Using Fully Differential Op Amps to Signal Conditioning High Voltage Input Signals to Drive ADCs

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High Speed Op Amps

Texas Instruments

Note associated Tina and Excel files and latest is on FAE Summit Sharepoint

Agenda

1) Overview
2) Differential Bipolar Input Circuit
3) Single Ended Bipolar Input
4) Single Ended Unipolar Input Circuit
5) New Product Overview THS4521

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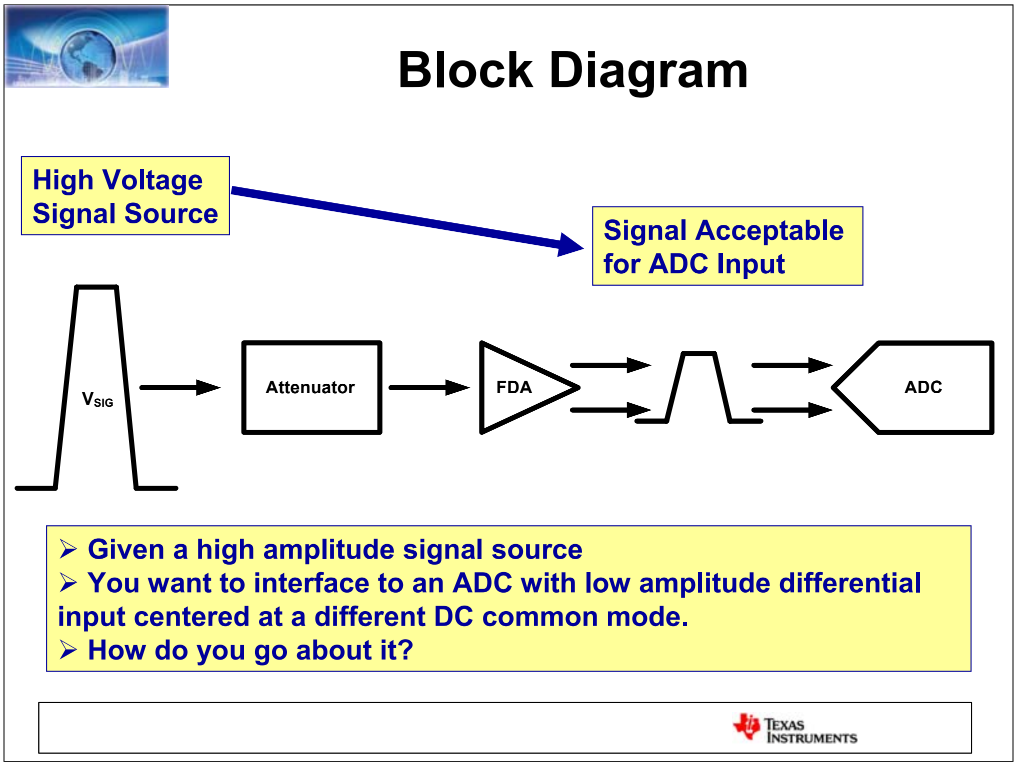
We will start with the easiest and move to the more difficult.



Given a signal source that provides a pulse from ground to 15V, you want to interface to a 3.3V CMOS ADC with 2Vpp differential full scale input centered at 1.5V common mode. How do you go about it?

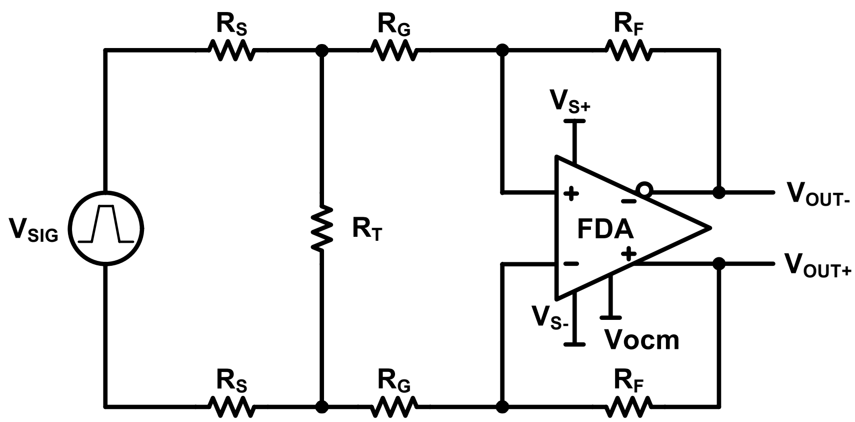
We will discuss one approach using a fully differential amplifier (FDA) as the active element.

With proper component selection, the circuit provides the required signal attenuation and level shift required.

The main function of the various components is described, the analysis is shown, and a methodology for selecting the correct values is given.

Differential (DIFF) Bipolar Input Circuit

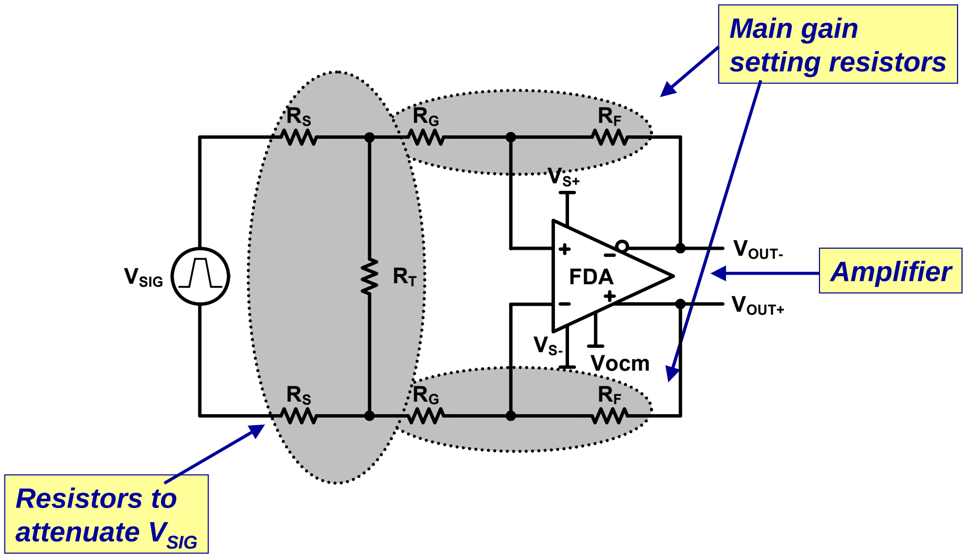
- **Easier to start with bipolar differential source into fully differential amp**
- **For amplifier stability we want to keep amp gain = 1V/V**

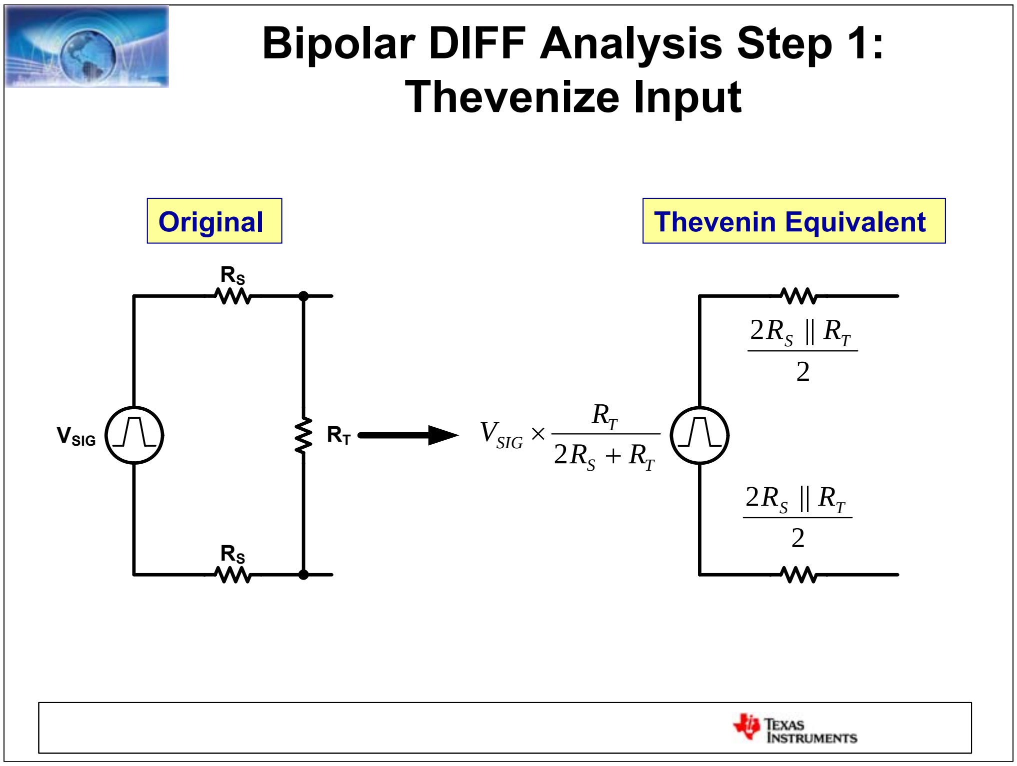


Let's start with Differential (DIFF) source feeding into a fully differential amplifier circuit. This makes the analysis easier and makes it easier to understand why we do what we do when we move to Single Ended (SE).

