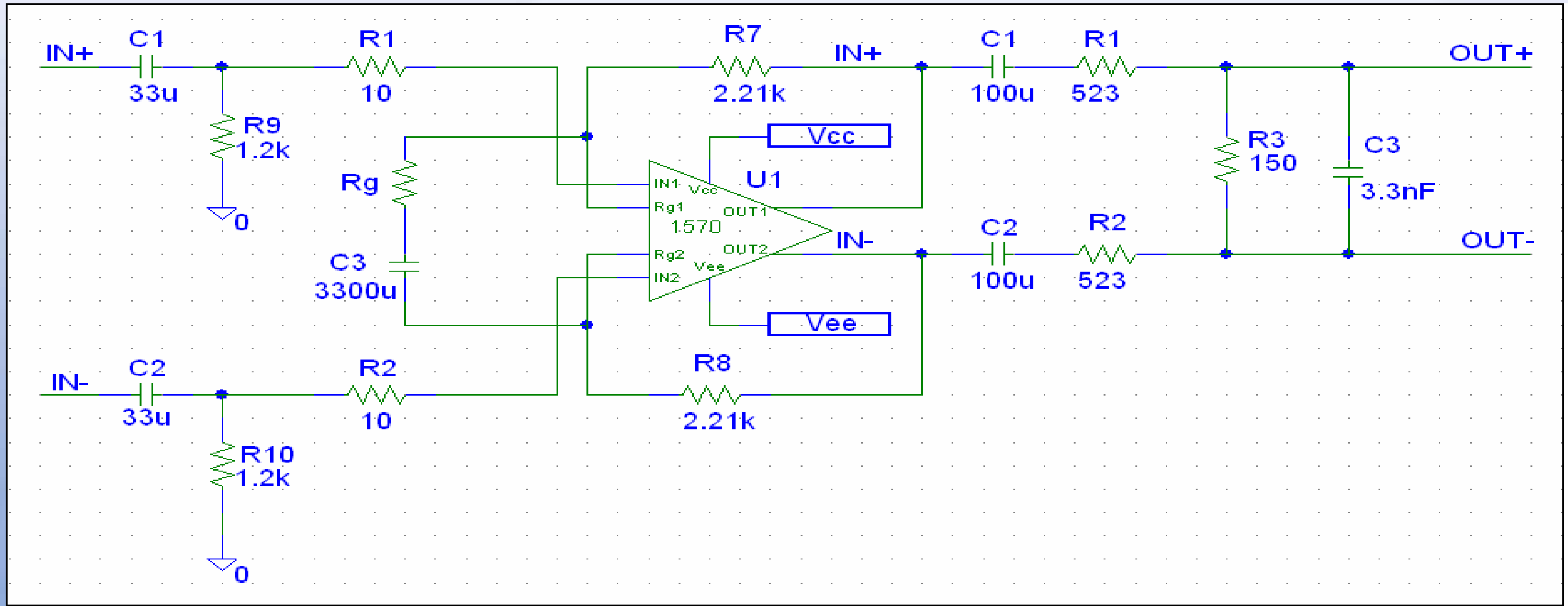
THD vs. Gain, +20 dBu Out, Rf = 2.21k



Noise Performance of 1570

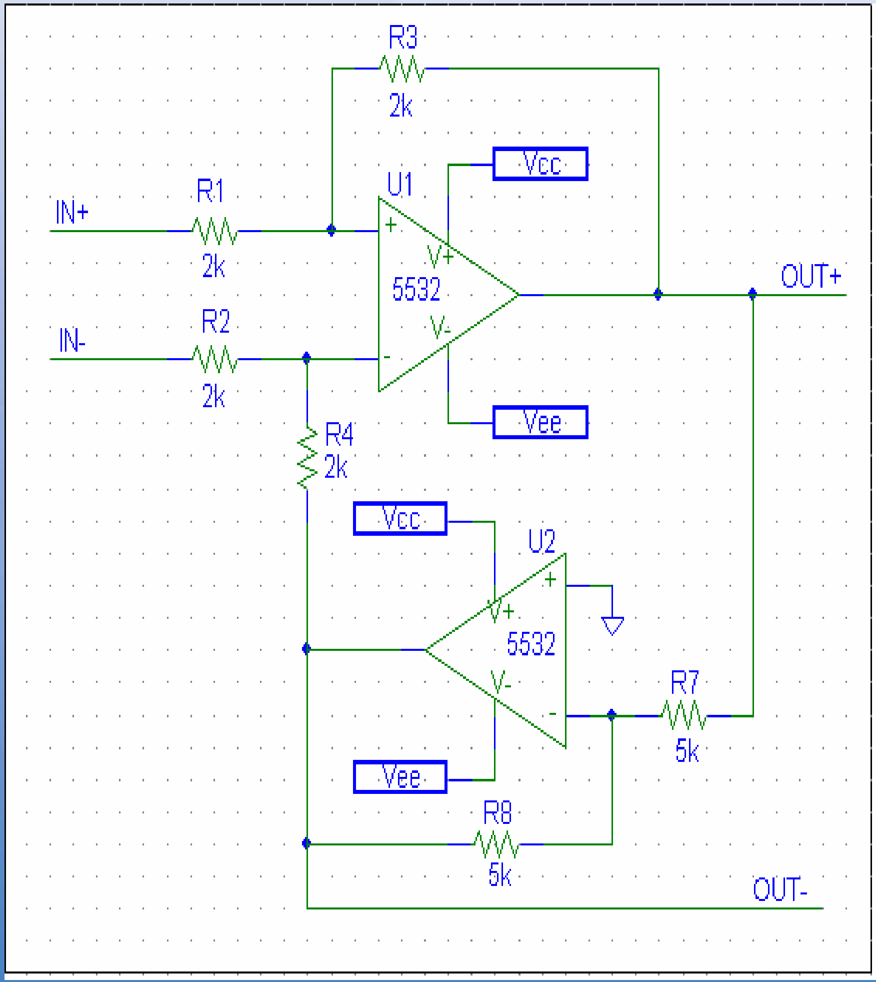


Utilizing the Differential Output to Drive A/D Converters



