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High-speed signal path tips and tricks: Using fully differential amplifiers for ADC driver applications

Combining different low-power signal path elements into high dynamic-range solutions across many different end system requirements

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Agenda

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- Introduction – Driving high-speed ADC's for AC-coupled apps
- Measuring and modeling baluns for ADC apps
- Using baluns combined with FDAs
- Single-to-differential FDA improved design flows
- Summary

AGENDA

Differential ADC input interface options for AC-coupled signal paths

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- Overall goal: To deliver a differential signal to the inputs of a high-clock-rate ADC where the F_{min} to F_{max} might be a significant portion of $F_s/2$ and might be in the 1^{st}, 2^{nd}, 3^{rd}, etc. Nyquist zones
- Since the ADC inputs are differential, baluns are often part of this solution
- There are many valid and effective approaches to this problem, each with its own set of pros and cons
- Emphasis is to explore ways to drive the even-order distortion terms down (mainly), as well as the odd order terms with better and better power efficiency

Getting from the amplifier outputs to the ADC inputs: Noise limiting filters

- Once you get a broadband differential signal available close to the ADC full-scale level, whatever dynamic range is available at the amplifier outputs must then be delivered to the ADC
- Normally, to get very low harmonic distortion in an amplifier solution, there is considerably more SSBW in the amplifier than the intended signal range
- This broadband noise is usually band-limited by a passive filter between the amplifier and ADC; this filter also acts to reduce out-of-band harmonic terms generated by the amplifier from arriving at the ADC
- Many options for this passive inter-stage filter. To the extent we can deliver lower harmonics at the differential amplifier outputs, lower order inter-stage filters can be used. Higher order filters right at the input of an ADC introduce their own set of issues.

Typical and emerging high-frequency ADC input interface options

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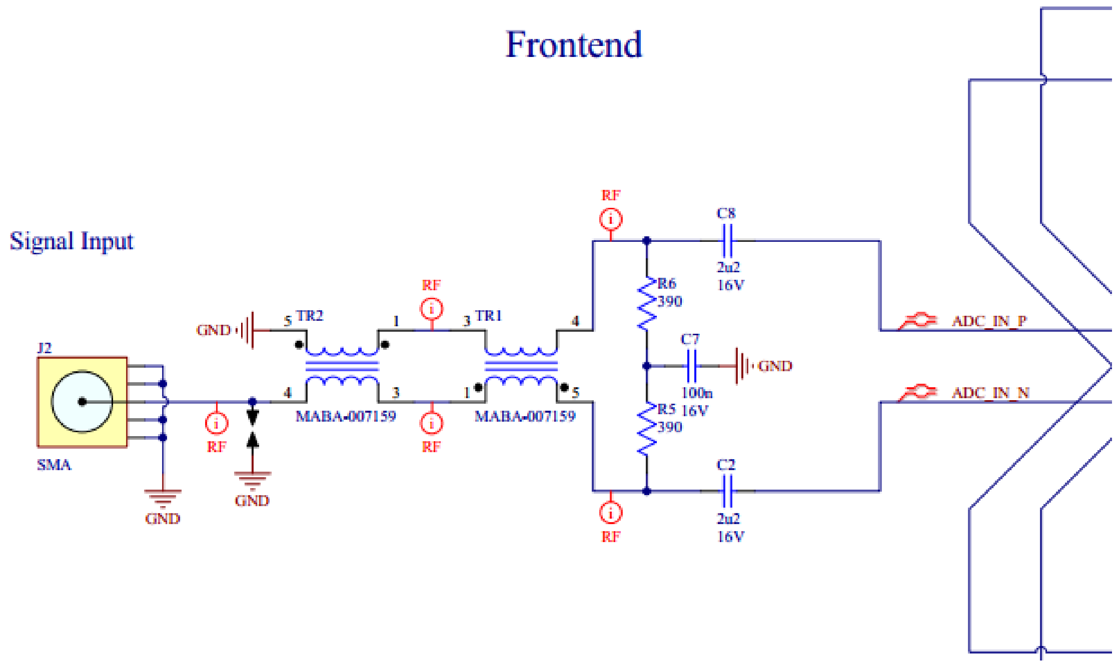
- Single ended I/O RF gain block or power amplifier driving a last stage single to differential balun interface.
  - This is essentially the ADC characterization circuit where the power amplifier is a lab synthesizer with a tuneable bandpass filter inserted from its output to the balun inputs
- Convert single-ended signal to differential with an input balun, then follow it with a differential I/O amplifier
- Use a fully differential amplifier (FDA) in an active balun mode to go single-ended-input-to-differential-output with no passive balun

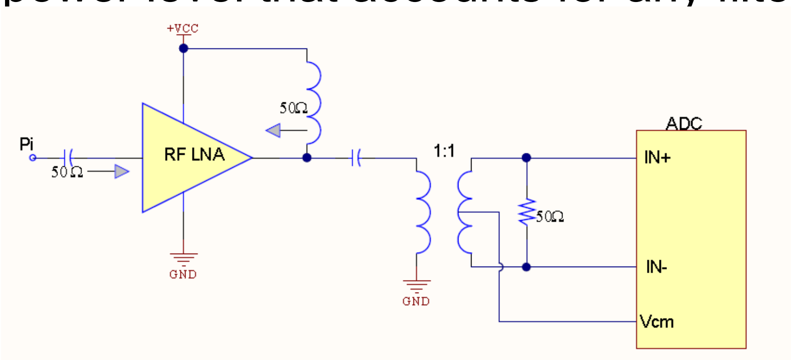
Typical ADC characterization interfaces

- Almost always 1 or 2 baluns of various types with different implementation approaches taken among ADC suppliers
- Example: What is usually not shown is the very narrow bandpass filter just before the SMA used to take specific frequency FFT data. Behind that filter is a lab signal generator. Real systems need to establish an actual signal bandwidth that is usually much broader bandwidth than these narrowband characterization filters



Classic RF-LNA-to-balun-interface-to-ADC

- Before differential output amplifiers became broadly available, most interfaces used a very linear RF amplifier driving into an input transformer. This has worked well but is not the most power efficient way to get the necessary harmonic distortion up to the ADC
- The final full-scale ADC input power appears single-ended at the output of the RF amplifier. While these can deliver very good OIP3, to get very low even-order suppression, they typically would need to run relatively high quiescent power
  - to get <-80dBc distortions levels, quiescent power in the LNA often exceeds 800mW
- A noise and/or IMD2 limiting filter can be included with the balun design. The RF amp then needs to be evaluated for stability driving this reactive load and deliver an output power level that accounts for any filter insertion loss



Design options using fully differential amplifiers (FDA)

- FDAs are a wideband differential gain block
  - Look like a differential inverting op amp
  - Includes a common-mode loop that controls the output-average voltage to a desired DC level
- Mainly intended to deliver a differential signal to an ADC centered on the required common mode input voltage for the ADC
- Output is always used as a differential signal where the low output impedance of this high-loop-gain device makes the filter design more straightforward
- Single ended source signal can be converted to differential by following an input balun with an FDA or using the FDA itself to perform an active balun operation. The active balun approach uses the FDA's internal common-mode loop to convert from single-ended input to a differential output

New options in getting single to differential

- Two new approaches for going from single ended to differential for a wideband ADC interface are shown below from two representative FDA data sheets. Both assume a wideband input match to a source impedance is desired
- Input balun can give a very low even-order harmonic distortion. One of many available wideband step-up baluns is shown below at the input of the THS4541
- FDA itself can provide a low noise, DC coupled, matched impedance input using a very low input R. This active match operation is shown below with the LMH6554, a current-feedback-based, 2GHz FDA. Running single to diff, this 8Ω input will look like 50Ω

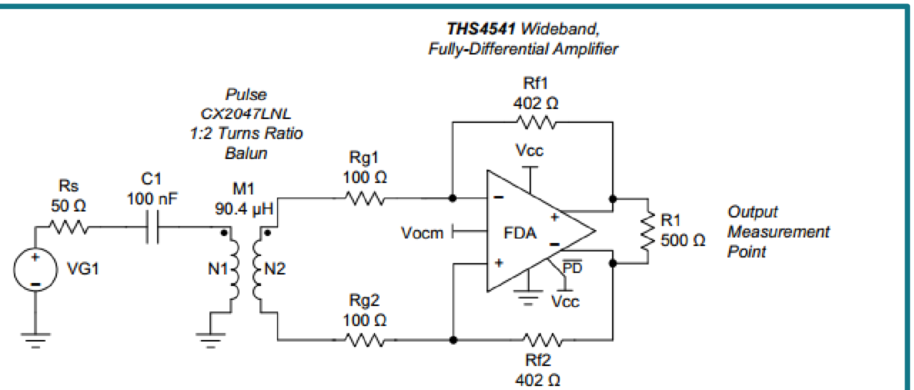
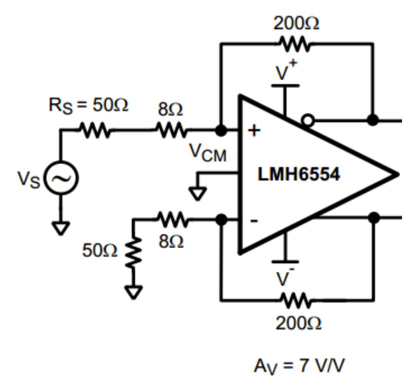


Figure 74. Input Balun Interface Delivers a Differential Input to the THS4541



"Active Balun" approach – can be DC coupled

AGENDA

Baluns in ADC-interface applications

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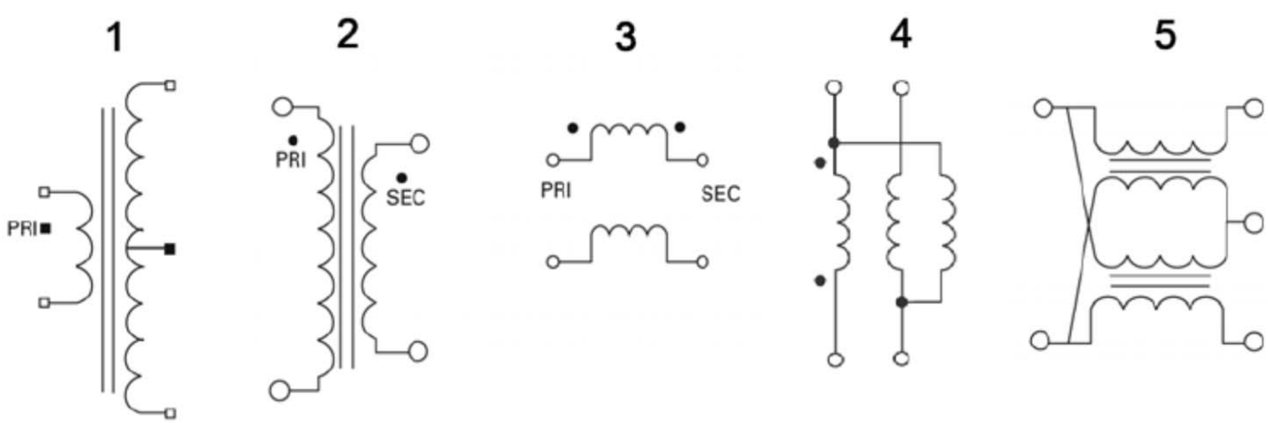
- Baluns offer an easy way for designers to convert single-ended to differential or differential to single-ended
- Simple measurement and modeling technique will be shown, along with a range of useful balun models for application-to-ADC input or DAC-output applications.
- Many different names for similar elements
  - Baluns (stands for “balanced to unbalanced”) are also called flux-coupled transformers, pulse transformers and transmission line transformers
  - Almost all wideband baluns can operate single to differential, differential to differential, differential to single, or even single-ended to single-ended I/O
  - Very flexible with nice ohmic isolation where an AC-coupled signal path is acceptable