Unity gain stable Fully Differential op Amps (FDA) are typically compensated so that a minimum gain of 1V/V is required for best stability and it is not recommended to use a FDA op amp directly as an attenuator like you can do with a standard unity gain op amp in inverting configuration.

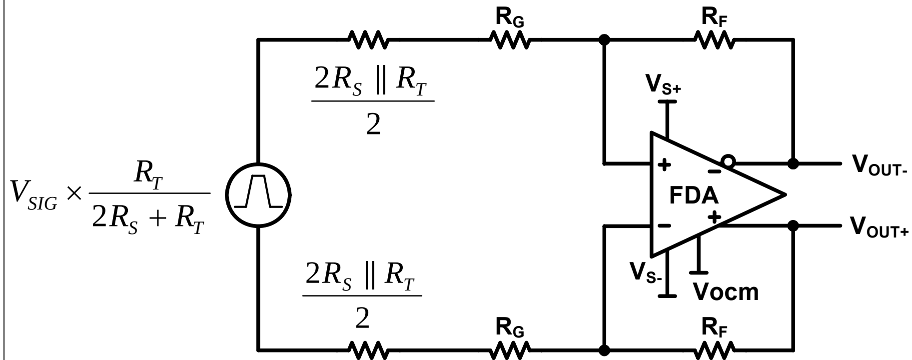
Bipolar DIFF In Circuit





Converting the input signal source and attenuator resistors to its Thevenin equivalent eases analysis.

Bipolar DIFF Analysis Step 2: Substitute Thevenin Equivalent



$$\frac{V_{OUT\pm}}{V_{SIG}} = \frac{R_T}{2R_S + R_T} \times \frac{R_F}{R_G + \frac{2R_S \parallel R_T}{2}}$$

With the input Thevenized, the overall gain of the circuit is easily calculated.

Bipolar DIFF Analysis Step 3: Set Design Constraints

For unity gain stable FDA want gain to be 1V/V min

$$\frac{R_F}{R_G + \frac{2R_S \parallel R_T}{2}} = 1$$

This leads to set equivalent input resistance equal to R_F

$$R_F = R_G + \frac{2R_S \parallel R_T}{2}$$

So the overall gain equals the input attenuation

$$\frac{V_{OUT\pm}}{V_{SIG}} = \frac{R_T}{2R_S + R_T}$$

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Unity gain stable Fully Differential op Amps (FDA) are typically compensated so that a minimum gain of 1V/V is required for best stability and it is not recommended to use a FDA op amp directly as an attenuator like you can do with a standard unity gain op amp in inverting configuration.

The gain is set to 1 by making the equivalent input resistance equal to the feedback resistor.

The result is the overall gain is set by the input attenuator.

Bipolar DIFF Design Step 1: Calculate Component Values

Choose R_S ($\approx Z_{IN}/2$) and calculate R_T

$$R_T = \frac{2R_S}{\dfrac{V_{SIG}}{V_{OUT\pm}} - 1}$$

Then Choose R_F and calculate R_G

$$R_G = R_F - \frac{2R_S \parallel R_T}{2}$$

Look at Z_{IN} when choosing R_S Note as attenuation goes to infinity $Z_{IN} = 2R_S$

$$Z_{IN} = 2R_S + R_T \parallel 2R_G$$

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You now have 2 degrees of freedom.

1st degree of freedom is the input attenuator: there is an infinite combination of R_S and R_T that will give desired attenuation.

Start with the input. Typically input impedance is a concern; not always that it has to be an exact value, but at least in a range. Considering input impedance leads to a good starting point is to choose $R_S = Z_{IN}/2$. Then you can calculate R_T based on overall gain using the equation shown.

2nd degree of freedom is the gain resistor values: there is an infinite combination of R_F and R_G to choose from.

By choosing R_F, you can calculate R_G based on unity gain criteria and input attenuator values chosen using the equation shown.

The input impedance can then be calculated using the equation shown, and the process can be iterated if the value is not acceptable.

Bipolar DIFF Design Step 2: Put Design Equations in Spreadsheet

Design Inputs (enter values)			
Vsig min	Vsig max	Vout Diff	Vocm
-5	5	2	1.5

Design Choices (enter values)	
Rs	Rf
499	499

Calculated Values (do not enter values)		
Vout/Vsig	Rt	Rg
0.100	110.889	449.100

Nearest Standard Values (enter values)	
Rt	Rg
110	453

Atten, FB Factor and Zin with Std Values (do not enter values)		
FB factor	Atten	Zin
0.502	0.099	1096.09

Output Voltages with Standard Values (do not enter values)				
	Min	Mid	Max	Vout Diff
Vout+	1.007	1.500	1.993	1.972
	Max	Mid	Min	Offset
Vout-	1.993	1.500	1.007	0.000

Wksht: "Bipolar DIFF FDA Atten"
Yellow = input values
Orange = output values
Note Vsig = 2x (max-min)

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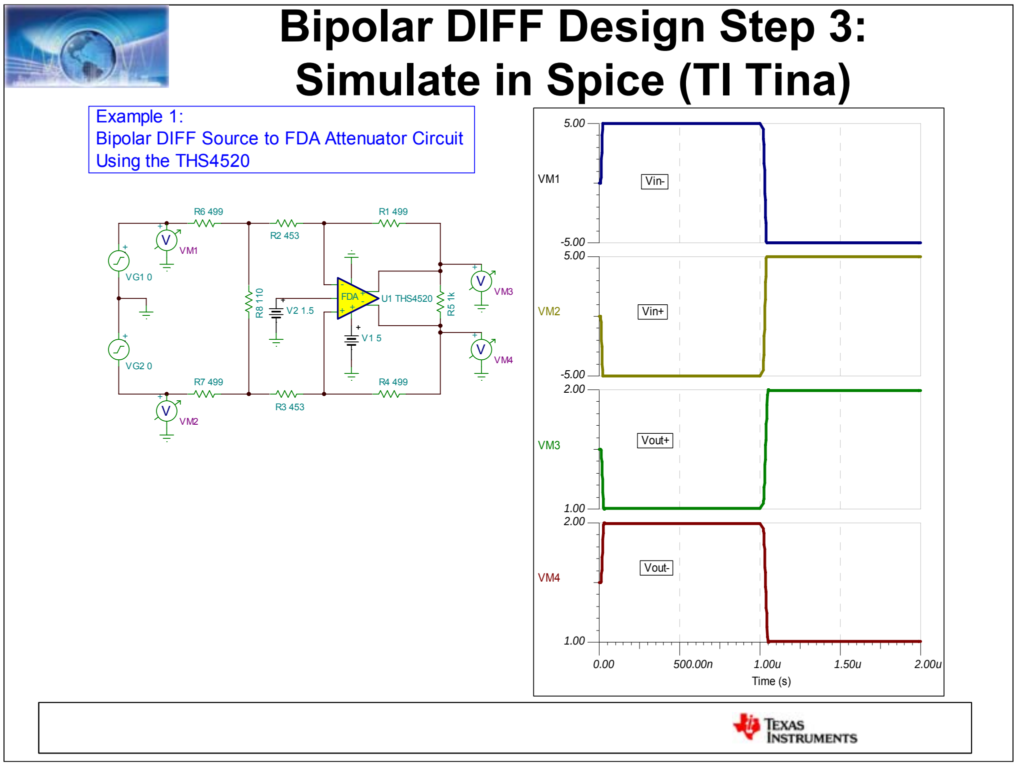
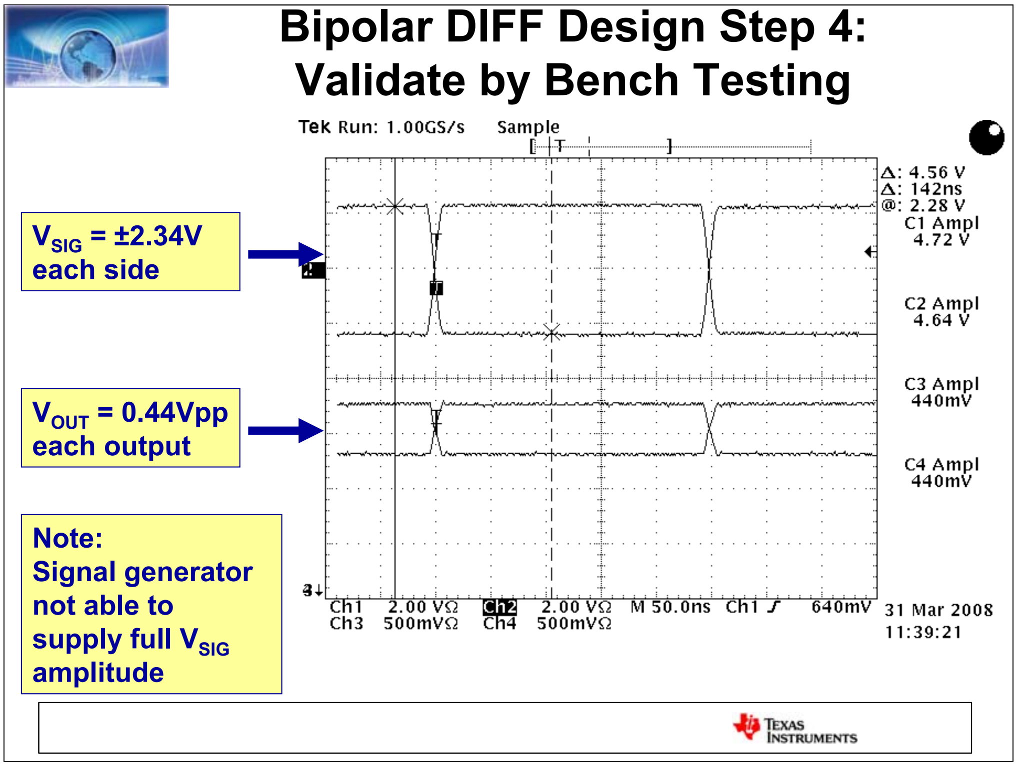
Building a spread sheet tool makes it easy to change and tweak design.



