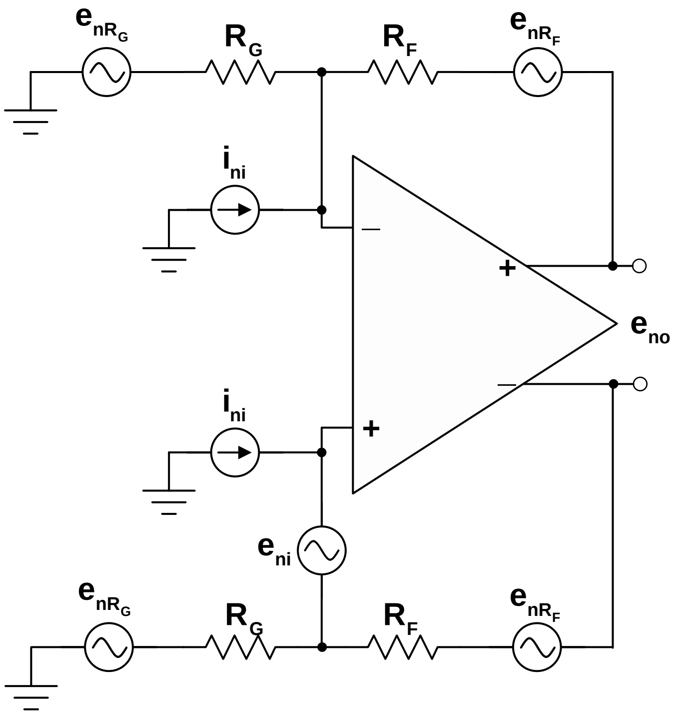
Fully Differential Amplifiers – 4

TIPL 2024

TI Precision Labs: Op Amps

Prepared and Presented by Samir Cherian

Noise Analysis



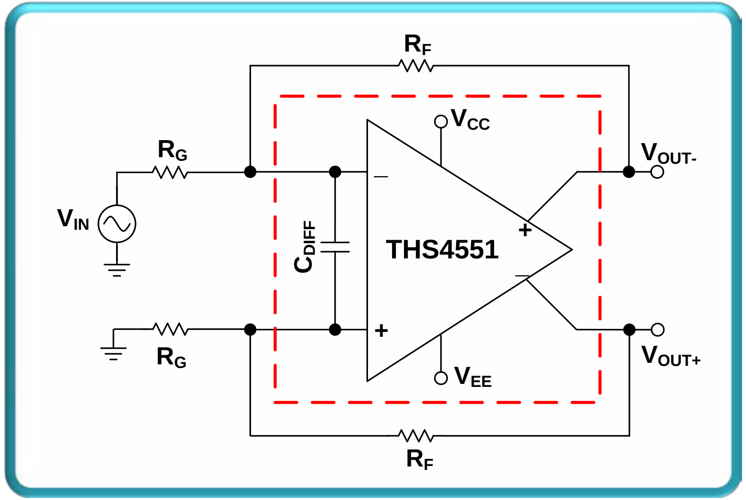
$$e_{no} = \sqrt{(e_{ni} \cdot NG)^2 + 2(i_{ni} \cdot R_F)^2 + 2(4kTR_F) + 2(4kTR_G \cdot (\frac{R_F}{R_G})^2)}$$

$$e_{no} = \sqrt{(e_{ni} \cdot NG)^2 + 2(i_{ni} \cdot R_F)^2 + 2(4kTR_F \cdot NG)}$$