Types of wideband baluns

- Wideband baluns are offered in several configurations, as shown below
- We'll focus on the first two, where the addition of the centertap in #1 can be useful in some cases, but normally it causes more problems than it solves
- Configuration 3 is also extremely useful as a common-mode-choke in differential signal path applications, but will not be explored here

Configuration Schematics



General cautions on balun specifications

- Baluns are passive elements that do not care what the source and load impedances are – they will pass some bandwidth regardless
- Most specifications assume some source impedance (Rs) and an n2*Rs as a load for specification purposes ("n" is the turns ratio)
- Two common specification points: 50ohm and 75ohm sources
- Baluns don't care and shifting those impedances around just shifts the passband
  - Moving the source and load up will shift the passband up; moving the impedances down will shift the passband down
- While the ubiquitous ADT1-1WT 1:1 transformer is specified as a 75Ω element, it works well in 50Ω systems with a passband shifted down in frequency
- Easy to generate a model that accounts for different source and load elements. This model also works well as part of filter design with the balun and with TI-provided amplifier simulation models

Transformer model for signal path applications

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- This approach uses mutually coupled inductors to model the various transformers
- Model is headed towards an L1 and L2 with either a coupling coefficient or mutual inductance for a spice model
- Aim is to add this to amplifier models, RLC filters and/or ADC input impedances to predict the flatband response region
- But first, how do we set up to measure the response shapes for these devices using standard 50Ω source and sense type network analyzers?
- This is easy with 1:1, but for a step-up transformer, we need to show the correct load but transition back to 50Ω source to avoid reflections in the measurement

Transformer, or step-up balun, modeling steps

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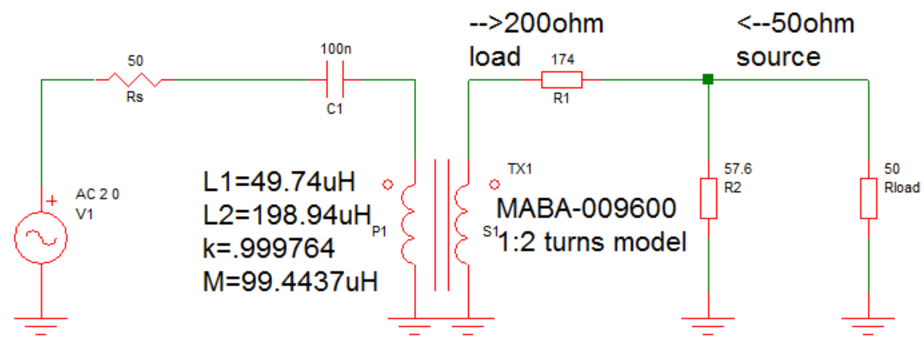
- Primarily need to pull out the high and low F-3dB frequencies with the load impedance set to n2Rs
- Top figure shows test set up to measure a 1:2 turns ratio MA/Com transformer (1:4Ω ratio) using a network analyzer and a simple thru calibration
- Output network looks like a 200ohm load to the balun, but a 50ohm source looking back into R2



$$R_2 = R_s \frac{n}{\sqrt{n^2 - 1}}$$

$$R_1 = R_s \left(n^2 - \frac{1}{1 + \sqrt{1 - \frac{1}{n^2}}} \right)$$

Once a thru cal is done, the measured midband gain should be given by this expression. The actual measurement will be slightly lower due to midband insertion loss – expecting a -11.44dB measurement here

$$20 * \log\left(\frac{1}{n + \sqrt{n^2 - 1}} \right)$$

Creating the transformer model

- Once you have the high and low F-3dB frequencies (fL is the high pass corner, fH is the low pass corner), the model elements are easily derived using the expressions here
- Assume test and modeling using the balun as a step-up device. Once created, the model can be operated in either direction – step up or step down
- Some simulators use a coupling coefficient (k), but TI's free spice simulator, TINA, looks for a mutual inductance, M

Input side L

$$L_1 = \frac{\frac{R_s}{2}}{2\pi f_L}$$

Output side L

$$L_2 = n^2 L_1$$

Coupling coefficient

$$k = \sqrt{\frac{1}{1+4\frac{f_L}{f_H}}}$$

Mutual inductance

$$M = k\sqrt{L_1 L_2}$$

Example measured/modeled MABA-009600

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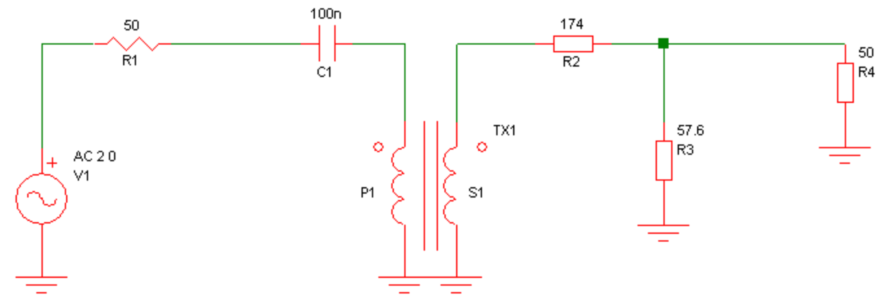
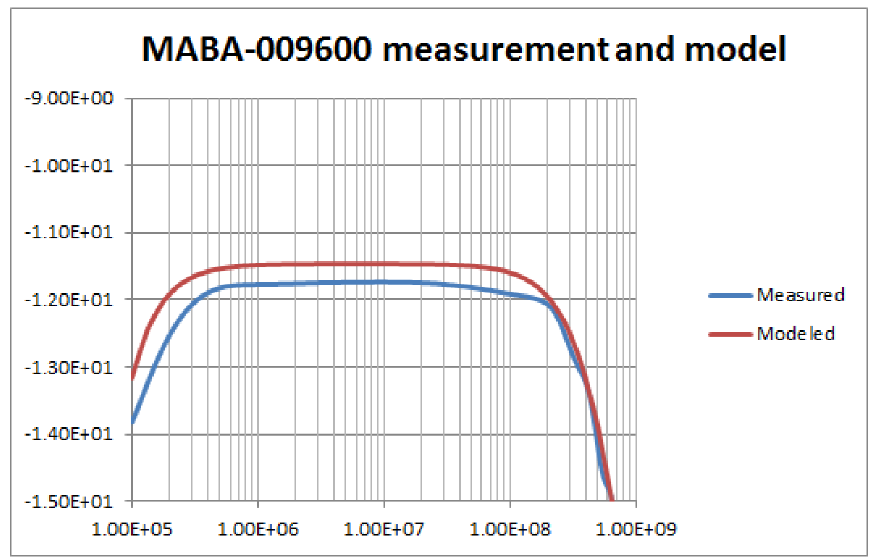
- Taking a network analyzer measurement showed:
  - fL = 80kHz (low frequency corner)
  - fH = 566Mhz (high frequency corner)
- Generating the coupled inductor model gives:
  - L1 = 49.74µH
  - L2 = 198.95µH
  - k=0.999717
- Mutual Inductance (this needs a lot of digits to hit the bandwidth right):
  - M=99.44373µH
- Simulating in the characterization circuit showed the results at right
  - Added attenuation in the measurement is the midband insertion loss of ≈-0.27dB

MABA-009600 1:2 base model
updated with measured data





TEXAS INSTRUMENTS

Comparison to data sheet numbers.

- Balun manufacturers do not generally specify low frequency F-3dB as low as the devices actually go, probably due to limited selection of low-frequency network analyzers
- Datasheet did not give F-3dB numbers, but they are needed for modeling using this simple approach
- HD testing has shown best results staying within the -0.5dB points of the passband.
  - The measured data shows a 250kHz to 220Mhz 0.5dB flatness span, far exceeding the suggested span on the data sheet

Balun datasheet example:
4:1 RF Flux Coupled Transformer (5-200MHz)

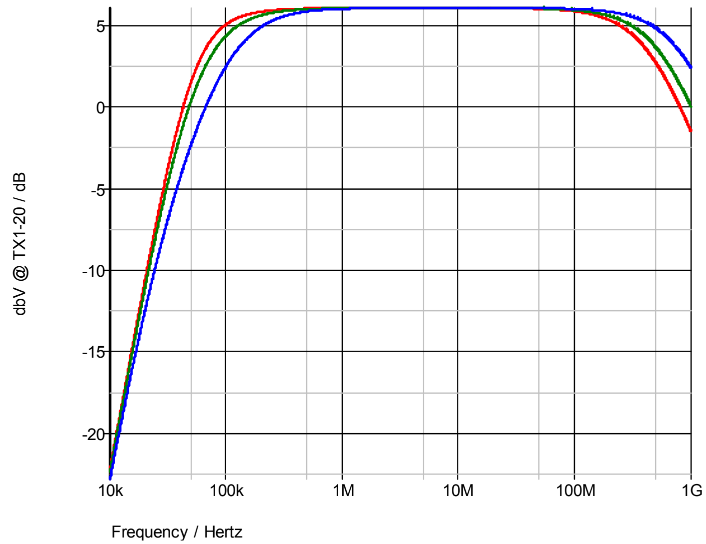
Electrical Specifications: T_A = 25°C, 0dBm, Z_0 = 50Ω

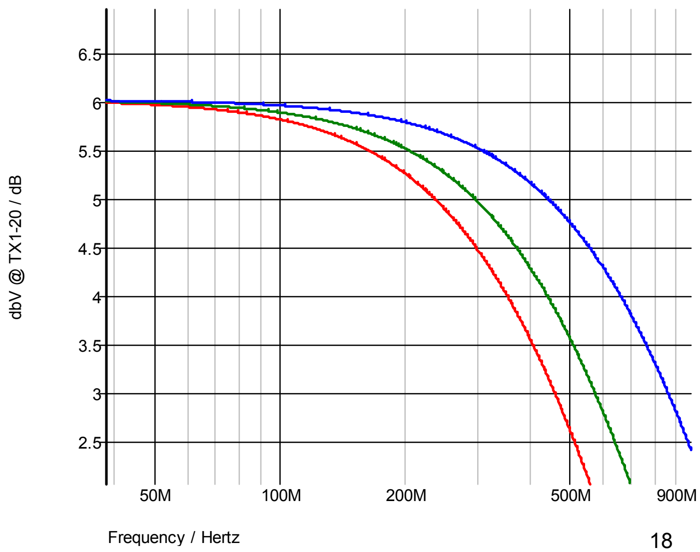
Parameter	Test Conditions	Units	Min	Typ	Max
Insertion Loss	5 - 65 MHz 65 - 200 MHz	dB dB	- -	0.4 0.9	0.7 1.5
Amplitude Unbalance	5 - 65 MHz 65 - 200 MHz	dB dB	- -	±0.02 ±0.2	±0.1 ±0.5
Phase Unbalance	5 - 65 MHz 65 - 200 MHz	° °	- -	±0.4 ±2.0	±2.0 ±8.0
Input Return Loss	5 - 65 MHz 65 - 200 MHz	dB dB	15 7	22 11	- -

- Almost always specified in “ohms” ratio
- Device is specified as a 4:1 RF Flux Coupled Transformer.
- Want to use it as a 1:2 turns ratio step up