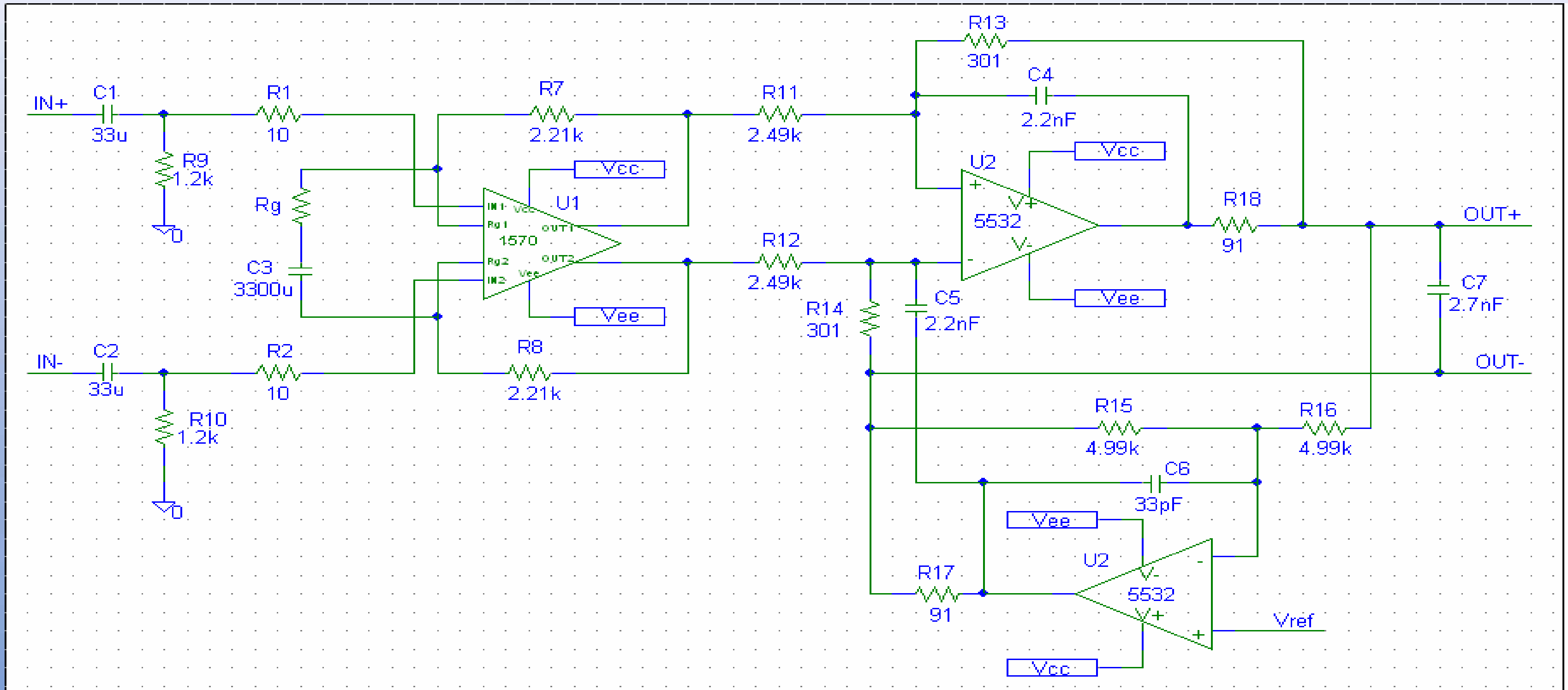
- The cheap and simple way:
- Rely on the A/D converter for CMRR at low gains
- Converter CM input range might be an issue as the pad does not attenuate CM signals