NG is the Noise Gain

Resistor Noise Power = 4kTR

Using large resistors with high-speed amplifiers



Recommended R_F = 402 Ω

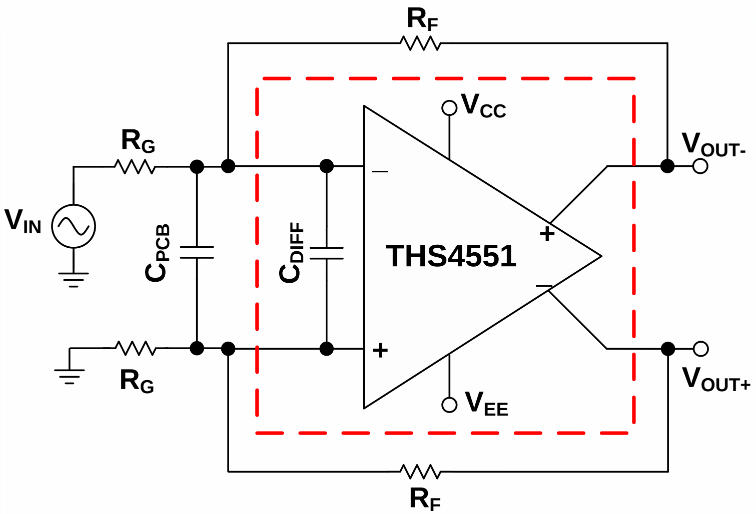
Voltage noise, E_N = 2.2 nV/√Hz

Current noise, I_{BN} = 1.9 pA/√Hz

Input offset current, I_{BOS} = 150 nA

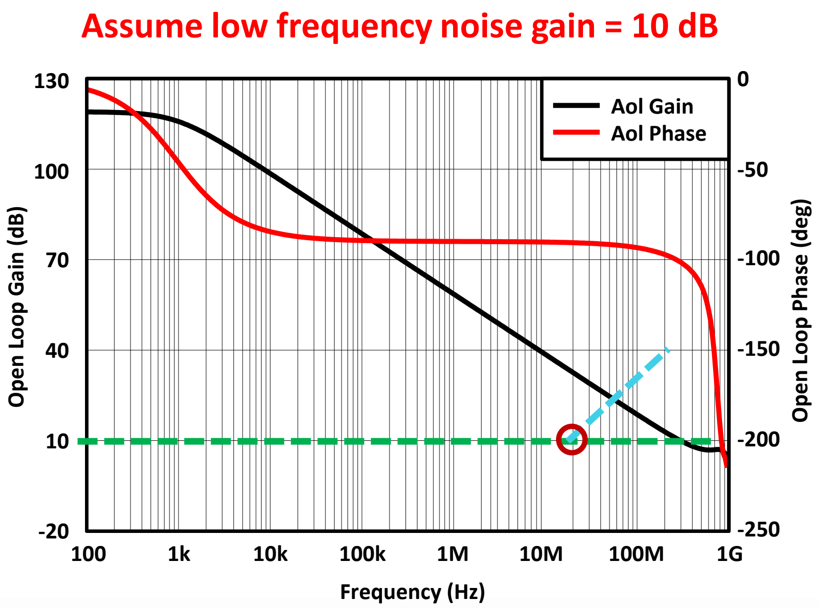
- Increasing R_F and R_G will result in larger noise contributions from the resistors compared to the amplifier.
- The current noise will be multiplied by R_F and will increase the overall system noise.
- Increased output offset voltage due to I_{BOS}.
- C_{DIFF} will introduce a noise gain zero which will reduce the phase margin and could cause oscillation. Large resistors lower the frequency of the zero within the amplifiers bandwidth