Other considerations in using baluns

- Once this simple model is developed, it will correctly adjust the simulated passband as the source and load impedances change
  - Shifting up in impedance will move the passband up, while moving it down will shift it down
- Simulations at right show 40Ω to 160Ω, the original 50Ω to 200Ω, and then 75Ω to 300Ω expected performance
- Zooming in, you can see the effect of increasing the impedance across the transformer (blue is 75Ω to 300Ω)
- Un-matched impedances across the transformer are fine as long as the resulting passband, input impedance and source impedances to the ADC are acceptable to the application





Example balun models for high-speed signal paths

- Table below is a representative range of baluns for ADC or DAC signal path work
- Red lines have been updated with lab measured response shapes
- Remaining are basing their elements on datasheet numbers and may not truly reflect the low frequency span available on these useful devices

				-1dB Frequencies		Midband				Model Elements							
Turns Ratio	Part Number	Specified Rs, or	Centertap	Fmin	Fmax	Insertion	Manufacturer	# of decades	# of decades	Fmin(-3dB)	Fmax(-3dB)	Turns Ratio	L1	L2	k	M	
		50ohm if measured		MHz	MHz	loss (dB)		-1dB points	-3dB points	MHz	MHz		uH	uH		uH	
1	ADT1-1WT	50	Yes	1	400	0.4	MiniCircuits	2.60	4.23	0.05	850	1	79.58	79.58	0.999882	79.56811114	measured
1	TT1-6T	50	Yes	0.1	50	0.4	MiniCircuits	2.70	4.88	0.004	300	1	994.72	994.72	0.999973	994.6918696	
1	WBC1-1L	50	Yes	0.5	380	0.6	Coilcraft	2.88	3.48	0.25	750	1	15.92	15.92	0.999334	15.90489458	
	WBC1-1TL	50	Yes	0.4	500	0.8	Coilcraft	3.10	3.40	0.3	750	1	13.26	13.26	0.999201	13.25231431	
1	PWB-1-BL	50	Yes	0.4	218	0.4	Coilcraft	2.74	3.51	0.13	425	1	30.61	30.61	0.999389	30.58801288	
1	MABA-009180	50	Yes	1	100	0.65	Macom	2.00	4.01	0.056	571	1	71.05	71.05	0.999804	71.03738147	measured
1.22	MABA-007766-CF28A0TR	50	Yes	1	320	0.6	Macom	2.51	1.85	5	350	1.22	0.80	1.18	0.972598	0.944241593	
1.22	CX2044NL	75	No	0.3	350	0.3	Pulse Eng	3.07	4.11	0.05	650	1.22	119.37	177.66	0.999846	145.604374	
1.41	MABACT0048	50	Yes	0.56	222	0.26	Macom	2.60	3.00	0.31	313	1.41	12.84	25.52	0.998025	18.0617154	updated measured
1.41	ADT2-1T	50	Yes	0.1	463	0.3	MiniCircuits	3.67	4.22	0.05	825	1.41	79.58	158.21	0.999879	112.1906368	updated measured
1.41	TX-2-5-1	50	Yes	4.1	1100	1.23	MiniCircuits	2.43	2.72	2.5	1300	1.41	1.59	3.16	0.996176	2.23550308	Updated measured
1.41	MABA-009250-CT0068	50	Yes	0.078	256	0.2	Macom	3.52	4.03	0.04	431	1.41	99.47	197.76	0.999814	140.2292674	updated measured
1.73	ADT3-6T	50	Yes	0.2	250	0.4	MiniCircuits	3.10	3.82	0.06	400	1.73	66.31	198.47	0.9997	114.6897864	
1.73	TC3-1T+	50	Yes	5	300	0.5	MiniCircuits	1.78	3.34	0.3	650	1.73	13.26	39.69	0.999078	22.92368706	
2	ADT4-1WT	50	Yes	6	260	0.8	MiniCircuits	1.64	2.59	2	775	2	1.99	7.96	0.994878	3.95849509	
2	ADT4-1T	50	Yes	14	500	0.6	MiniCircuits	1.55	1.84	9	625	2	0.44	1.77	0.972387	0.859779143	
2	ADT4-6T	50	Yes	0.04	178	0.3	MiniCircuits	3.65	3.97	0.027	250	2	147.37	589.46	0.999784	294.6677347	updated measured
2	WBC4-1TL	50	Yes	0.5	380	1	Coilcraft	2.88	3.48	0.25	750	2	15.92	63.66	0.999334	31.80978916	
2	PWB-4-BL	50	Yes	0.272	356	0.5	Coilcraft	3.12	3.70	0.14	700	2	28.42	113.68	0.9996	56.81832832	
2	MABA-009600-CF48A0	50	Yes	0.145	300	0.3	Macom	3.32	3.85	0.08	566	2	49.74	198.94	0.999717	99.4437321	updated measured
2	MABACT0067	50	Yes	0.336	448	0.46	Macom	3.12	3.63	0.174	743	2	22.86708952	91.46836	0.999532	45.7127735	updated measured
2	CX2047LNL	50	Yes	0.083	270	0.2	Pulse Eng	3.51	3.93	0.044	372	2	90.43	361.72	0.999764	180.8151215	Updated measured
3	WBC9-1L	50	Yes	0.58	261	0.54	Coilcraft	2.65	3.22	0.3	500	3	13.26291192	119.3662	0.998802	39.74107506	
4	WBC16-1TL	50	Yes	1.2	157	0.8	Coilcraft	2.12	2.70	0.6	300	4	6.631455962	106.1033	0.996024	26.42035296	

What to do with the centertap on balun devices?

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- While many baluns offer a secondary centertap, it is best to leave it disconnected
- Centertap is often used to establish the ADC input Vcm voltage for ADC characterization
- In other applications where the DC operating points are set via other techniques, leaving the centertap unconnected will usually give lower harmonic distortion levels
- All single-supply signal paths with FDAs, mixers, DVGAs, etc. generate current noise into the ground through the power supply decoupling capacitors that is a full-wave-rectified version of the desired differential output swing
- Creates HD2 in the ground plane that can find its way back into the signal path via any centertap ground connections (AC or DC)

Balun datasheet example:
4:1 RF Flux Coupled Transformer (5-200MHz)

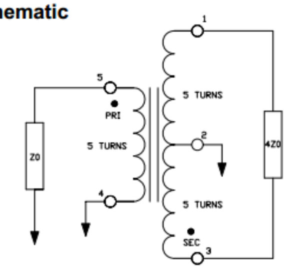
Features

- Surface Mount
- 4:1 Impedance
- 260°C Reflow Compatible
- RoHS* Compliant, Pb Free SAC305
- Recommended for Lead Free process only
- Available on Tape and Reel.

Description

4:1 RF-flux-coupled step-up transformer in a low-cost, surface-mount package. Suited for high-volume CATV/Broadband applications

Schematic

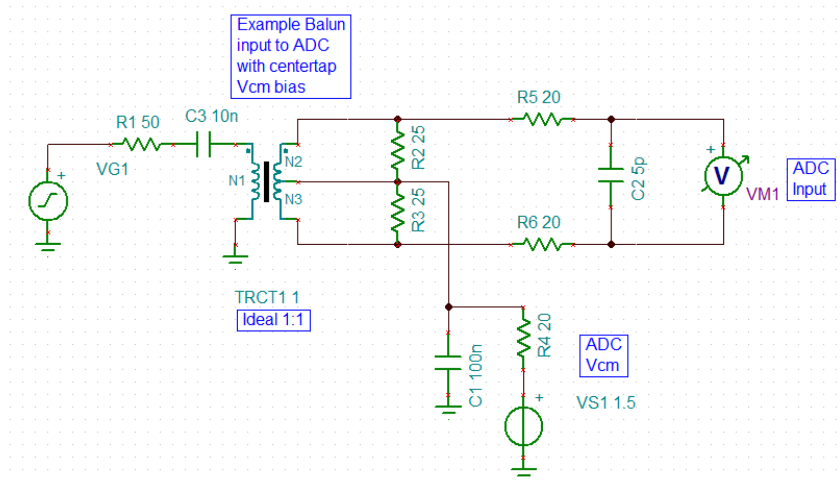


Case Style: SM-138

While the example balun shows a grounded centertap, leaving it open is fine and will eliminate the balance issues in the specification table

Example showing centertap hazard

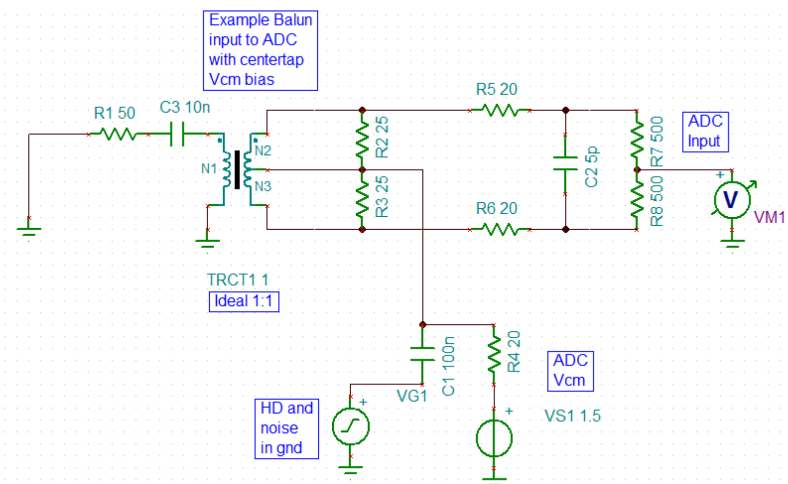
- Circuit at right is similar to numerous characterization or implementation interfaces
- Works fine, but to illustrate the hazard of bringing in DC biases, look closely at decoupling cap for Vcm reference

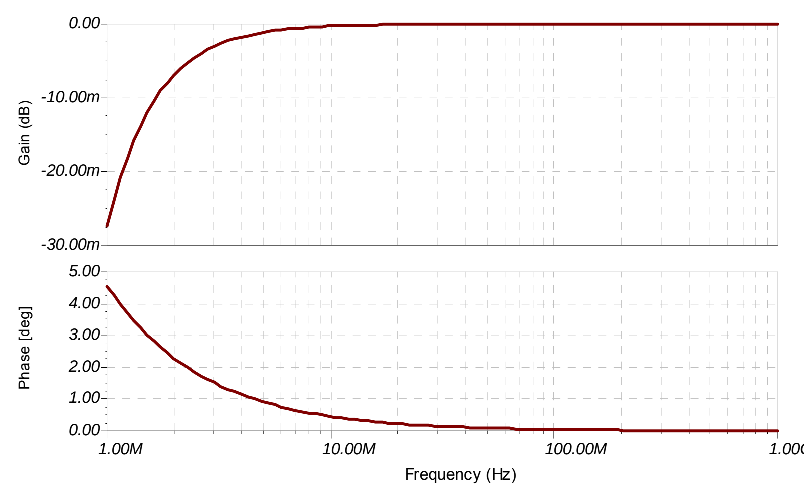


- Imagine that “gnd” actually has signal-related harmonics in it that will couple through the cap into the signal path as a common-mode harmonic signal
- Depend on the CM-to-DM conversion being very low to reject this
- This becomes a concern if the CM injection happens earlier in the signal chain with gain following that point, or if you have imbalanced filter elements to create the CM to DM conversion.
- If your goal is <-90dBc up to the ADC on the harmonics, everything matters

Example showing centertap hazard

- Change the circuit to inject a signal where gnd is, and look at the CM signal at the ADC inputs
- Above the cap high pass, it passes the signal straight through
  - Many more details here to assess if this is a problem, but something to keep in mind
- Only becomes an issue if the CMRR is reducing, which it always does, going up in frequency. This could be more of an issue moving into higher operating frequencies where a very low HD interface is desired





Using baluns with FDAs

- A typical approach is to bring the IF signal up to a last-stage RF amplifier and use it to drive a single-to-differential balun into the ADC
- While this works, in lower frequency ranges (<1GHz), putting the balun in front of an FDA might provide as good or better SFDR performance with much improved power efficiency
- If the Nyquist filter is placed prior to this last balun + FDA stage, it can operate at lower power levels
- From this bandwidth-constrained input, the goal is to provide a very low-distortion last-stage gain, where only a 2nd or 3rd order noise-power-bandwidth limiting filter is needed from this to the ADC inputs

Typical RF + balun designs to the ADC

- RF signal is often down-converted, passed through a very high Q SAW filter into the last IF amplifier (often actually an RF amplifier being used in an IF) and then into a Balun into the ADC
- Simplified schematic below seems fairly typical. One concern is that while the BW out of the last SAW is very narrow, the IF amplifier output noise is very broadband. So, with no subsequent filtering, any out-of-band noise and harmonics will get folded into Nyquist by the ADC. Need some filtering at the ADC input for any design to get the best performance, even if that filter is just a simple RC single pole

THS9001

SLOS426C – NOVEMBER 2003 – REVISED DECEMBER 2013 www.ti.com

Figure 21 shows an example of a single conversion receiver architecture and where the THS9001 would typically be used.