Spice simulation is a great way to verify the design formulas and values calculated using the spreadsheet are correct.

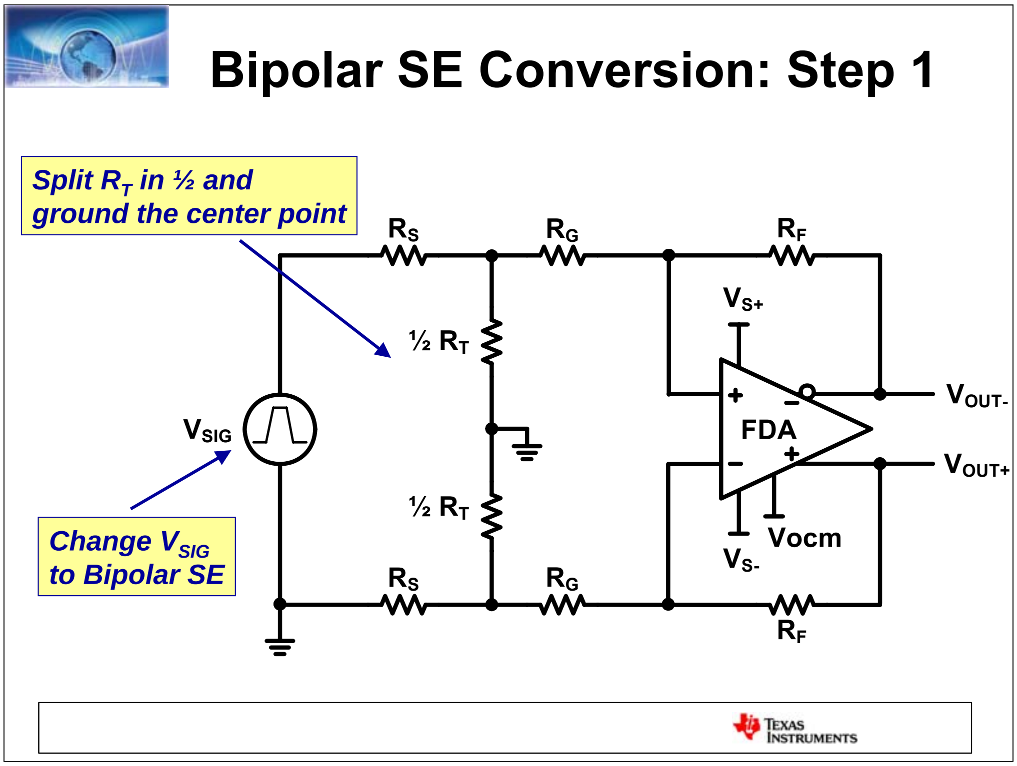


Validation is completed by testing in the lab.

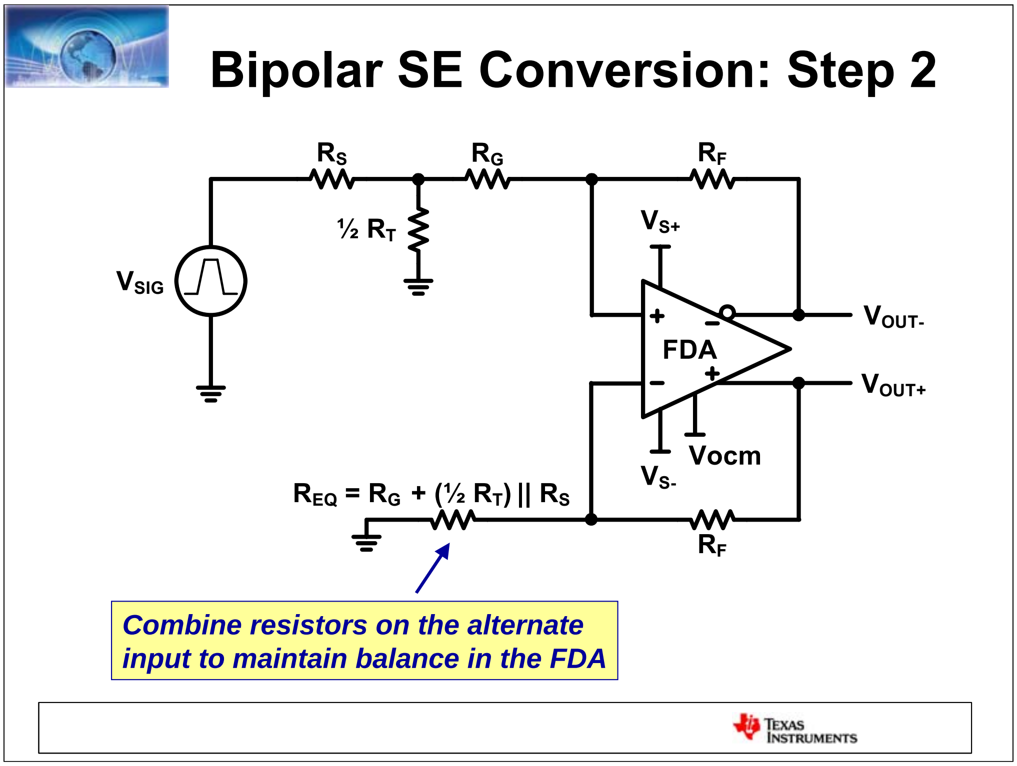
Note: Signal generator not able to supply full VSIG amplitude, but circuit is right.

Next: Move Design to Single Ended (SE) Bipolar Input

➢ **We will now convert the bipolar differential input source and circuit to a single ended bipolar input source and circuit**

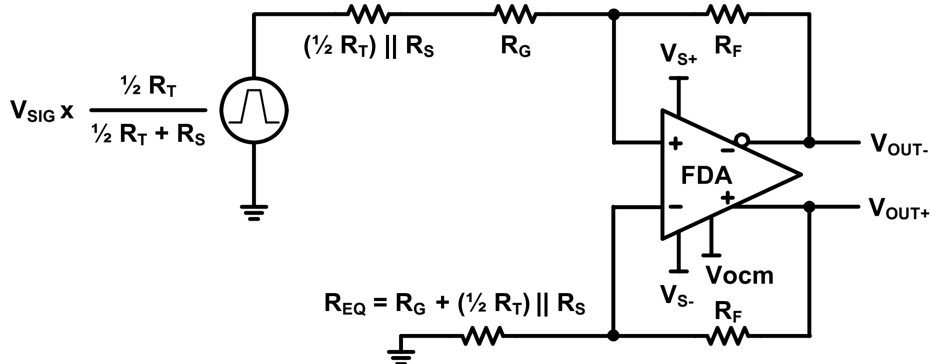


First step to convert the previous differential input to single ended is to change the input source to single ended, split R_T in ½ and ground the center point.



Combine resistors on the alternate input to maintain balance in the FDA.

Bipolar SE Analysis: Step 1
Thevenize and Substitute



$$\frac{V_{OUT\pm}}{V_{SIG}} = \frac{\frac{R_T}{2}}{R_S + \frac{R_T}{2}} \times \frac{R_F}{R_G + R_S \,||\, \frac{R_T}{2}}$$

Converting the input signal source and attenuator resistors to its Thevenin equivalent eases analysis.