Effect of the noise gain zero



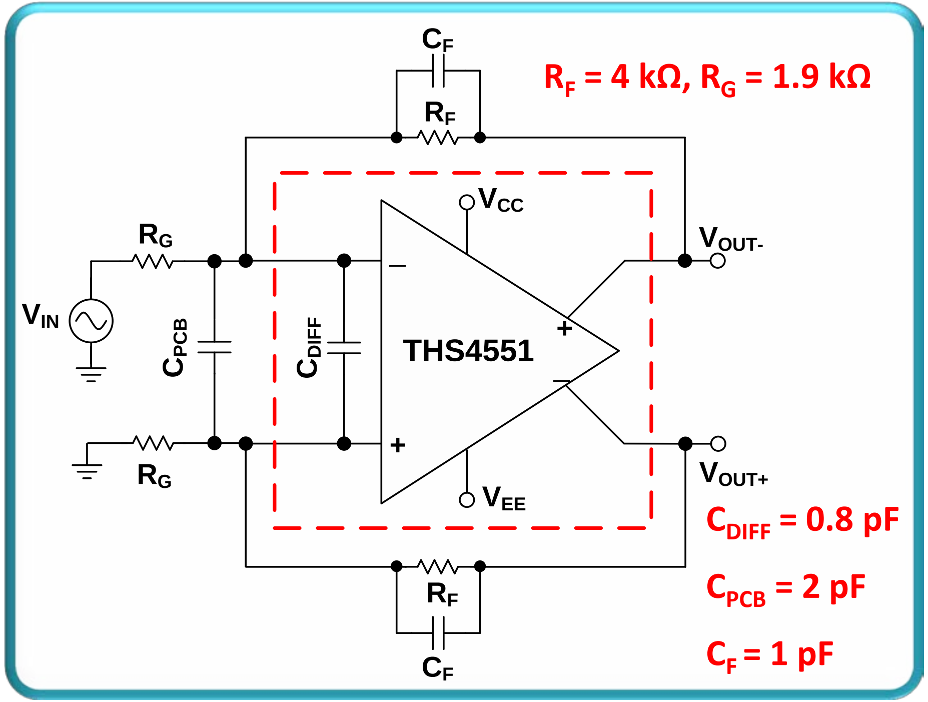
Case 1: R_F = 402 Ω, R_G = 187 Ω C_{DIFF} = 0.8 pF

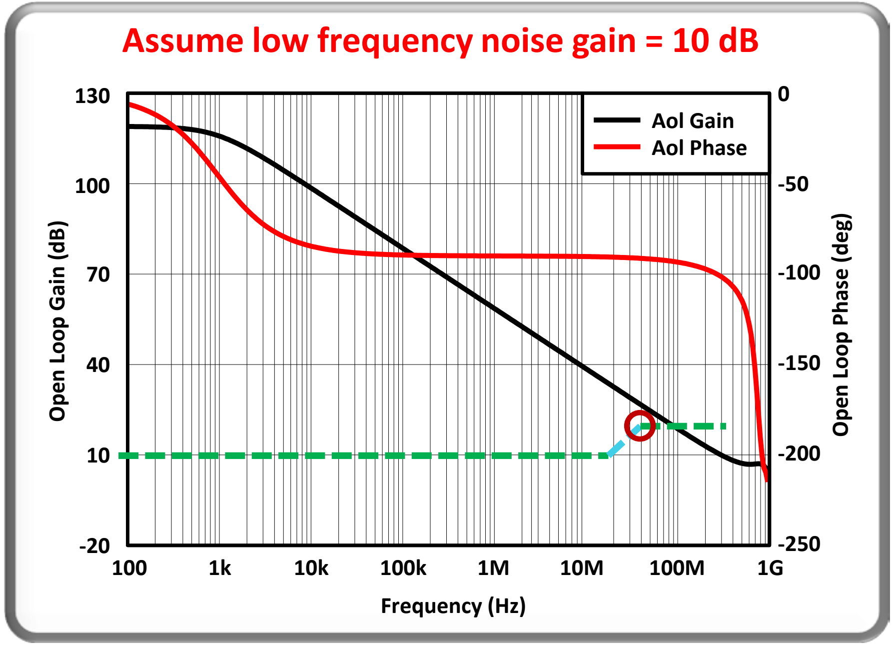
Case 2: R_F = 4 kΩ, R_G = 1.9 kΩ C_{PCB} = 2 pF



- The noise gain zero will occur at: $\dfrac{1}{2\pi(R_F \parallel R_G)(2C_{DIFF\_IN} + C_{CM\_IN})}$