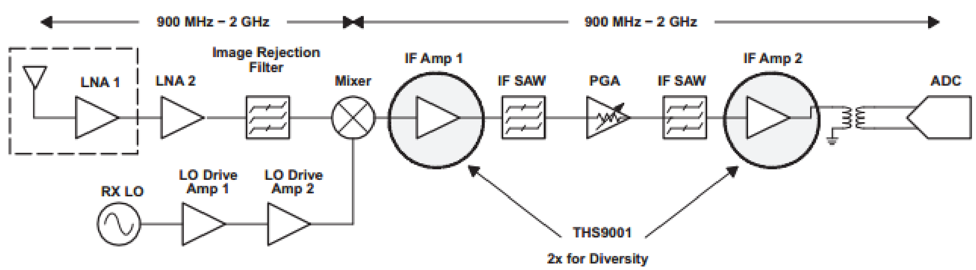


Figure 21. Example Single Conversion Receiver Architecture

Filter considerations between the balun and ADC

- While it is possible to insert an LC filter after this last balun, the job becomes a bit more challenging
  - Now the filter impedance has to come through balun to keep the amplifier operating well
- Filter-source impedance is now what the ADC sees; not hard to make this ok but should be considered
- ADC input impedance in the band of interest becomes part of the filter design (always an important point)
- Aggressive filtering often includes higher insertion loss that has to be recovered in the output power delivered; this often degrades IMD2 and maybe IMD3 up to the ADC
- Since the RF amplifier is driving single-ended at high power, the HD2 and IMD2 terms usually need a lot of quiescent power to suppress. A postfilter can help this but has its own issues if made higher order

Alternate topological approach

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- If you know you need to get differential to the ADC, a fully differential amplifier (FDA) is another approach with considering
- Taking single-ended op amps and making them differential stages picks up a significant reduction in even-order harmonics for a given output Vpp target and quiescent power in the amplifiers. The odd orders also go down, as the power is now shared between the two output stages, but not as dramatically as the even-order terms
- If you construct a very balanced signal path using baluns and FDAs, the HD2 and IMD2 should go down at reduced quiescent power levels
- This can be used to get a higher dynamic range signal path up to the ADC where perhaps lower-order interstage filters will be adequate right at the ADC input. This is assuming a Nyquist filter prior to this last stage balun + amplifier

Single to differential with balun + FDA

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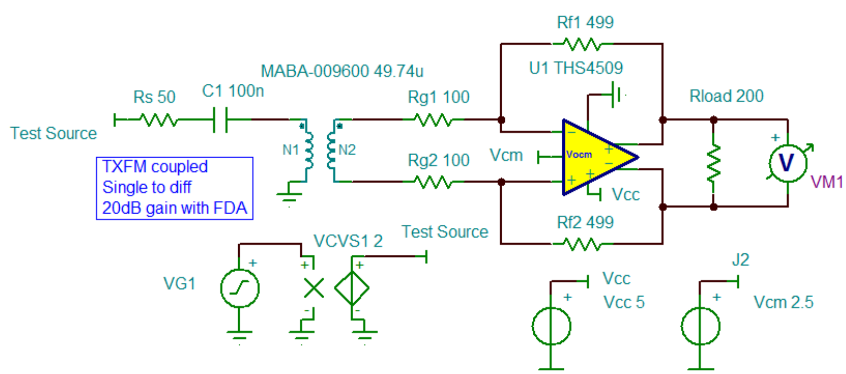
- Circuit below is an example schematic using the wideband THS4509 voltage feedback FDA and the example balun 1:2 turns ratio step-up model
- Coming from a 50Ω source, the 1:4 ohms ratio transformer would like to see 200Ω load to input refer as a 50Ω termination to the source. That is provided here by the 2 -100Ω Rg elements looking into a differential virtual ground
- FDA includes an output-common-mode control loop forcing the DC voltage to the 2.5V shown here. This circuit then biases the inputs (and the txfm secondary) to that voltage as well.
  - No need for DC or AC connection to the secondary centertap because no connection there keeps ground noise and even-order harmonics out of the signal path at this sensitive early point in the signal chain

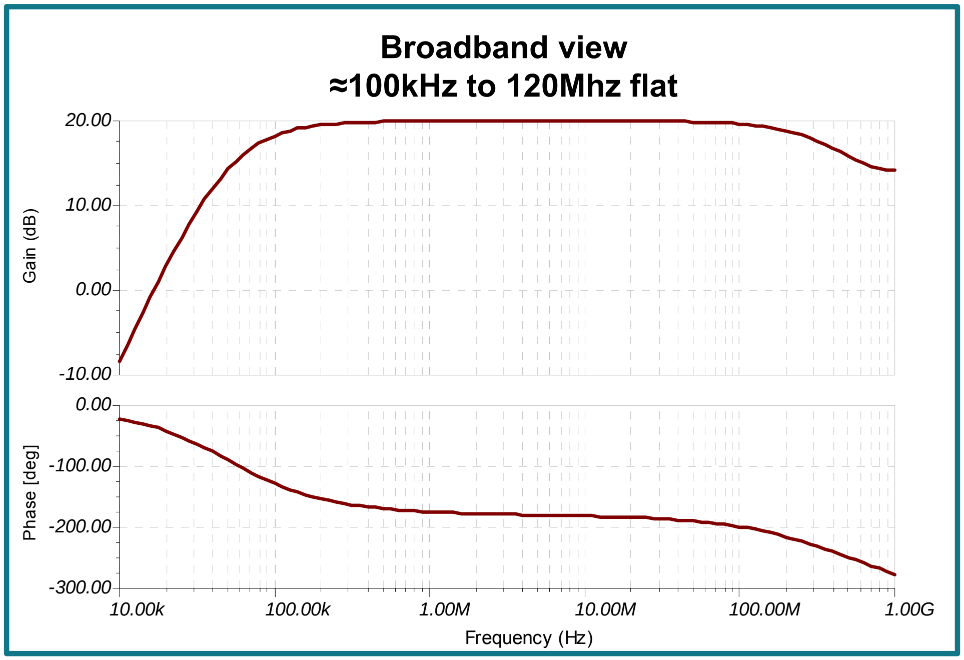


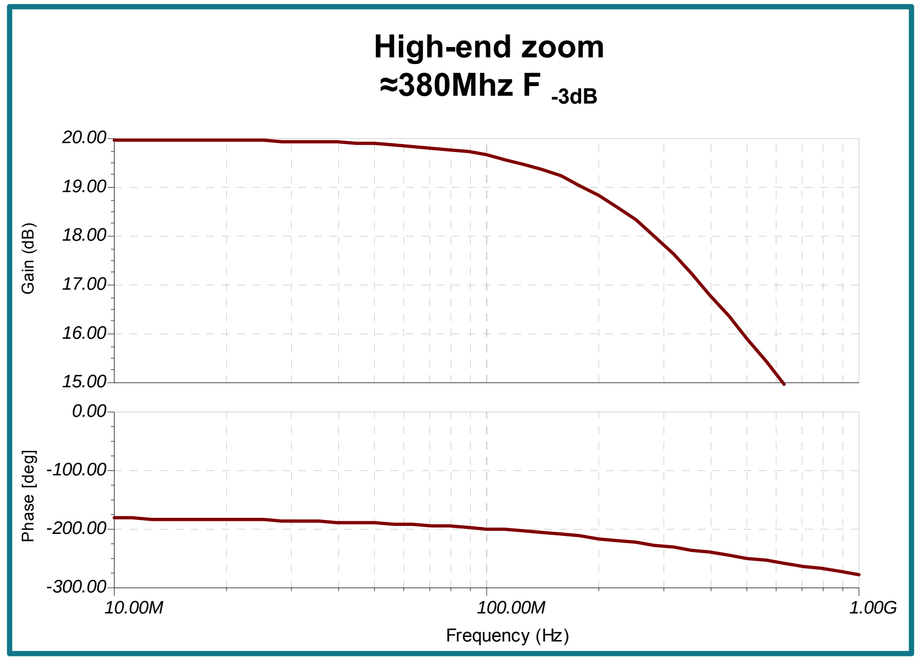
Operating description and topological benefits

- From the input of the balun, the signal will see a 2X step in voltage to the secondary. This purely differential signal will then get a gain to the FDA output of 5X (499/100) for an overall gain of 10X (20dB)
- Keeping the transformer termination fixed at 200Ω with the 2-100Ω gain resistors means gain changes are easy with the feedback R values
- If the source 50Ω comes through the transformer as 2-100Ω (looking back from the FDA summing junctions to the source), those add to the physical Rg resistors to reduce the apparent noise gain for the FDA down to 1+499/200 = 3.5V/V. This has the effect of extending the bandwidth for the FDA and reducing the gain for the FDA differential voltage noise
- THS4509 offers a 2.5GHz gain bandwidth product. At a noise gain of 3.5V/V, its approx. 714MHz BW should combine with the balun 566MHz to show approx. a F-3dB of 440MHz

Expected 1:2 stepup + THS4509 response

- From the input of the balun, the signal will see a 2X step in voltage to the secondary
- The purely differential signal will get a gain to the FDA output of 5X (499/100) for an overall gain of 10X (20dB)
- This shows a lower F-3dB than expected in the TINA-TI simulation





Even-order harmonic suppression features

- Balun provides nearly distortionless step-up at the low power levels required at this input point:
  - 2Vpp output at the FDA is 200mVpp max input -10dBm and 400mVpp at the balun output
- On the balun output side, you can think of this as:
  - Purely differential voltage signal
  - Single-signal current to the virtual grounds of the FDA operating in a balanced differential I/O mode
- With nothing connected to the centertap, the balun gain and phase balance specifications are inconsequential
- If you assume the ground plane probably has output-signal-related harmonic distortion terms in it from supply current rectification, having no connection from thecentertap into the signal path isolates that possible source of SFDR degradation
- If the centertap were connected to ground through a cap (very common), harmonic terms will come into the signal path as a CM term and then get converted to DM via component mismatches. Not connecting that centertap relaxes the component matching requirements