Bipolar SE Analysis Step 2: Set Design Constraints

For unity gain stable FDA want gain to be 1V/V min

$$\frac{R_F}{R_G + R_S \parallel \frac{R_T}{2}} = 1$$

This leads to set equivalent input resistance equal to R_F

$$R_F = R_G + R_S \parallel \frac{R_T}{2}$$

So the overall gain equals the input attenuation

$$\frac{V_{OUT\pm}}{V_{SIG}} = \frac{\frac{R_T}{2}}{R_S + \frac{R_T}{2}}$$

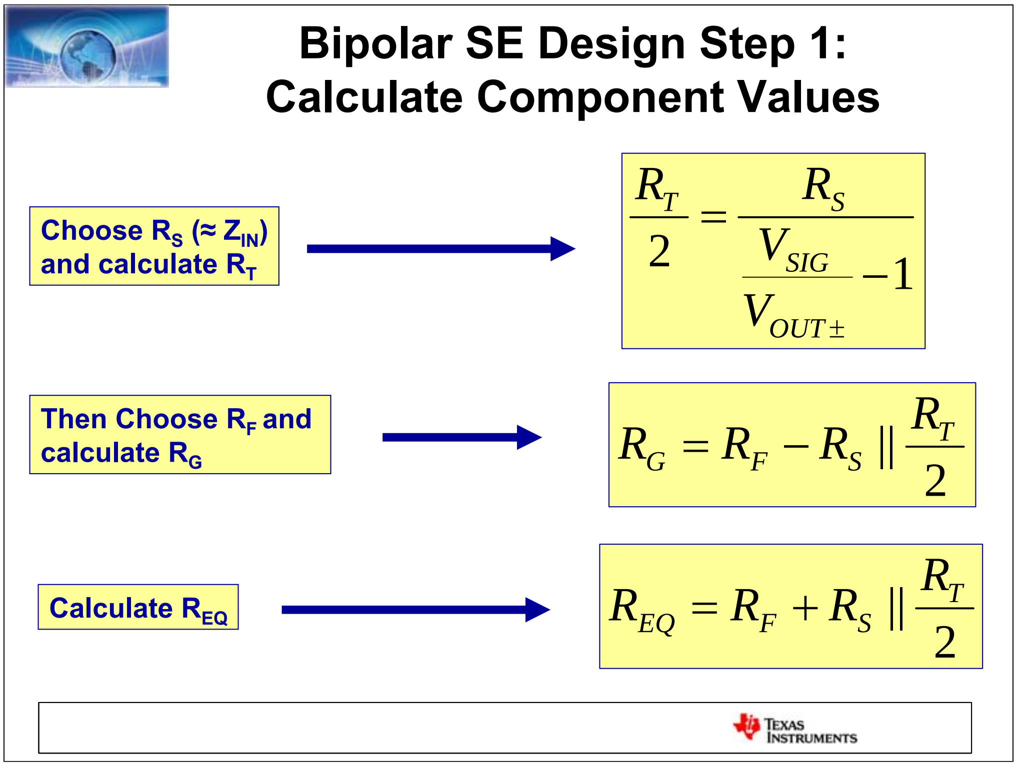
Texas Instruments

Same as before:

Unity gain stable Fully Differential op Amps (FDA) are typically compensated so that a minimum gain of 1V/V is required for best stability and it is not recommended to use a FDA op amp directly as an attenuator like you can do with a standard unity gain op amp in inverting configuration.

The gain is set to 1 by making the equivalent input resistance equal to the feedback resistor.

The result is the overall gain is set by the input attenuator.



Same as before, you now have 2 degrees of freedom.

1st degree of freedom is the input attenuator: there is an infinite combination of R_S and R_T that will give desired attenuation.

Start with the input. Typically input impedance is a concern; not always that it has to be an exact value, but at least in a range. Considering input impedance leads to a good starting point is to choose $R_S = Z_{IN}$. Then you can calculate ½ R_T based on overall gain using the equation shown.

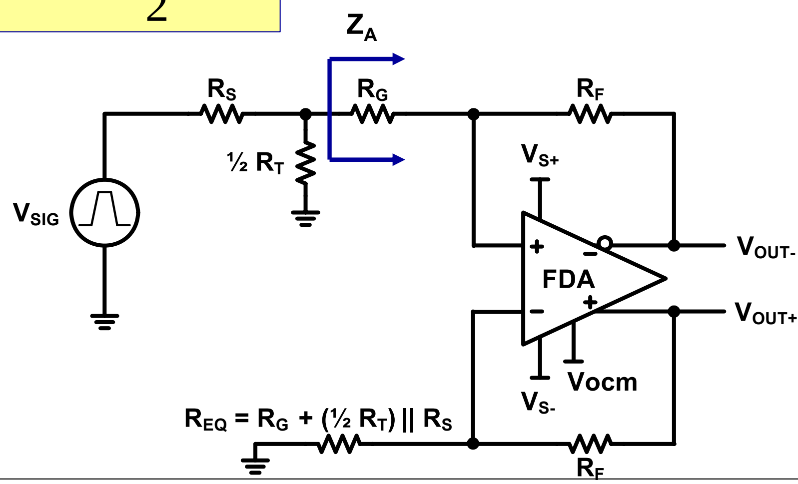
2nd degree of freedom is the gain resistor values: there is an infinite combination of R_F and R_G to choose from.

By choosing R_F, you can calculate R_G based on unity gain criteria and input attenuator values chosen using the equation shown.

The input impedance for this SE circuit is much more complex than the DIFF circuit. We will discuss how to analyze next.

Bipolar SE Design Sidebar: How to Calculate Z_{IN}

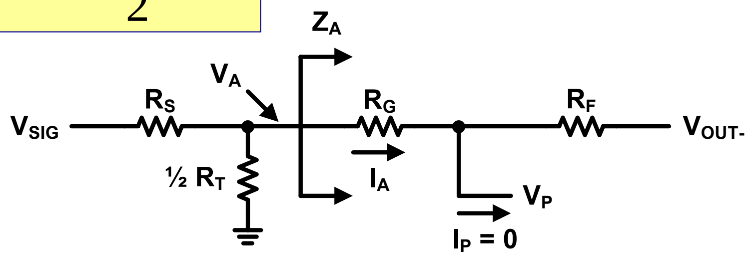
$$Z_{IN} = R_S + \frac{R_T}{2} \,||\, Z_A$$



The input impedance in the SE case is complicated by the fact that it now depends on the impedance looking into RG, which depends on the value of the resistor and the gain of the amplifier.

Bipolar SE Design Sidebar: How to Calculate Z_{IN}

$$Z_{IN} = R_S + \frac{R_T}{2} \,||\, Z_A$$



$$Z_A = \frac{V_A}{I_A}$$

$$I_A = \frac{V_A - V_{OUT-}}{R_G + R_F}$$

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The outline of how to approach calculating Z_{IN} for the SE circuit is shown above.

Bipolar SE Design Step 2: Put Design Equations in Spreadsheet

Design Inputs (enter values)				
Vsig min	Vsig max	Vout Diff	Vocm	
-10	10	2	1.5	
Design Choices (enter values)				
Rs	Rf			
1000	499			
Calculated Values (do not enter values)				
Vout/Vsig	1/2 Rt	Rg	Req	
0.100	111.11	399.00	499.00	
Nearest Standard Values (enter values)				
1/2 Rt	Rg	Req		
110	402	499		
Atten, FB Factors, and Zin with Std Values (do not enter values)				
B+	B-	Atten	Zin	
0.501	0.500	0.099	1092.16828	
Output Voltages with Standard Values (do not enter values)				
	Min	Mid	Max	Vout Diff
Vout+	1.008	1.502	1.996	1.976
	Max	Mid	Min	Offset
Vout-	1.992	1.498	1.004	0.003

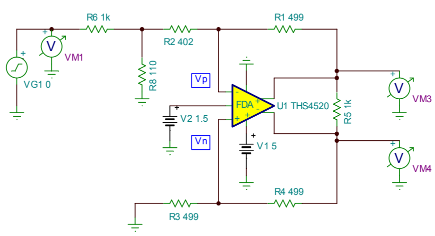
Wksht: “Bipolar SE FDA Atten”
Yellow = input values
Orange = output values

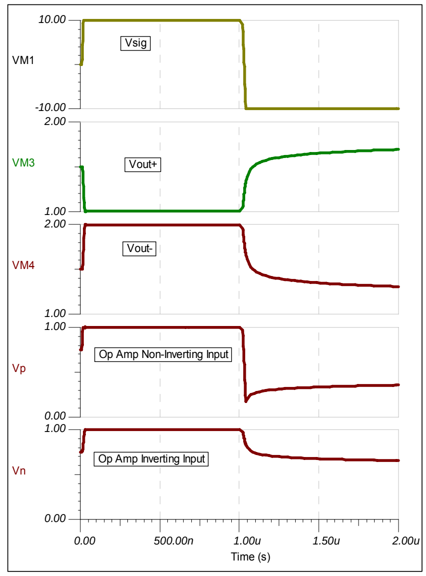
Texas Instruments

Building a spread sheet tool makes it easy to change and tweak design.

Bipolar SE Design Step 3: Simulate in Spice (TI Tina)

Example 2:
Bipolar SE Source to FDA Attenuator
Circuit Using the THS4520





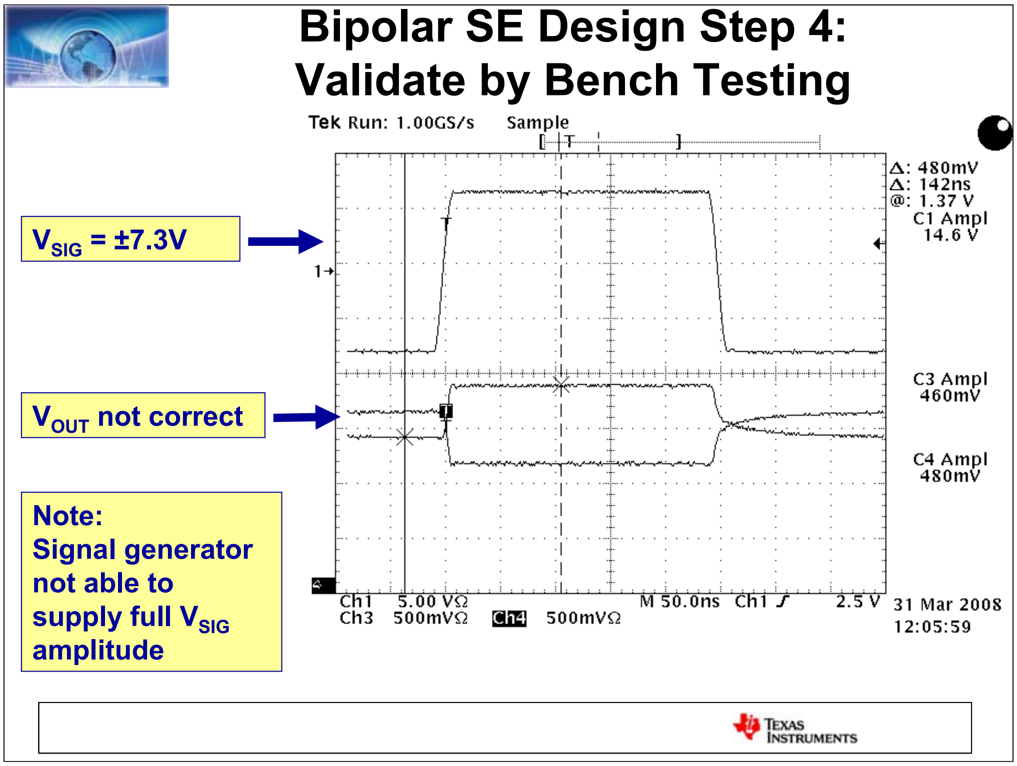
- The outputs are not correct!!!
- AARGHHHHHHH
- V_{ICR} of the THS4520 is violated
- What can we do?
- Call Jim => no; we can fix it

Spice simulation is a great way to verify the design formulas and values calculated using the spreadsheet are correct.