Birt Circuit



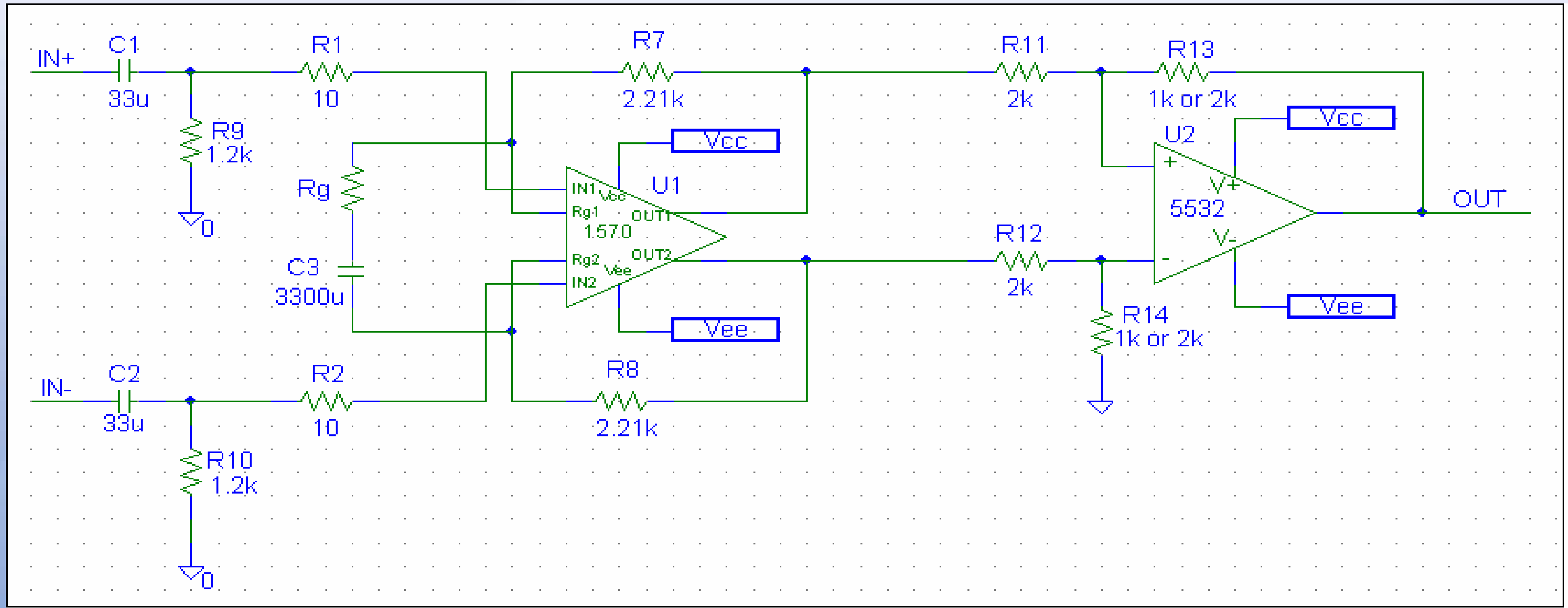
- David Birt, 1990
- Provides CMRR
- Gain = R_3/R_1
- Provides a convenient input for a CM DC reference voltage
- U2 input offset and noise appear as CM at OUT+ - OUT-