Noise improvement features for the balun + FDA

TECH DAYS Texas Instruments

- Noise gain reduction reduces the total output noise and the apparent input-referred noise for any gain
- Using an input step-up transformer will often reduce the input NF if the amplifier's current noise terms are relatively low.
  - The transformer provides a "nearly noiseless" voltage gain at the cost of higher impedance values on the FDA side of the circuit
  - VFA-based FDAs always have very low current noise terms
- Sweeps of NF vs total target gain can be generated for various steps of turns ratio values using the THS4509 input-spot-noise voltage and current terms
- THS4509 input noise terms:
  - En = 1.9nV (differential spot input noise)
  - In = 2.2pA (spot current noise at each input)

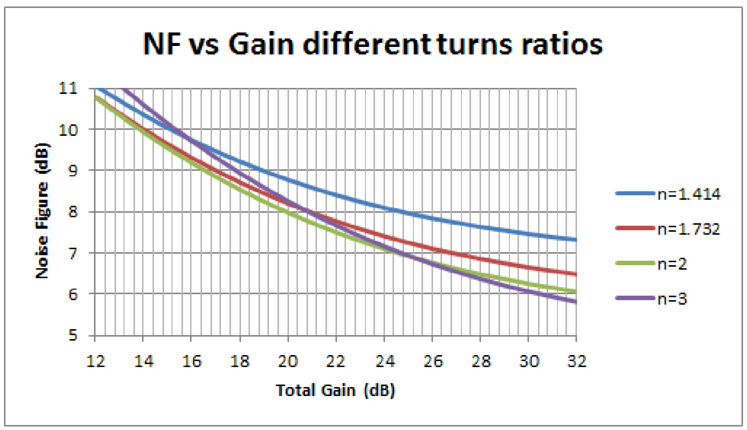
Example: Input-referred noise figure sweeping total gain

- If a turns ratio "n" is selected, the input resistors (Rg) will be set to get the termination
- Then sweeping the total target gain is just stepping the Rf values up
- So both the Rg and Rf values are constrained by the turns ratio and target total gain and drop out explicitly from the overall NF expression
- 3 ratios are all that are needed to describe the NF expression:
  - Turns ratio – "n"
  - Amplifier gain – Rf/Rg = "α"
  - Transformer midband insertion loss as a linear attenuation (not dB) = "β"
- Putting all of this together gives a very accurate (if somewhat involved) expression for the expected input noise figure in this balun + FDA

$$NF = 10 * Log\left(\frac{(1+\beta^2)}{\beta^2} + \frac{8}{\alpha\beta^2} + \frac{4}{(\alpha\beta)^2} + \frac{\left(\frac{e_n}{\beta n} * \left(\frac{1}{2} + \frac{1}{\alpha}\right)\right)^2 + \frac{1}{2}\frac{(n * i_n * R_s)^2}{\beta^2}}{kTR_s} \right)$$

Example: Input NF sweeps for several baluns

- Stepping the turns ratio up with a selection of available baluns and sweeping the total target gain from 12dB up to 32dB gives the estimated input NF for a 50 source shown below; the baluns and their parameters are also provided
  - For example, the 0.3dB insertion loss for the example balun becomes a β = (10^(-0.3/20))=0.966
- NF around 20dB gain clusters around the same 8dB range for n = 1.73 to 3. Using the highest "n" consistent with BW targets will extend the bandwidth of the FDA for a given total gain target
  - 8dB noise figure is an input referred spot noise of about 1nV/√Hz
  - Baluns reduce the effect of the THS4509 intrinsic differential input spot noise of 1.9nV/√Hz



Part Number	Turns Rati	Midband Insertion loss (dB)	Beta (β)	Manufacturer	Model Elements Fmin(-3dB) MHz	Fmax(-3dB) MHz
ADT2-1T	1.414	0.6	0.933	MiniCircuits	0.4	450
ADT3-6T	1.732	0.4	0.955	MiniCircuits	0.06	400
MABA-009600	2	0.3	0.966	Macom	0.08	566
WBC9-1L	3	0.54	0.940	Coilcraft	0.3	500

Alternate FDA devices from TI improve balun + FDA performance

- Newer amplifier options from TI improve noise, bandwidth and SFDR in higher frequencies (newer than THS4509)
  - Example1: LMH3401, 7GHz, ultra-wideband FDA
  - Example2: LMH6554, 2GHz, wideband FDA
- Here is a table of options to consider (as of late 2014)
- Next we dive deeper into the LMH6554 as an example

<6V operating max supply FDA devices		Ascending BW, Red are New										
Part #	Nominal total Supply	Quiescent Icc Typ (mA)	Quiescent Power (mW)	VFA/CFA	Rf if CFA	GBP/BW (MHz)	Slew Rate V/µsec	Input En nV/√Hz	Input In pA/√Hz	Min operating Supply	AbsMax Supply	Related Devices
THS4541	5	10.1	50.5	VFA		850	1500	2.2	1.9	2.7	5.4	
THS4520	5	14.2	71	VFA		1300	570	2	2	3	5.5	
THS4509	5	38	190	VFA		3000	6600	1.9	2.2	3	5.5	
LMH6554	5	52	260	CFA	250	2000	6200	0.9	11	4.7	5.5	LMH6552 slightly slower version
LMH3401	5	56	280	VFA		7000	18000	1.3	2.5	3.3	5.25	Fixed Gain 16dB

Example: 2.8GHz, ultra-linear LMH6554 FDA

Features

▪ **Small signal bandwidth**	**2.8 GHz**
▪ **0.1 dB gain flatness (A_v=2)**	**830 MHz**
▪ OIP3 (f=150MHz,V_{od}=2V_{pp})	47 dBm
▪ HD2/HD3 (f=75 MHz,V_{od}=2V_{pp})	-96/-97 dBc
▪ **HD2/HD3 (f=250 MHz,V_{od}=2V_{pp})**	**-79/-70 dBc**
▪ Input Noise Voltage	0.9 nV/√Hz
▪ Supply voltage	5 V
▪ Package	14-LLP

Benefits

- Differential current feedback ➔ Allows operations at higher gains with more constant BW and SFDR over gain
- >800MHz 0.1 dB gain flatness ➔ High accuracy for wideband signal amplification
- Low noise & low distortion ➔ Achieves very low output noise at higher gain for improved dynamic range

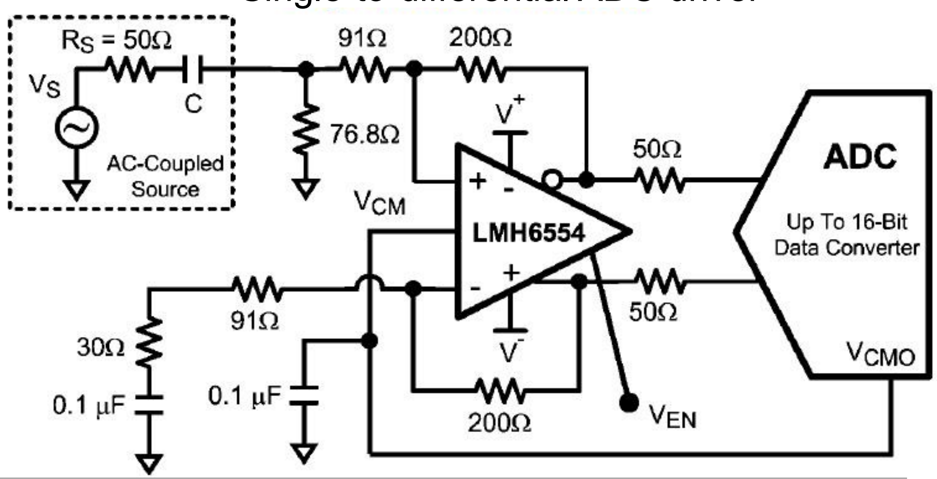
Applications

- Differential ADC driver
- Single-ended to differential converter
- IF/RF and baseband gain blocks
- Oscilloscopes

This example circuit is typical, but you can also use an input balun

EVM PART # (LMH6554LE-EVAL)

Single-to-differential ADC driver



Alternate FDA devices from TI improve bandwidth

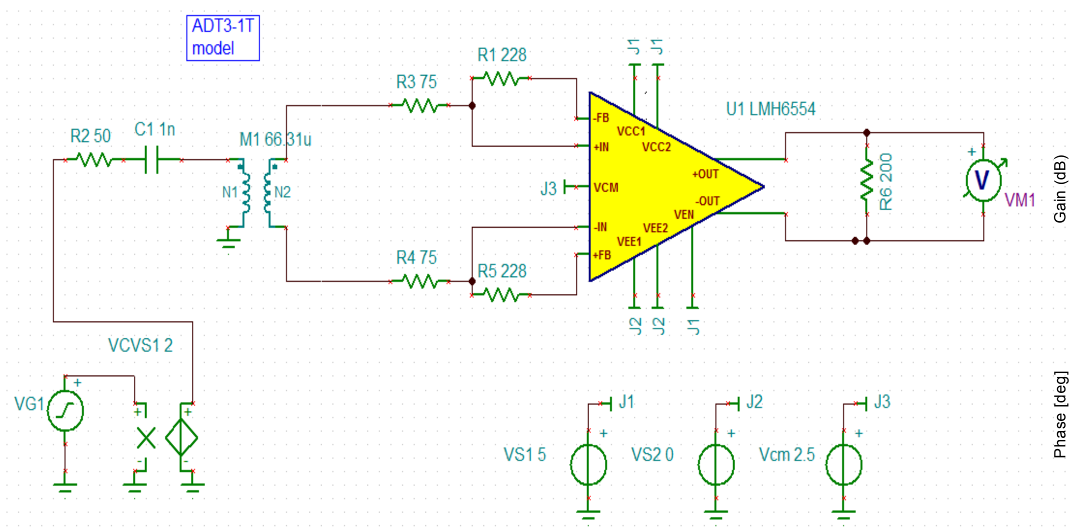
TECH DAYS
Texas Instruments

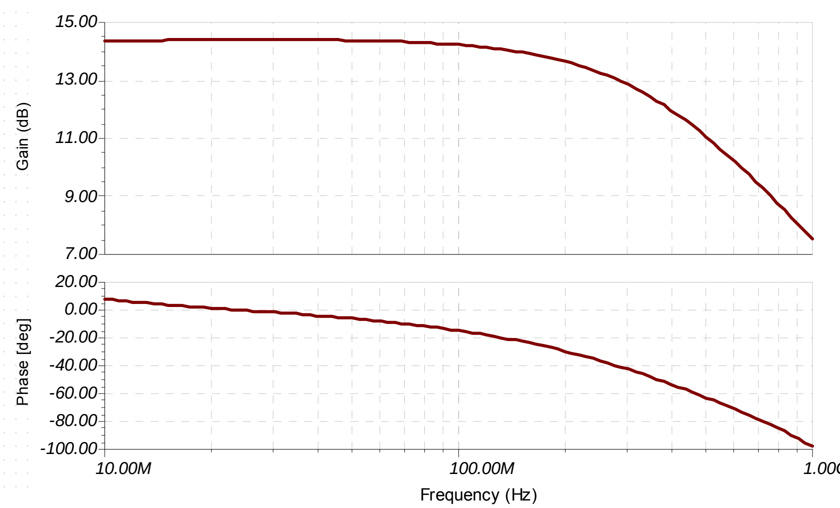
- Running the design sweeps vs gain using the LMH6554 gives some estimated NF and BW numbers
- In this case, the signal BW will be set by the input balun if the Rf is around 250ohm. Try a 1:1.73 turns ratio (ADT3-1T)