We see from results above there is a problem; the outputs are not correct.

Upon examination, we find the input voltage range of the THS4520 is violated causing the input to saturated.

What can we do?

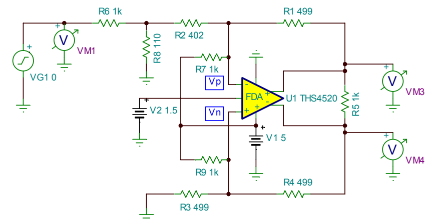


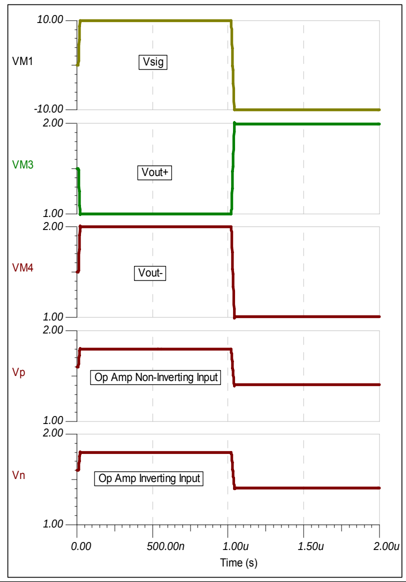
Validation is completed by testing in the lab.

Note: Signal generator not able to supply full VSIG amplitude, but we can still see the circuit is not right.

Bipolar SE Design Step 3: Simulate in Spice (TI Tina)

Example 3:
Bipolar SE Source to FDA Attenuator Circuit
Using the THS4520 with Pull-Up Resistors





- Adding 1k Pull-Up resistors fixes the problem

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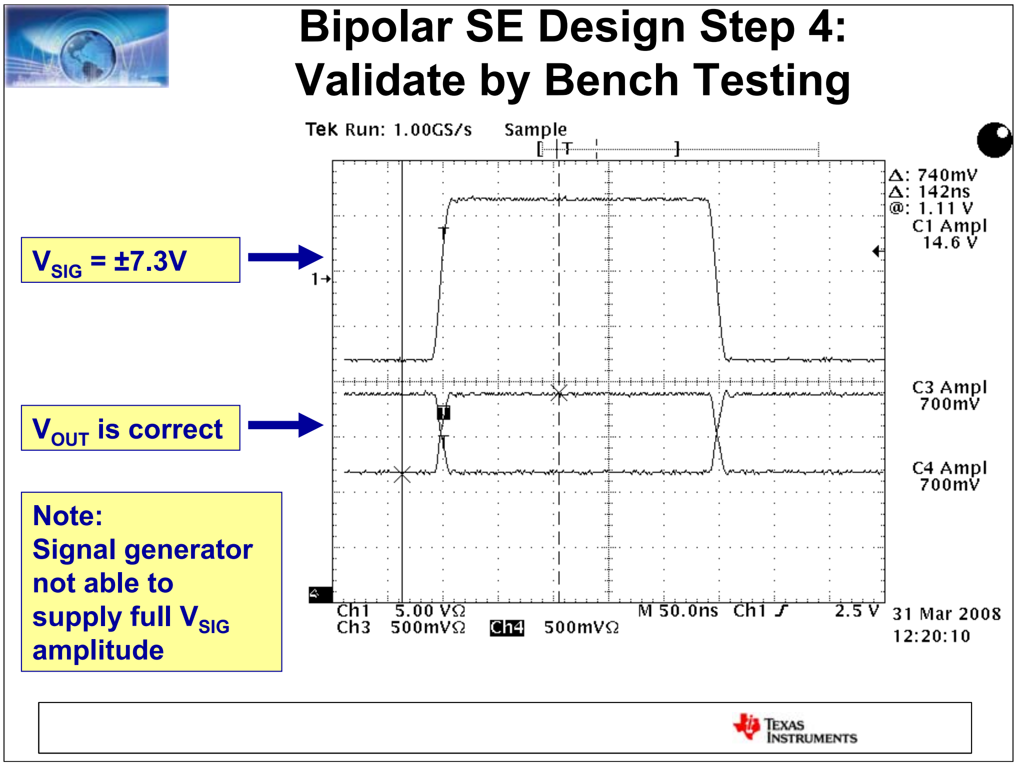
Pull up resistors fix the problem.

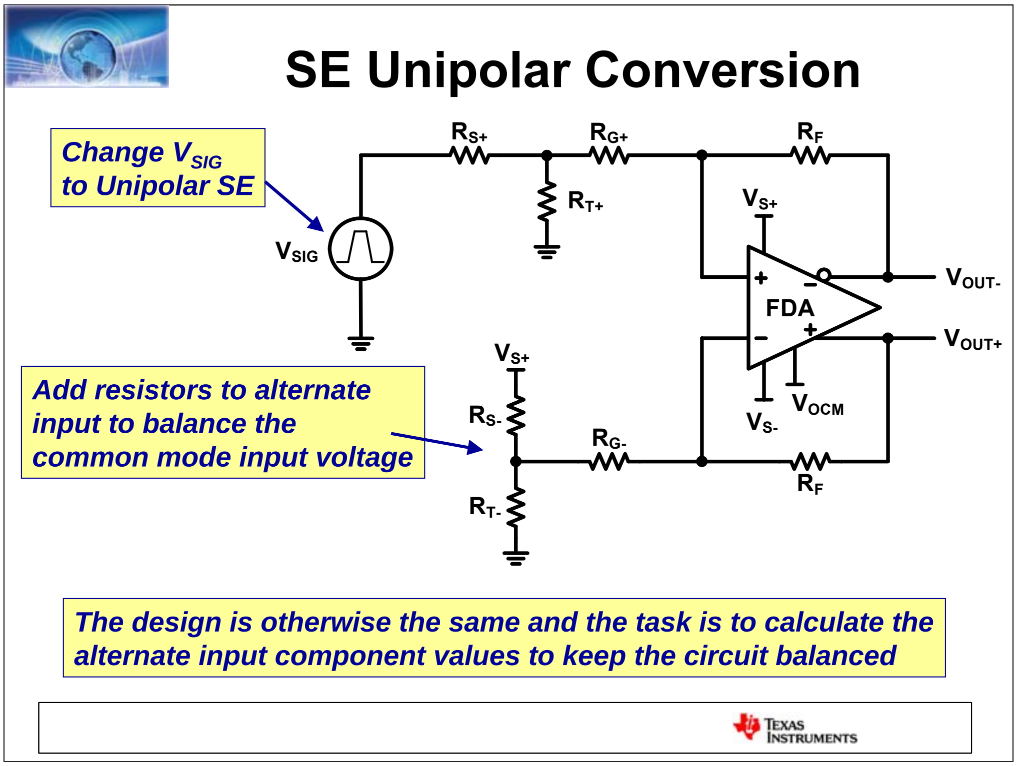


Validation is completed by testing in the lab.

Note: Signal generator not able to supply full VSIG amplitude, but we can see the circuit right.

Last: Move Design to Single Ended (SE) Unipolar Input

> We will now convert the input source and circuit to a single ended input unipolar source and circuit



To convert the previous single ended bipolar input to single ended unipolar we add a resistor divider to the alternate input to balance the common mode input voltage.

The design stays otherwise the same and the work left is to calculate the alternate input values to keep the circuit balanced.

Unipolar SE Design: Step 1
Calculate Component Values

Choose R_{S-} and calculate R_{T-}

$$R_{T-} = \frac{R_{S-}}{\dfrac{1}{\dfrac{V_{SIG\max} + V_{SIG\min}}{2V_{S+}} \times \dfrac{R_{T+}}{R_{S+} + R_{T+}}} - 1}$$

Then calculate R_{G+}

$$R_{G-} = R_F - R_{S-} \parallel R_{T-}$$

TEXAS INSTRUMENTS

For the positive side use the same formulas as for the bipolar SE input.

Although not required, it is probably best to keep the R_F resistor value the same on both side.

Choose R_{S-} and calculate R_{T-} and R_{G-} to adjust for the change in input common mode voltage and balance the amplifier using the equations shown.