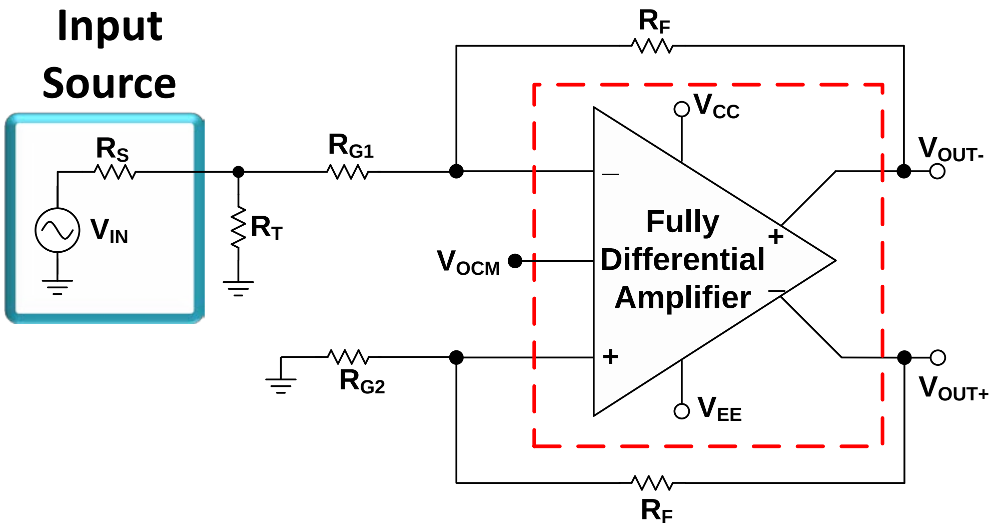
Feedback compensation





- Adding C_F introduces a pole in the noise-gain response which compensates for the zero. Pole is at: $\frac{1}{2\pi R_F C_F}$
- The high frequency noise gain is: $1+\frac{\left(2C_{DIFF\_IN}+C_{CM\_IN}\right)}{C_F}$

Input Terminations



- Matched termination is needed when the PCB trace > λ/8, where λ = 300/f_{MHZ}
- E.g., the wavelength of a 600-MHz signal is: λ = 300/f_{MHz} = 300/600 = 0.5 m= 19.7 in.

A cable or PCB trace is a transmission line if it's longer than 0.5/8 = 0.0625m or 2.5 in.

R_S is Source Resistance

R_T is Termination Resistance

$R_{G2} = R_{G1} + (R_S || R_T)$

$$R_T^2 - R_T * \frac{2R_S\left(2R_F + \frac{R_S}{2}A_V^2\right)}{2R_F(2+A_V) - R_S A_V(4+A_V)} - \frac{2R_F R_S^2 A_V}{2R_F(2+A_V) - R_S Av(4+A_V)} = 0$$

Excel calculator for single-ended to differential matched termination configuration

Solving for Rt and then Rg1 and Rg2 in the single to differential FDA configuration with input impedance matching.				
ENTER ONLY THE RED BOLD FIELDS				
MAIN RESULTS IN BLUE BOLD FIELDS				
Enter Source Rs	**50**	Ω	*This is single ended input to differential output design with Rf selected and other elements solved for.*	
Enter Feedback Rf	**402**	Ω		
Maximum gain	14.32502263	V/V		
Must enter a gain < this for valid solution				
Enter Target Gain	**5**	V/V	13.9794	dB

Now get standard 1% values			
Required Rt value	**79.65389444**	Ω	78.7
Closest 1% value	**80.6**	Ω	80.6
Required Rg1 value	**68.07085543**	Ω	66.5
Closest 1% value	**68.1**	Ω	68.1
Required Rg2 value	**98.78875048**	Ω	97.6
Closest 1% value	**97.6**	Ω	100
Snapping Rf to closest 1%	402	Ω	402
Closest 1%	**402**	Ω	412

Some example FDAs from Texas Instruments

Product Name	I_Q (mA)	GBP (MHz)	Slew-Rate (V/µs)	Voltage Noise (nV/√Hz)	Key Features
THS4531A	0.25	27	190	10	Low Power.
THS4551	1.35	135	220	3.3	Low Noise and High Precision.
THS4541	10.1	850	1500	2.2	Wide Bandwidth with Precision.
THS4509	37.7	3000	6600	1.9	
LMH5401	55	6200	17500	1.25	Ultra-wide bandwidth.
LMH3401	55	7000	18000	1.4	Fixed Gain with integrated resistors.
LMH6552	20.4	1500	3800	1.1	± 10V supplies. Current Feedback topology.
OPA1632	14	180	50	1.3	± 30V supplies and low-noise. Optimized for audio.