Birt Circuit Applied to 1570 and A/D Drive



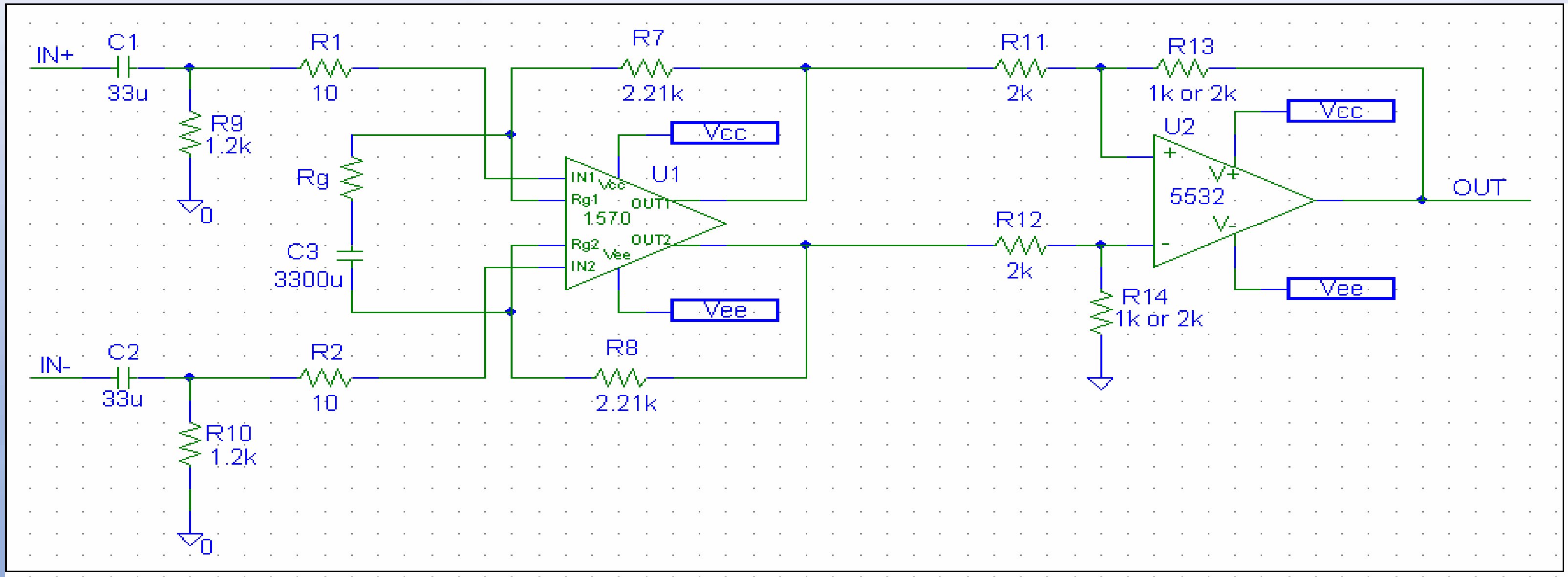
- The resistor ratios provide 18 dB of attenuation before the A/D
- The feedback networks enable capacitive load driving with low audio-band output impedance