Required terms to compute the Noise Figure for the transformer coupled FDA design								
Starting total gain		4	V/V	Select the Amplifier -->			LMH6554	
Transformer Part #		ADT3-6T	Selected transformer					
Enter values				Amplifier terms				
	n =	1.732	turns	En =	9E-10	V/√Hz		
Transformer Loss		0.4	dB	In =	1.1E-11	A/√Hz		
				GBP =	2E+09	Hz	Actually a CFA	
Estimated ambient		24	C	4kT =	1.6E-20	Joules	at T = 290K	
Midband txfm loss		0.954993	Beta	T(kelvin) T	297			
dB gain step		2	dB	NF at this initial sett		10.04699	dB	
	Rs =	50	Ohms					
	Rg =	74.9956	Ohms					
Initial	Rf =	181.3627	Ohms					
	4kT at Ta	1.64E-20	Joules	At T =	297	Kelvin		
				Amplfier				
Total gain	Total gain	Rf value	Noise Figure	BW (MHz)				
V/V	dB	ohms	dB					
4.00	12.04	181.36	10.05	>2000				
5.04	14.04	228.32	9.48	>2000				
6.34	16.04	287.44	9.00	1500.00				
7.98	18.04	361.87	8.61	1000.00				

Example simulation with LMH6554

- Design point hits 14dB total gain where the Rf on the LMH6554 is near its optimum point for this CFA device
- Should show about 9.5dB noise figure for 50Ω source
- Signal bandwidth through the transformer will set the overall bandwidth to about 500Mhz, but the >2GHz bandwidth for the LMH6554 will give exceptional HD performance to its output pins





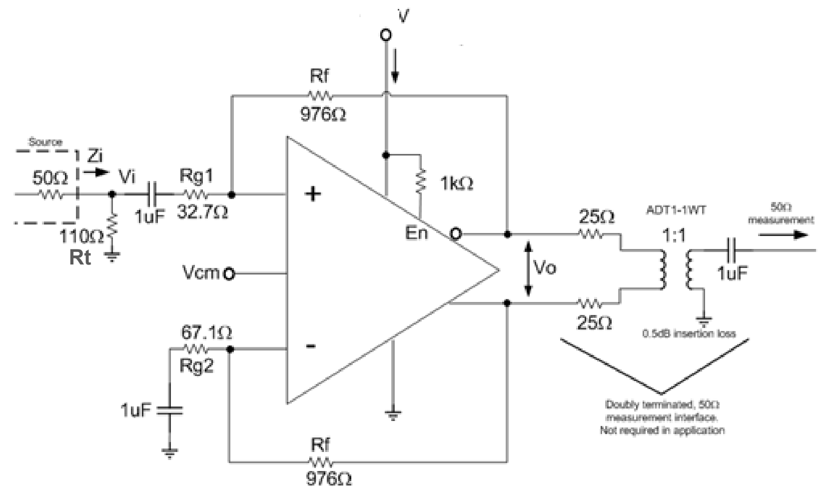
AGENDA

Single-to-differential FDA improved design flows

- FDAs can convert a single-ended input to a differential output without using an input balun
  - This can be either DC or AC coupled
  - The resistor value solutions are the same for a target input impedance and gain, but the voltage swings on the input pins will be different
- Considerable differences between FDA suppliers in describing the details, but the common elements are:
  - Feedback R's are equal
  - AC impedance looking back from each summing junction must be equal to get differential feedback balance

Example: Gain of 20V/V design with 50Ω input matched impedance

- Input match (Zi) is split between the Rt element and the apparent impedance looking into the Rg1 element
  - Key computational difficulty is that impedance towards Rg1 is an active impedance > than the physical value
- Once Rt and Rg1 are set, the Rg2 will be set to Rg1 + Rt||Rs to get differential balance

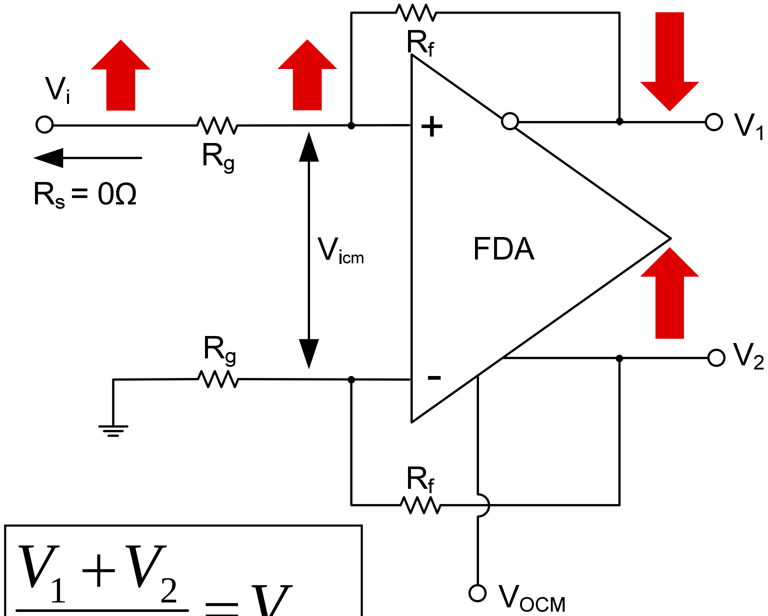


Gain of 20 (Vo/Vi) Typical Implementation

Output side above is a test circuit for getting back to single ended as for harmonic distortion measurements – in this case with 100ohm load

Why is there an active input Impedance?

- Looking at the FDA topology with a simple voltage source input (0ohm source), what causes the input impedance to be different than just Rg?
- Input-common-mode voltage must move with the input signal if the output common mode is fixed
- Example: Drawing is for a zero ohm source, non matched
  - If the input signal moves up, the Vicm must move up with it to satisfy the simple resistor divider equation to a fixed output Vocm
  - FDA's common-mode loop forces this effect



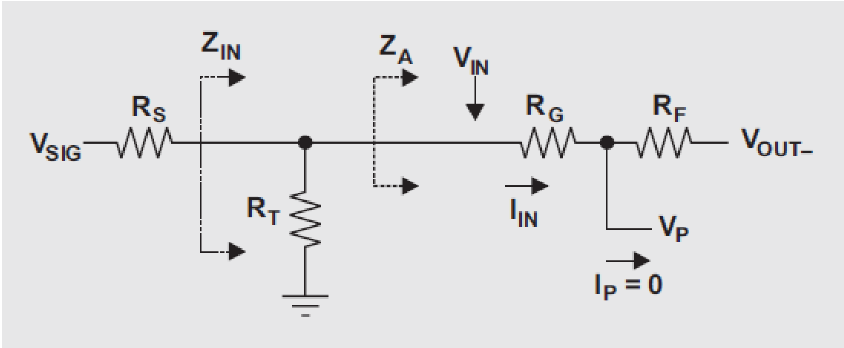
$$\frac{V_1 + V_2}{2} = V_{ocm}$$

$$(V_2 - V_1) = V_i \frac{R_f}{R_g}$$

$$V_{icm} = \frac{V_{ocm} R_g + (0.5Vi) R_f}{R_g + R_f}$$

Getting to the single-to-differential FDA design equations

- Going back to just the signal input side of the FDA design, when the design needs to match a source impedance (Rs) using both Rt and active input impedance (Za)
- Defining a couple of divider ratios on each side allows the active input impedance developed to be described as shown here
  - Rg in the schematic is Rg1
- Rg2 is the element on the non-signal input side that will be set to get differential divider balance once the Rg1 and Rt elements are set



$$\beta^{+} = \frac{R_{g1}}{R_{g1} + R_{f}} \qquad \beta^{-} = \frac{R_{g2}}{R_{g2} + R_{f}}$$

$$Z_A = \frac{(R_{g1} + R_f) * (\beta^{+} + \beta^{-})}{\beta^{-} + 1}$$

Or,

$$Z_A = R_{g1} \frac{\left(1 + \frac{R_{g1}}{R_{g2}}\right)\left(1 + \frac{R_f}{R_{g1}}\right)}{2 + \frac{R_f}{R_{g2}}}$$

Getting to the single-to-differential FDA design equations

- With these targets and constraints, if Rt||Za is set to equal Rs (divide by 2 from the source to the input of Rt) the voltage gain from the input of Rt to the differential output will be given as shown to the right

$$Av = 2 * \frac{R_f}{R_{g1} + (R_s \parallel R_t)} * \frac{R_t}{R_t + R_s}$$

- All equations are here to isolate on one variable to get a closed-form solution
  - One approach is to take a target gain from a source Rs (assuming matching is required to that) and simply pick an Rf value and isolate on the Rt solution
  - Just picking an Rf is a useful design flow to include CFA-type FDAs in the flow; that solution becomes (after considerable algebra):

$$R_t^2 - R_t * \frac{2R_s(2R_f + \frac{R_s}{2}A_v^2)}{2R_f(2+Av) - R_s Av(4+Av)} - \frac{2R_f R_s^2 Av}{2R_f(2+Av) - R_s Av(4+Av)} = 0$$

Using the single-to-differential solutions

- Once you have the Rt element out of the quadratic, the required input resistor Rg1 will be given by equation 1
- The Rg2 element on the other side of the circuit will again be set to get differential divider match by setting it to Rg1 + Rt||Rs
- Or, it is also given by equation 2
- Starting out with the Rf element as something that is simply selected is useful to limit the added loading of very low feedback values or where CFA-type FDAs need a certain range of Rf for their frequency response control
- Having the quadratic for Rt also allows a number of other insights to be delivered

$$R_{g1} = \frac{2\frac{R_f}{Av} - R_s}{1 + \frac{R_s}{R_t}}$$

Equation 1

$$R_{g2} = \frac{2\frac{R_f}{Av}}{1 + \frac{R_s}{R_t}}$$

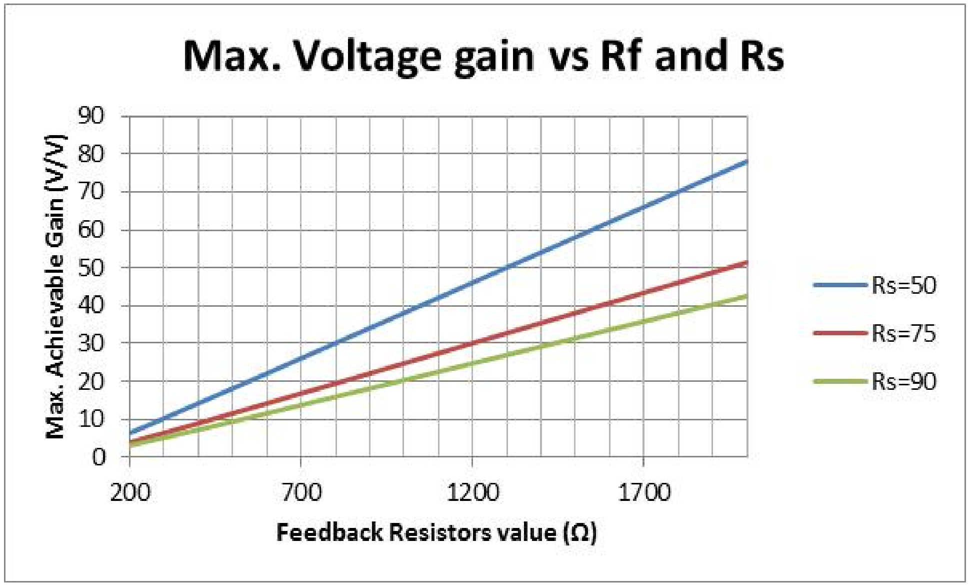
Equation 2

Manipulating the FDA single-to-differential resistor solution

TECH DAYS Texas Instruments

- Once you pick a feedback resistor value (for a CFA type FDA for instance) for any particular Rs that need to be matched, the quadratic will start to solve for negative Rt values above a certain gain. That max gain is given here, along with some swept curves
- Sets a hard limit on the gain achievable in this single-to-differential stage with input matching if the Rf needs to be fixed
- Not too restrictive here, but something to be aware of

$$Av_{max} = \left(\frac{R_f}{R_s} - 2\right) * \left(1 + \sqrt{1 + \frac{4\frac{R_f}{R_s}}{\left(\frac{R_f}{R_s} - 2\right)^2}}\right)$$