http://www.ti.com/lsds/ti/amplifiers/op-amps/fully-differential-amplifiers-overview.page

Digital Variable-Gain Amplifiers (DVGA)

- Wide gain range can be programmed through SPI or parallel-mode.
- Single-ended OR Differential Input to Differential Output.
- Input signals can be AC or DC coupled.
- Commonly used in Test & Measurement and Communications.

Product Name	I_Q (mA)	Gain Range	Noise Figure	Key Features
LMH6401	69	-6dB to 26dB	7.7 dB @ 100 Ω	4.5 GHz BW @ A_V= 26 dB
LMH6881	100	6dB to 26dB	9.7 dB @ 100 Ω	2.4 GHz BW @ A_V= 26 dB. SE or DIFF I/P
LMH6517	80	-9.5dB to 22dB	5.5 dB @ 100 Ω	1.2 GHz BW @ A_V= 22 dB
LMH6521	112.5	-5.5dB to 26dB	7.3 dB @ 200 Ω	1.2 GHz @ 0dB Gain. AC Coupled Only

Fully Differential Amplifiers - 4

Exercises

TI Precision Labs: Op Amps

Questions

1. The 1.9 GHz THS4509 fully-differential amplifier is configured in a signal gain of 2V/V (6dB).
   a) What is the output noise contribution due to the amplifiers inherent voltage noise?
   b) How large should the feedback resistor R_F be for the total current noise contribution to be equal to the total amplifier voltage noise?

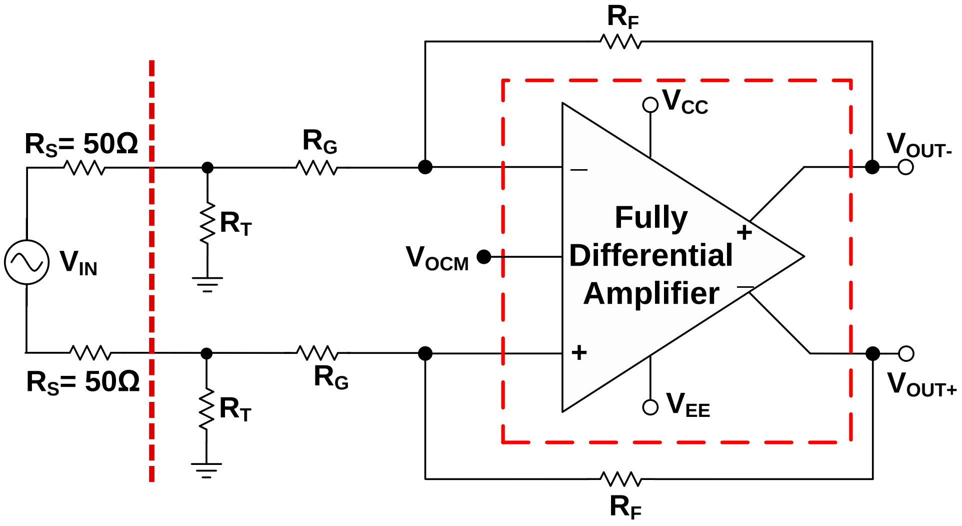
2. For an FDA with the specifications and configuration shown below, at what frequency is the noise gain zero located?

Parameter	Specification	Units
Feedback Resistance, R_F	10	kΩ
Signal Gain	5	V/V
Amplifier differential input capacitance, C_{AMP_D}	2	pF
Amplifier common-mode input capacitance, C_{AMP_C}	1	pF
Parasitic PCB capacitance at each amplifier input, C_{PCB}	0.5	pF

3. An FDA is configured as a differential in to differential out amplifier. It is driven by a differential source with 50Ω source impedance (on each side).

a) If the amplifier is configured in a gain of 10V/V, what is the value of R_T, R_G and R_F?

b) If the amplifier is in a gain of 10V/V and R_F = 10 kΩ what is the value of R_T and R_G?