Unipolar SE Design Step 2: Put Design Equations in Spreadsheet

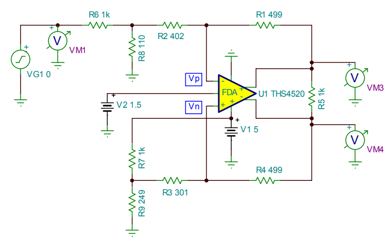
Design Inputs (enter values)				
Vsig min	Vsig max	Vout Diff	CM	Vs+
0	20	2	1.5	5
Design Choices (enter values)				
Rs+	Rf	Rs-		
1000	499	1000		
Calculated Values (do not enter values)				
Vout/Vsig	Rt+	Rg+	Rt-	Rg-
0.10	111.11	399.00	250.00	299.00
Nearest Standard Values (enter values)				
Rt	Rg+	Rt-	Rg-	
110	402	249	301	
Atten and Feedback Factors with Std Values (do not enter values)				
B+	B-	Atten +	Atten -	Zin
0.501	0.501	0.099	0.199	1092.168
Output Voltages with Standard Values (do not enter values)				
	Min	Mid	Max	Vout Diff
Vout+	1.004	1.497	1.991	1.974
	Max	Mid	Min	Offset
Vout-	1.996	1.503	1.009	-0.005

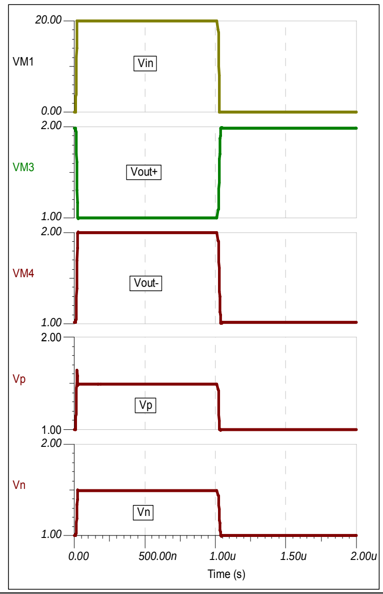
Wksht: "Unipolar SE FDA Atten"
Yellow = input values
Orange = output values

Again building a spread sheet tool makes it easy to change and tweak design.

Unipolar SE Design Step 3: Simulate in Spice (TI Tina)

Example 4:
Unipolar SE Source to FDA Attenuator Circuit
Using the THS4520

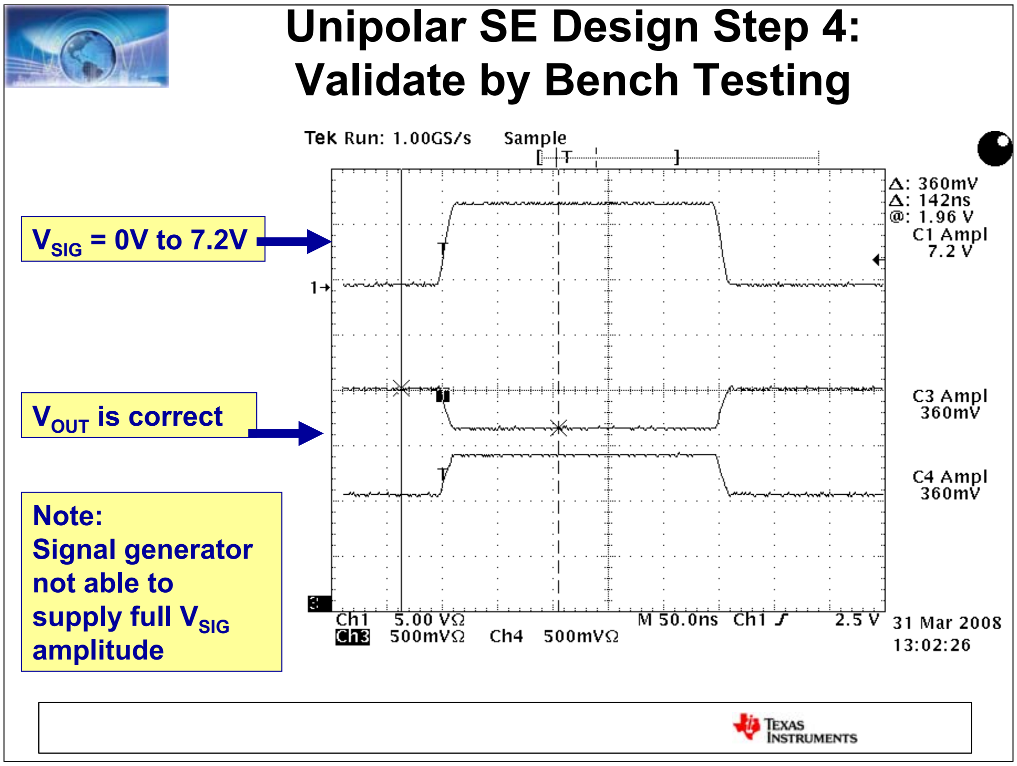




Things look OK, but per the data sheet V_{ICR} is too low and we may want to pull it up a bit to be safe

Texas Instruments

The Spice simulation shows no real problem, but the input voltage range of the THS4520 is close to being violated and we may want to pull it up a bit to make for a more robust design

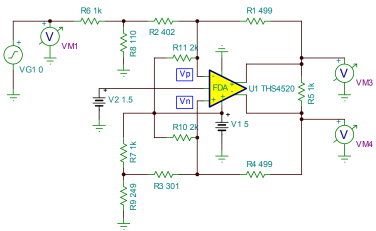


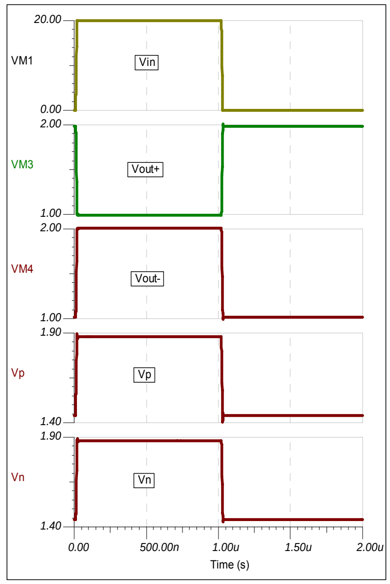
Validation is completed by testing in the lab.

Note: Signal generator not able to supply full VSIG amplitude. The circuit looks ok or we can not see any issues, but the PDS says the V_{ICR} should be 1.2V to 4.25V, which may be an issue down the road = so we will show using pull-up resistors again.

Unipolar SE Design Step 3: Simulate in Spice (TI Tina)

Example 5:
Unipolar SE Source to FDA Attenuator Circuit
Using the THS4520 with Pull-Up Resistors





- Adding 2k Pull-Up resistors fixes the problem

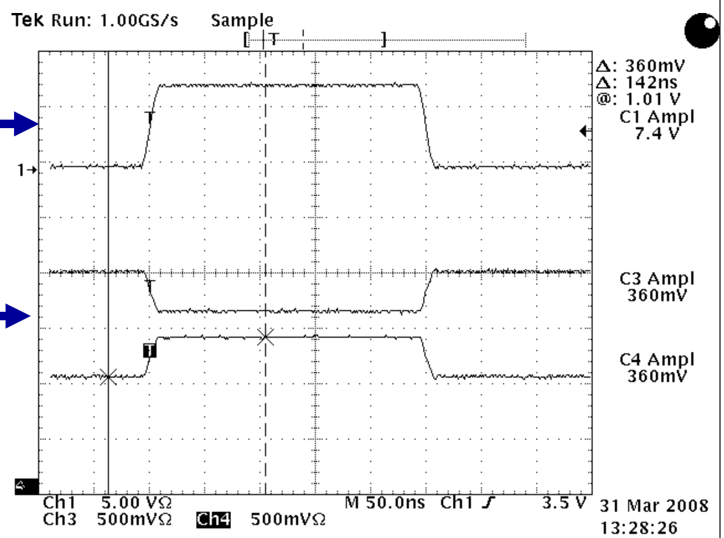
Pull up resistors move the inputs to an operating point with more margin

Unipolar SE Design Step 4: Validate by Bench Testing

V_{SIG} = 0V to 7.2V

V_{OUT} is correct

Note: Signal generator not able to supply full V_{SIG} amplitude



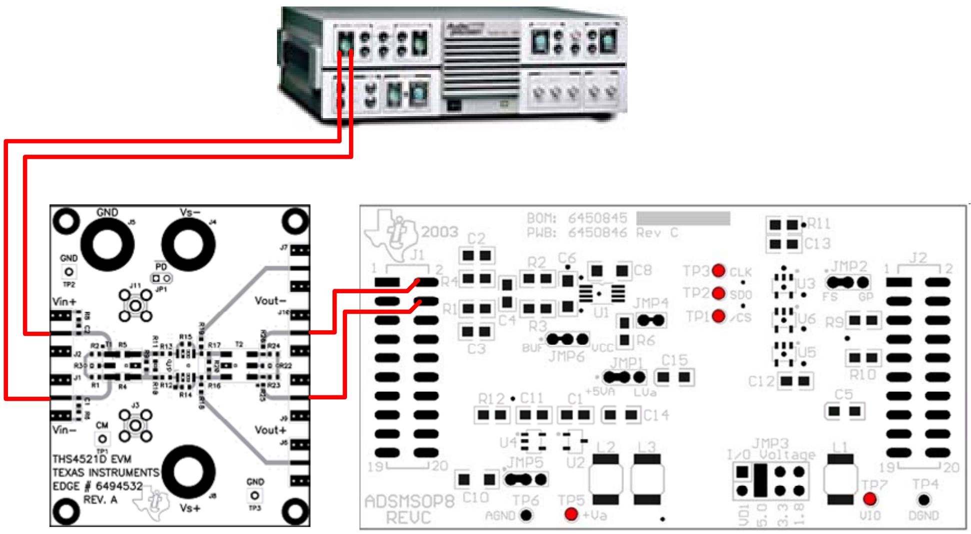
Validation is completed by testing in the lab.