Manipulating the FDA single-to-differential resistor solution

- If the Rf can be adjusted freely, such as for most VFA-type FDA devices, an interesting option of eliminating the Rt element and setting the input match using just the Rg1 element comes out of the quadratic

$$2R_f(2+A_v)-R_sA_v(4+A_v)=0$$

- Solving for the coefficient denominator to equal zero forces Rt = ∞. This gives the simple solution here, where once you have the required Rf element, then the Rg1 that will simultaneously hit the input impedance and Av is given next

$$R_f=\frac{Av(Av+4)R_s}{2(Av+2)}$$

$$R_{g1}=\frac{R_s}{1+\frac{A_v}{2}}$$

- While Rg2 will now be just Rg1+Rs, or the expression at the right putting everything in terms of the design targets gives this expression

$$R_{g2}=R_s\frac{A_v+4}{A_v+2}$$

Exploiting the active match in FDAs

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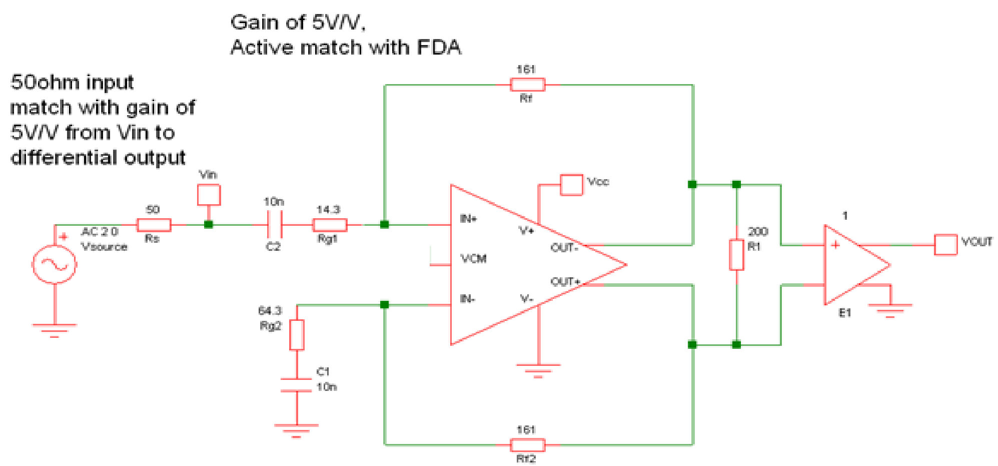
- Since the common-mode loop will act to deliver an input impedance higher than the physical resistor element, this can be used to drive the noise down in the implementation
  - For a fixed-source impedance that needs to be matched, sweep the target gain up from 14dB to 34dB in 2dB steps solving for the unique Rf, Rg1, and Rg2 values required

Rs =	50 ohm				
Gain (dB)	Gain (Av)	Rf	Rg1	Rg2	Noise gain
14	5.01	161.04	14.26	64.26	3.51
16	6.31	195.71	12.03	62.03	4.15
18	7.94	238.53	10.06	60.06	4.97
20	10.00	291.67	8.33	58.33	6.00
22	12.59	357.88	6.85	56.85	7.29
24	15.85	440.62	5.60	55.60	8.92
26	19.95	544.26	4.56	54.56	10.98
28	25.12	674.28	3.69	53.69	13.56
30	31.62	837.60	2.97	52.97	16.81
32	39.81	1042.88	2.39	52.39	20.91
34	50.12	1301.05	1.92	51.92	26.06

- Note the extremely low Rg1 values
  - This also acts to reduce the Rf value required for the gain vs. designs using an Rt element
  - Noise gain is lower than the signal gain
- These are solutions for the FDA topology and apply to any FDA

Example: 14dB gain design with active match to 50Ω

- Diagram below shows the gain of 5V/V or 14dB design conditions shown in the table for the 50ohm matched sweep
  - 14.3ohm resistor implements a 50ohm match using the CM loop feedback
  - Rg2 becomes the sum of Rg1 and Rs
- AC-coupled example, but DC coupling is also possible, usually with split supplies if the source is ground-centered and the FDA input pins are not negative rail swing
  - THS4541 and LMH3401 offer negative rail inputs; they can operate in this active match DC coupled on single supply with bipolar input signals



Resulting noise figure expression using active match with the FDA

- Using the forgoing equations, and the total output spot noise equation for an FDA shown to the right, sweeps of NF can be generated for different FDAs (NG = noise gain)

$$e_o = \sqrt{(e_{ni}NG)^2 + 2(i_n R_f)^2 + 2(4kTR_f NG)}$$

- Each of the elements required in the output spot noise equation can be recast in terms of the:
  - Desired gain Av from the input of Rg1 to the differential output
  - Source impedance Rs that is setting the input impedance target
- That will give the NF expression shown here where:
  - eni is the differential spot noise for the FDA
  - in is the current noise on each input of the FDA

$$NF = 10\log\left(2 + \frac{4}{A_v} + \frac{\left(e_{ni}\left(\frac{1}{2} + \frac{1}{A_v}\right)\right)^2 + \frac{1}{2}\left(i_n R_s \frac{A_v + 4}{A_v + 2}\right)^2}{kTR_s}\right)$$

Design sweeps for noise figure vs signal gain using TI FDAs

- Going back to the high-speed FDA table shown earlier, the predicted noise figure vs. gain settings can be generated using the purely active match approach
- Reduced table of noise and bandwidth for those parts is shown in Table 1; an example sweep of values for the THS4509 is shown in Table 2

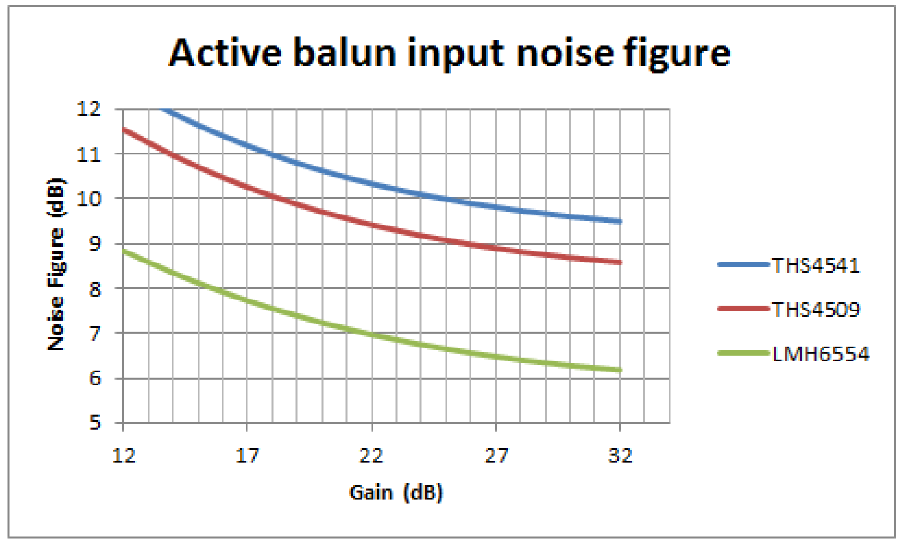
Table 1

Part #	Eni	In	Gain Bandwidth Product (MHz)	
THS4541	2.20E-09	1.90E-12	850	
THS4509	1.90E-09	2.20E-12	3000	
LMH6554	9.00E-10	1.10E-11	2000	CFA, changing Rf will change BW

NOTE: The LMH6554 needs an Rf in the 250Ω range. The Rf column in Table 2 is the same for any FDA swept in this active balun approach. The LMH6554 is probably applicable for gains of 16dB to 20dB and would give <8dB NF in this range

					Can compute the ouput noise from this and then NF			
					Pick a part -->		THS4509	
						Eni ->	1.9E-09	
						In ->	2.2E-12	
						4kT -->	1.6E-20	
Rs =	50	ohm	For any Rs, these set of R's apply to any FDA					
Gain (dB)	Gain (Av)	Rf	Rg1	Rg2	Noise gain	eo	Noise Figure	
12	3.98	132.81	16.72	66.72	2.99	6.72E-09	11.54	
14	5.01	161.04	14.26	64.26	3.51	7.92E-09	10.96	
16	6.31	195.71	12.03	62.03	4.15	9.42E-09	10.47	
18	7.94	238.53	10.06	60.06	4.97	1.13E-08	10.05	
20	10.00	291.67	8.33	58.33	6.00	1.37E-08	9.70	
22	12.59	357.88	6.85	56.85	7.29	1.66E-08	9.41	
24	15.85	440.62	5.60	55.60	8.92	2.04E-08	9.17	
26	19.95	544.26	4.56	54.56	10.98	2.51E-08	8.98	
28	25.12	674.28	3.69	53.69	13.56	3.10E-08	8.82	
30	31.62	837.60	2.97	52.97	16.81	3.84E-08	8.69	
32	39.81	1042.88	2.39	52.39	20.91	4.78E-08	8.58	

Table 2



Purely active match FDA offers a new type of circuit function

- Moving the CM loop bandwidth way up allows a kind of “active balun” function to convert a terminated single-ended-input-to-differential output, delivering resulting noise figures that rival balun + RF amp solutions
- HD2 will typically not be as good as a balun + FDA solution for a given power dissipation target
  - Balun flatness spans are typically no more than 3decades
  - “Active balun” approach can go from DC to >2GHz in flat frequency response using the LMH3401
- Key missing piece then becomes the small signal bandwidth for the internal common-mode loop
  - Often, this is different than the reported bandwidth from the control input pin, and usually much higher.
  - Control input path is often bandlimited to reduce the output CM noise, but the internal loop bandwidth is usually close to the differential loop bandwidth