Answers

1. The 1.9 GHz THS4509 fully-differential amplifier is configured in a signal gain of 2V/V (6dB).
   a) What is the output noise contribution due to the amplifiers inherent voltage noise?
   b) How large should the feedback resistor R_F be for the total current noise contribution to be equal to the total amplifier voltage noise?

a) The THS4509 noise specification from the datasheet is shown below:

Parameter	Typical value	Unit
Input voltage noise	1.9	nV/√Hz
Input current noise	2.2	pA/√Hz

Since the amplifier is in a signal gain of 2V/V, its noise gain is 3V/V and the total output noise is = 3 × 1.9 nV/√Hz = **5.7 nV/√Hz**

b) The output current noise contribution for each side $= I_{NOISE} \times R_F$. Since the noise on each side is uncorrelated the total noise at the output $= \sqrt{2} \times I_{NOISE} \times R_F$.

The value of feedback resistance that would therefore make the total current noise contribution equal the amplifiers voltage noise contribution is given by:

$$\sqrt{2} \times 2.2\ \text{pA}/\sqrt{\text{Hz}} \times R_F = 5.7\ \text{nV}/\sqrt{\text{Hz}}$$

$$\Rightarrow R_F = \frac{5.7\ \text{nV}/\sqrt{\text{Hz}}}{\sqrt{2} \times 2.2\ \text{pA}/\sqrt{\text{Hz}}} = 1832\ \Omega$$

2. For an FDA with the specifications and configuration shown below, at what frequency is the noise gain zero located?

Parameter	Specification	Units
Feedback Resistance, R_F	10	kΩ
Signal Gain	5	V/V
Amplifier differential input capacitance, C_{AMP_D}	2	pF
Amplifier common-mode input capacitance, C_{AMP_C}	1	pF
Parasitic PCB capacitance at each amplifier input, C_{PCB}	0.5	pF

The zero is located at : $$\frac{1}{2\pi\left(R_F \,||\, R_G\right)\left(2C_{DIFF\_IN} + C_{CM\_IN}\right)}$$

With R_F = 10kΩ and Gain = 5V/V, R_G = 2kΩ.

The total common-mode capacitance = C_{AMP_C} + C_{PCB} = 1 pF + 0.5 pF = 1.5 pF

The noise gain zero is located at: $$\frac{1}{2\pi\left(10k\Omega \,||\, 2k\Omega\right)\left(2\cdot 2pF + 1.5pF\right)} = 17.4\text{ MHz}$$

3. An FDA is configured as a differential in to differential out amplifier. It is driven by a differential source with 50Ω source impedance (on each side).

   a) If the amplifier is configured in a gain of 10V/V, what is the value of R_T, R_G and R_F?
   b) If the amplifier is in a gain of 10V/V and R_F = 10 kΩ what is the value of R_T and R_G?

a) The complicated equation shown in the training video is only needed in case of a single-ended to differential configuration. In a differential in to differential out configuration, the amplifiers input pins are fixed and therefore independent of the amplifiers gain configuration.

Therefore in this case R_G = 50 Ω and R_T can be left open. Since the signal gain is 10 V/V - R_F = 50 Ω × 10 V/V = 500 Ω

b) If the amplifier is in a gain of 10V/V and R_F = 10 kΩ what is the value of R_T and R_G?

b) In this case the value of the feedback resistance is fixed so we have to work backwards.

With R_F = 10 kΩ and a signal gain of 10 V/V -

R_G = 10 kΩ / 10 V/V = 1 kΩ

The load seen by the source is therefore 1 kΩ. In order for the source to see a load of 50 Ω set the value of R_T such that (R_T || R_G) = 50 Ω.

$$\frac{R_T \times 1\ \text{k}\Omega}{R_T + 1\ \text{k}\Omega} = 50\ \Omega$$

$$\Rightarrow R_T = 52.6\ \Omega$$