Note: Signal generator not able to supply full VSIG amplitude, but we can see the circuit right.

THS4521 Single
THS4522 Dual
THS4524 Quad

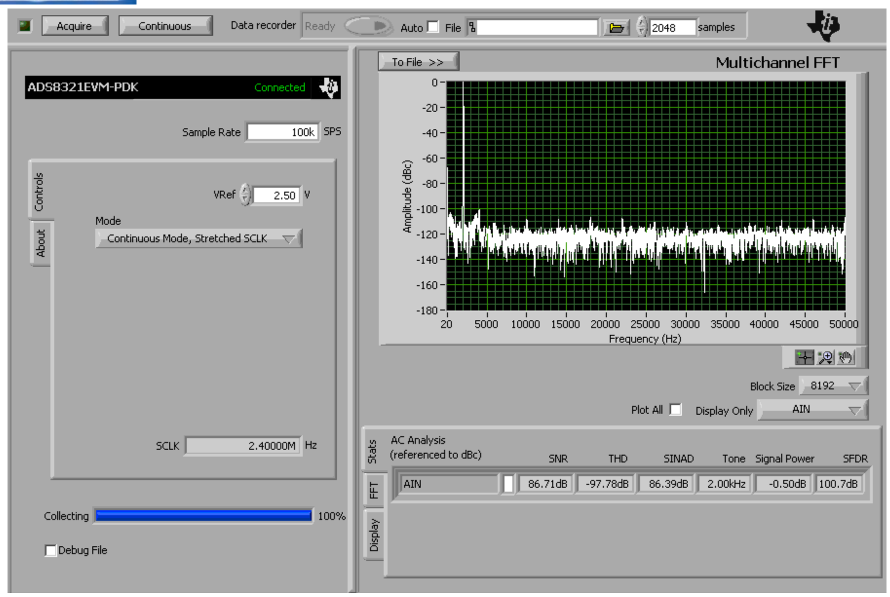
Lowest Power Fully Differential Op Amp Drivers for High Performance SAR and ΔΣ Converters

THS4521 + ADS8321 Hardware…



The hardware setup used in testing the ADS8321 with the THS4521 includes the actual THS4521EVM with the ADS8321EVM-PDK and a system 0ne Audio Precision signal source. The cabling was 'generic' in nature, nothing special was needed to achieve data sheet performance from this combination of hardware.

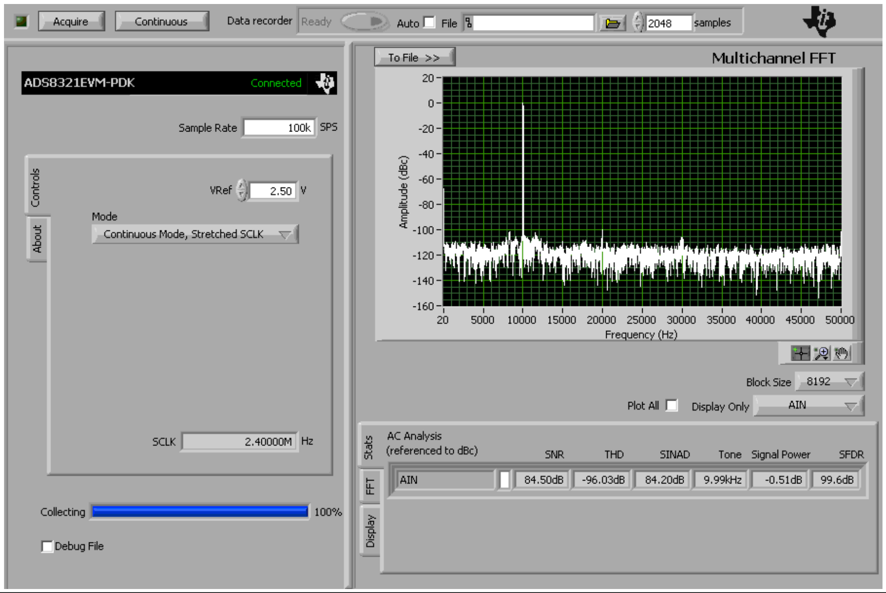
ADS8321 with 2K Sine Wave



Texas Instruments

This screen capture from ADCPro shows the FFT performance of the ADS8321 with the THS4521 EVM’s cabled together with a full scale 2K sine wave input signal.

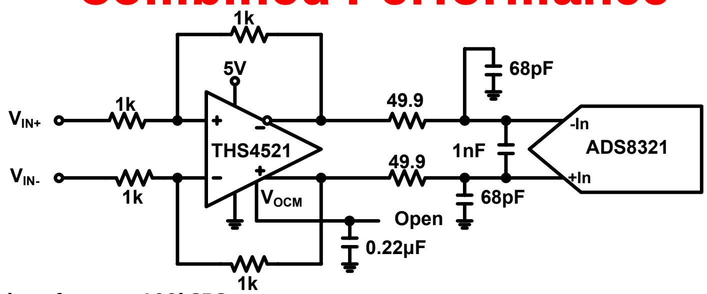
ADS8321 with 10K Sine Wave



Texas Instruments

This screen capture from ADCPro shows the FFT performance of the ADS8321 with the THS4521 EVM's cabled together with a full scale 10K sine wave input signal.

THS4521 and ADS8321 Combined Performance



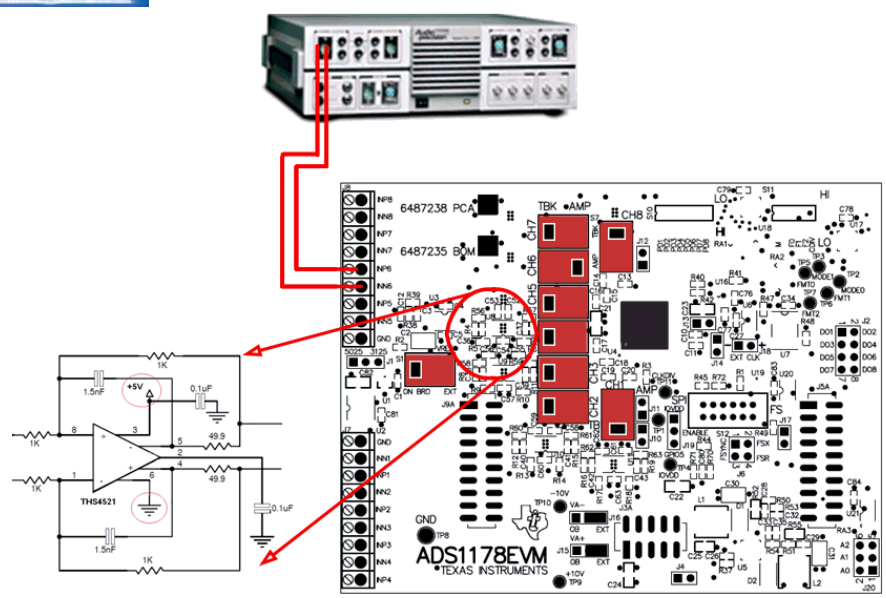
AC Analysis at f_{SAMPLE} = 100kSPS

Configuration	Tone (Hz)	Signal (dBFS)	SNR (dBc)	THD (dBc)	SINAD (dBc)	SFDR (dBc)
THS4521 + ADS8321	2k	-0.5	87	-98	86.4	100.7
THS4521 + ADS8321	10k	-0.5	85	-98	85.2	102.2
ADS8321 PDS (typ)	10k	-0.5	87	-86	84	86

Texas Instruments

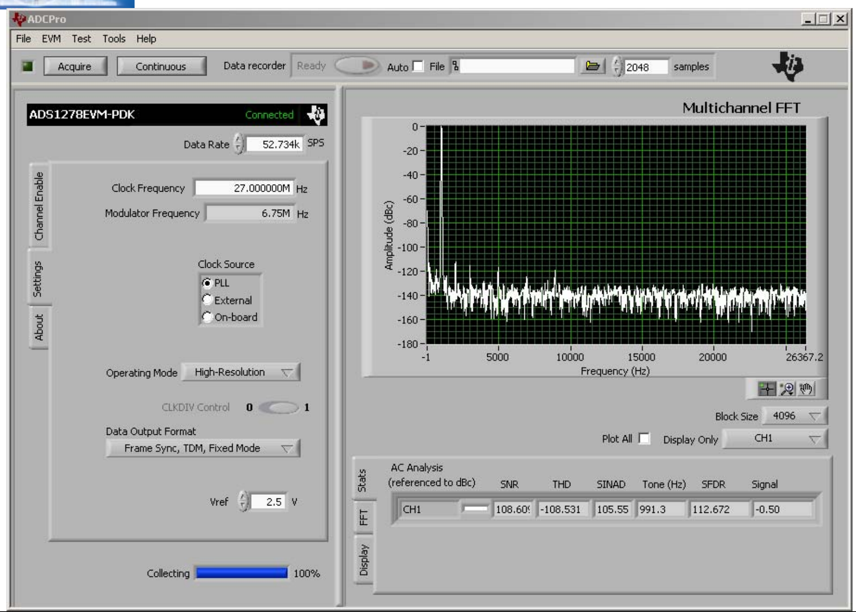
The table above and the schematic diagram show the performance of these two boards. Note that the typical data sheet numbers (bottom row). The SNR is a little low, but the SINAD and THD numbers show better than datasheet performance.