Converting Differential Output to Single-Ended



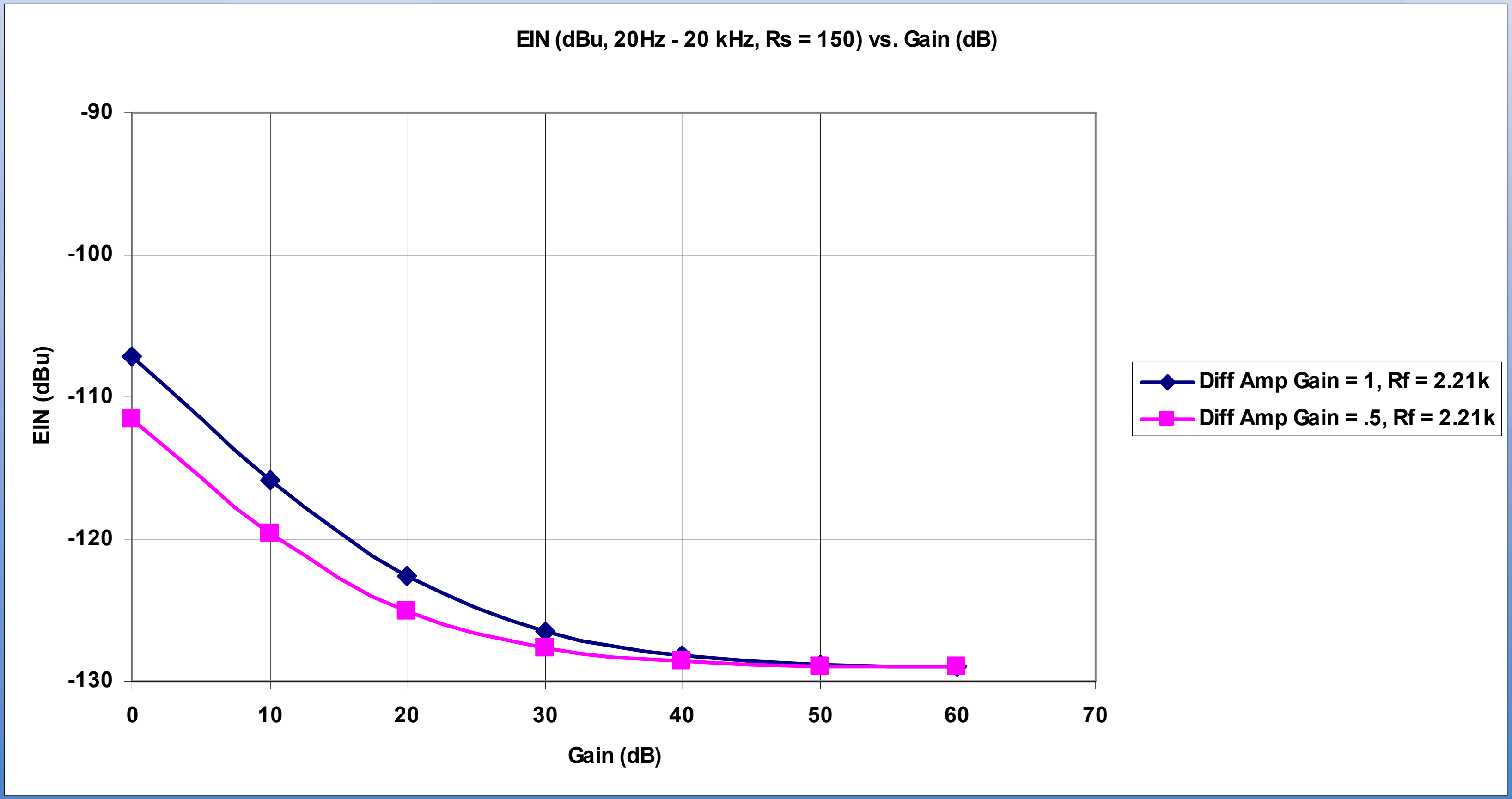
- The traditional 4-resistor differential amplifier works fine
- At low gains, the noise of this stage can become important
- Resistor matching controls the CMRR

Differential to Single-Ended Conversion



- What should the gain of the diff amp be?
- If G=1, we leave headroom on the table
- If G=.5, we take advantage of all of the swing capability of the differential output
- For the case of G=.5, the front end gain is always 6 db higher

1570 + Differential Amplifier Noise vs. Gain Performance



Conclusions

- Microphone preamplifiers with a wide gain range controlled by a single resistance involve tradeoffs between low-gain noise and high-gain distortion performance
- The current-feedback instrumentation amplifier is capable of good performance at both extremes
- An integrated approach can provide excellent performance in very small PCB area at moderate cost

Amplifier References

David Birt, "Electronically Balanced Analogue-Line Interfaces," Proceedings of the Institute of Acoustics, Vol. 12, Part 8 (1990)

Graeme John Cohen, "Double Balanced Microphone Amplifier", 1984 Audio Engineering Society Australian Regional Convention, Preprint Number 2106, September 1984

Graeme John Cohen, "Microphone Amplifier History and Design", presented at the Audio Engineering Society Adelaide Section, August, 2006

Fred Floru, "An Improved Microphone Preamplifier Integrated Circuit", 2001 Audio Engineering Society 16th UK Conference on Silicon For Audio

Scott Wurcer, "A Programmable Instrumentation Amplifier for 12-Bit Sources", IEEE Journal of Solid-State Circuits, Volume SC-17, Number 6, December, 1982

Acknowledgements

Thanks to Steve Green for preparing the "Support Circuitry" section.

Thanks to Greg Benulis, Rosalfonso Bortoni, Fred Floru, Bob Moses, and Les Tyler for their assistance in the preparation of this tutorial

Questions ?

THAT Corporation