THS4521 + ADS1278 Hardware…



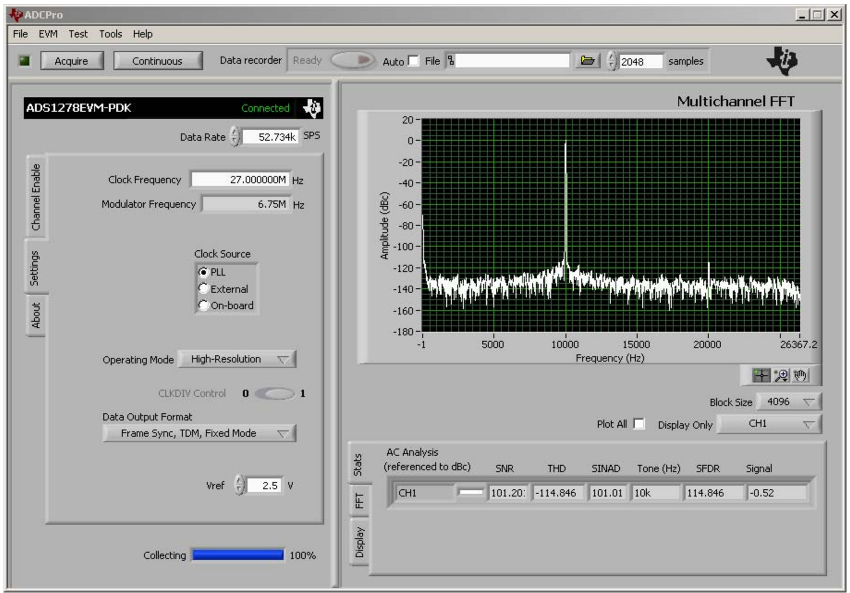
The hardware setup used in testing the ADS1278 with the THS4521 actually took the existing ADS1278EVM and replaced one of the input drives found on that hardware (an OPA1632) with the THS4521 device. A System 0ne Audio Precision signal source was used to provide the input signal. The cabling again was 'generic' in nature, nothing special was needed to achieve performance from this combination of hardware. The breakout in the lower left corner shows the actual connection modifications to the EVM. The power connections were modified by adding a zero ohm resistor in place of the bypass cap on the (-) supply. The +VA supply was reduced from the nominal +10 to only +5VDC.

ADS1278 with 1K Sine Wave



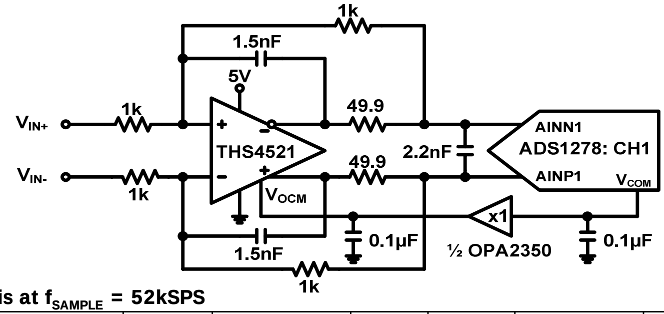
This screen capture from ADCPro shows the FFT performance of the ADS1278 with the THS4521 device mounted on the board with an applied full scale 1K sine wave input signal.

ADS1278 with 10K Sine Wave



This screen capture from ADCPro shows the FFT performance of the ADS1278 with the THS4521 device mounted on the board with an applied full scale 10K sine wave input signal.

THS4521 and ADS1278 Combined Performance



AC Analysis at f_{SAMPLE} = 52kSPS

Configuration	Tone (Hz)	Signal (dBFS)	SNR (dBc)	THD (dBc)	SINAD (dBc)	SFDR (dBc)
THS4521 + ADS1278	1k	-0.5	109	-108	105	114
THS4521 + ADS1278	10k	-0.5	102	-110	101	110
ADS1278 PDS (typ)	1k	-0.5	110	-108	NA	109

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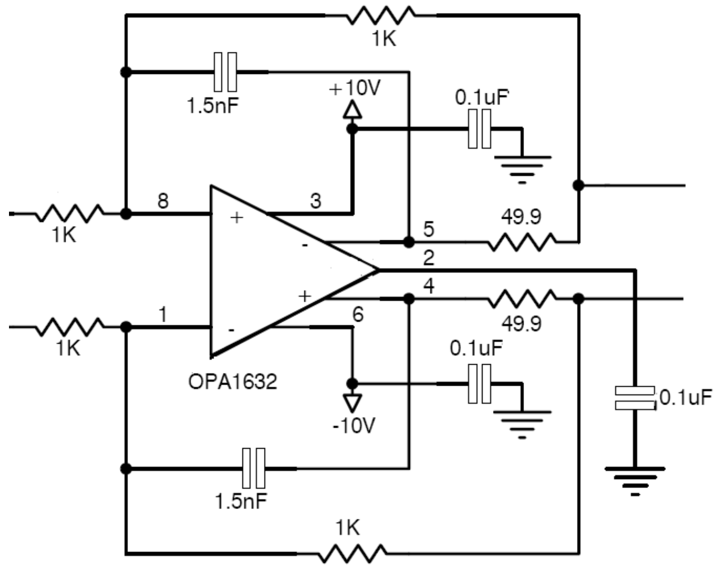
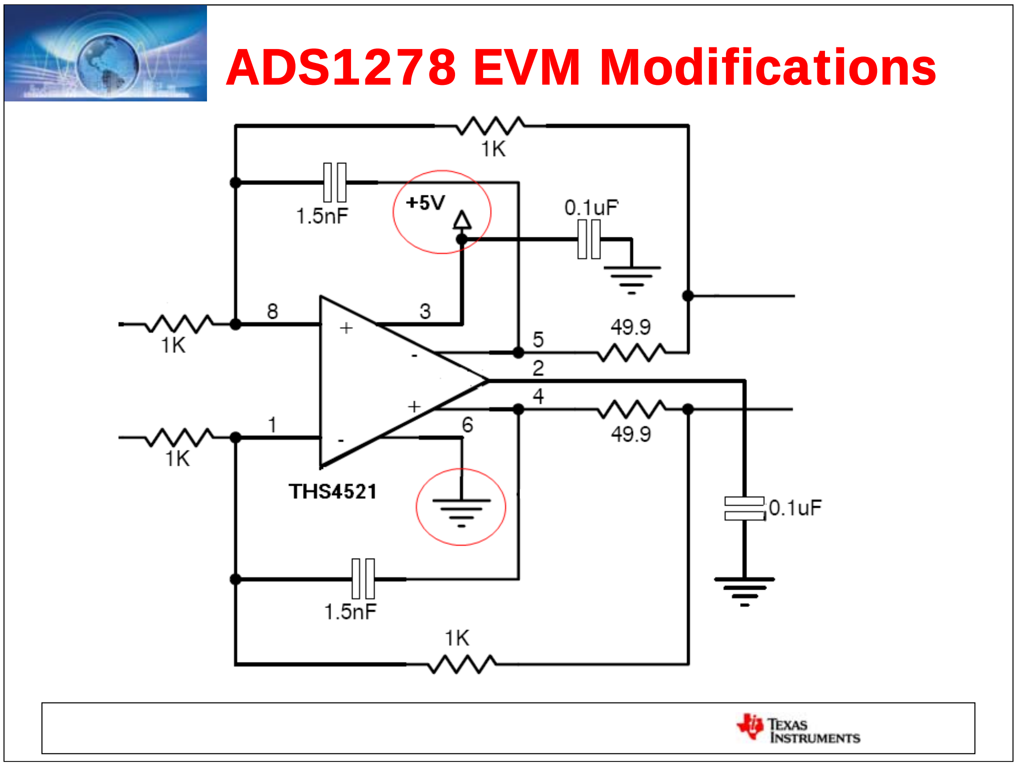
The table above and the schematic diagram show the performance of the ADS1278 being driven from the THS4521. Note that the typical data sheet numbers (bottom row). The SNR is a little low, but the SINAD and THD numbers show better than datasheet performance. Remember, this was a simply R&R of the amplifier on the EVM, no additional changes were made.

ADS1278 EVM As Shipped



This is the original configuration of a typical input drive circuit found on the ADS1278EVM. The driver is an OPA1632 which consumes over 8x the power of the THS4521. Replacing all OPA1632's with the THS4521 on the EVM requires less power than running a single input with the OPA1632 without compromising performance.



This is the modified circuit on the ADS1278EVM board. Vcc is 0-5V…

The End

Questions?

Comments?

Thank You

The End