Example: 7-GHz wide-bandwidth, fixed gain LMH3401FDA

Features

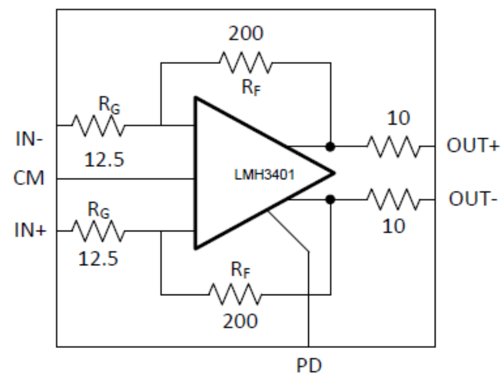
- 3 dB bandwidth of 7 GHz @ 16 dB gain
- Optimized for single ended 50 Ω input to differential conversion (DC to 7GHz active balun operation)
- Fully differential output on settable common mode voltage
- NF= 9 dB (Rs = 50 Ω) @ 1GHz, G=16dB, SE input
- Low distortion at high output (2Vpp, 200 Ω, SE-DE):
  - 10 MHz: HD2 @ -96 dBc, HD3 @ -102 dBc
  - 500MHz HD2 @ -79 dBc; HD3 @ -77 dBc
  - 1 GHz: HD2 @ -64 dBc, HD3 @ -72 dBc
  - 2 GHz: HD2 @ -55 dBc, HD3 @ -40 dBc
- OIP3 of 45 dBm @ 200MHz
- OIP3 of 33 dBm @ 1GHz and 24 dBm @ 2 GHz
- OIP2 of 71 dBm @ 1GHz and 56 dBm @ 2 GHz
- Supply operation from 3.3 to 5.0 V @ 56 mA
- Split supply operation supported
- Power down feature
- Fabricated on CBC8 Complementary SiGe process
- 2.5 x 2.5 mm^2 14 lead QFN package

Applications

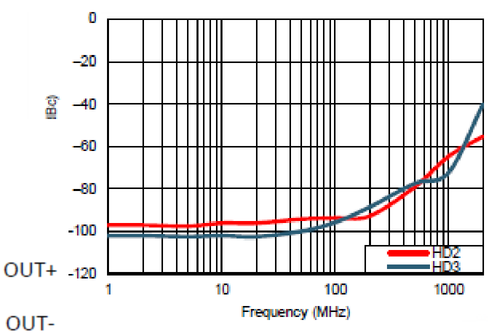
- Gig ADC driver
- Communications receivers
- IF / RF and baseband gain blocks
- SAW filter buffer/ driver
- Test and measurement
- Defense/Radar

Benefits

- Industry-leading usable bandwidth with excellent linearity performance through 2GHz
- Supports DC-coupled operation, with either single- or split-supply operation
- Easy single-ended-input-to-differential-output conversion without external baluns (active balun configuration)
- Low power (280 mW on 5V supply) for use in a variety of wide-band, high-dynamic-range applications where power and board space savings are desirable
- External gain-set version: LMH5401

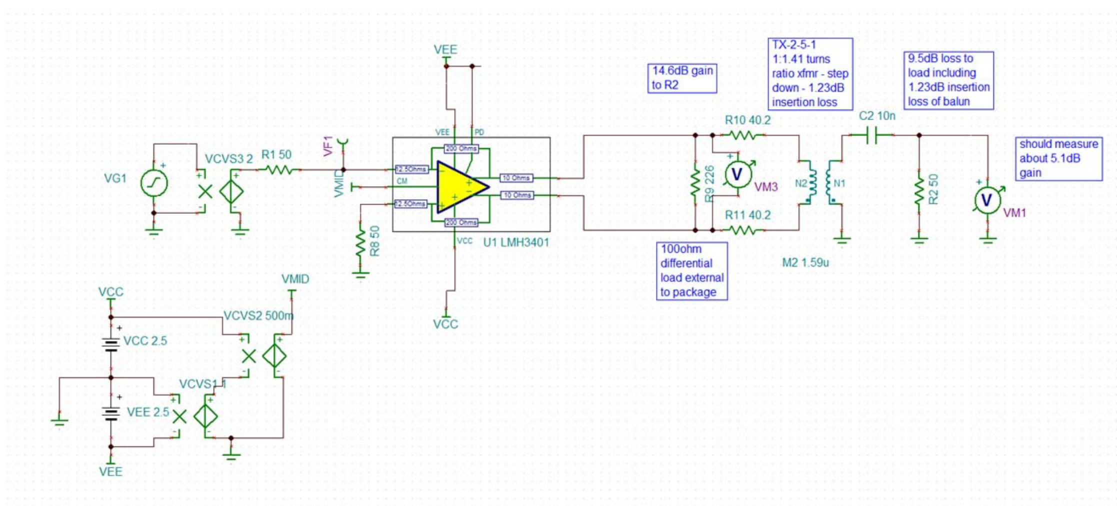


Distortion Products vs Frequency



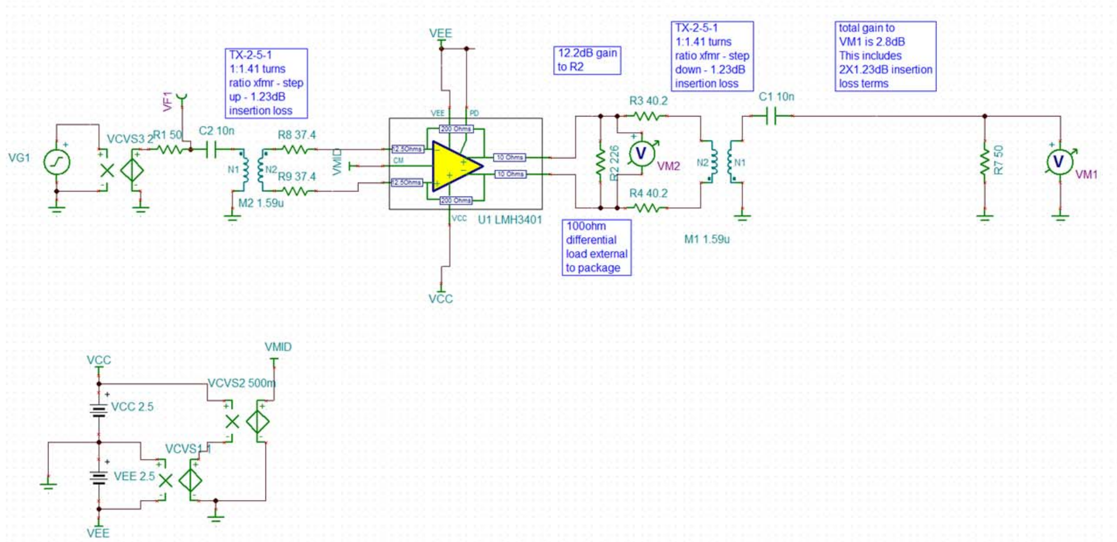
Example: Comparing active-balun-to-input- balun operation using LMH3401

- While it can operate DC-coupled in the active balun configuration, an AC-coupled interface is shown on the output side to get single-ended to measure HD in the active balun configuration test circuit below
  – Gain to the differential output pins is 14.5dB to a 100ohm test load
  – Output-side balun is only used to convert to single-ended for harmonic distortion and frequency response measurements; this configuration gives a 9dB NF
- With 200ohm internal feedback R's, the 12.5ohm input R looks like 50ohm to the test source; terminate the other external input pin with 50ohm to ground



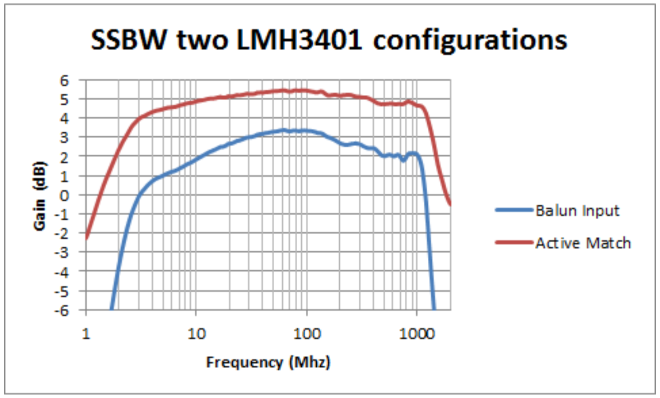
Example: Using an input balun

- LMH3401 is generally intended for active balun configuration, but you can add an input 1:1.41 step-up balun and add external resistors to the internal 12.5ohm elements to achieve the balun input configuration shown below
  - Gives a little lower gain to the 100ohm load = 12.2dB
  - Noise figure will be a bit higher at 9.3dB vs the active balun approach, which gives 9dB
- Test here is to produce 2 closely spaced tones at the 100ohm load, each at 1Vpp and measure the IMD3 and IMD2 spurious levels
- I/O baluns constrained this test to +/-10Mhz spacing with 80Mhz to 400Mhz center frequencies



Measured response and IMD comparisons

- Measured response shapes are shown below
  - Main goal is flatness from 80Mhz to 400Mhz. Actual gains include the insertion loss of the output balun interface. Add 9.5dB to these curves for the gain to the 100ohm load
- Rippling and rolloff are the baluns – removing the output balun would flatten the balun input curve to the same rippling as the active input match curve
- Removing the output balun for the active balun circuit would give a DC-to-2GHz flat span
- 3rd order output IM3 was the same for both configurations and below -95dBc until 300Mhz rose to -92dBc at 400Mhz for this relatively high power output
- F1+F2 higher IMD2 term was more measureable and summarized in the table below; input balun approach considerably reduces the even order distortion



	Upper IMD2 THS3401 test	
	Active Balun	Balun Input
Center F (MHz)	dBc	
80	-85.5	-93.1
100	-84.5	-89.6
150	-81.5	-90.6
200	-80.5	-91.1
250	-74.5	-87.1
300	-69.5	-86.6
350	-71.5	-85.6
400	-73.5	-83.1

AGENDA

Summary comparisons and comments

TECH DAYS Texas Instruments

- One of the primary aims in this last stage solution is to hold very low harmonic terms up to the amplifier outputs
- To the extent we can improve the SFDR at the final amplifier output pins, lower order filters can possibly be used from there to the ADC
- Active balun approach using the LMH3401 can provide a very flat response shape from DC to >2GHz in a fixed gain device
  - LMH5401 will offer the same AC capability with a flexible externally set gain and input impedance
- Where a relatively narrow band application is desired, with a low order interstage bandpass filter providing enough stopband attenuation for the even order terms, an active balun approach might be most suitable

Summary comparisons and comments

TECH DAYS
Texas Instruments

- For very broadband applications, where the best even-order harmonic suppression is desired to the amplifier output pins, consider the input balun approach, which adds no power to the low 280mW (5V supply) of the LMH3401
- Using the input balun, the response bandwidth is normally limited by the balun response shape when using >1GHz bandwidth FDAs
- FDAs with external gain setting, like the 2GHz LMH6554, expand the range of application by allowing flexible gain and input impedance
  - Fixed gain LMH3401 was used in our examples, but the external gain set version, the LMH5401, is a more flexible solution

Summary comparison of solutions shown for driving high-speed ADCs

- Best approach for your system depends on your requirements
- Some potential pros and cons to consider:

RF Gain block followed by a Balun		
	Pros	Cons
	Wide range of well known choices	Fixed gain by device part number
	Lowest input NF	Single ended output requires higher power for good HD2
		Post filter as part of Balun presents heavy/reactive load
		Filter design normally forced to 50ohm source impedance
		Often not specified < some Fmin
Balun input to FDA		
	Pros	Cons
	Lowest HD2 vs power dissipation	Application Fmin to Fmax set by Balun
	Easy to fine tune gain with Rf	Moderate Noise Figures (7.5 to 9dB depending on gain)
	Input DC bias eliminates balun imbalance	Source impedance reflected to be part of loop gain
	Very flexible for source impedance	HD changes with gain setting & frequency (Loop gain dependence)
	Low Zo output, post filter design very flexible	
Active Balun application of FDA		
	Pros	Cons
	DC coupled is possible	Worse HD2 than Balun Input to FDA
	Widest BW solution (if DC coupled is used)	Input return loss not described well (CM loop bandwidth)
	Lower input NF than Balun input (down to 6dB)	HD performance changes with configuration and frequency
	Very flexible for source impedance and gain	Source impedance reflected to be part of loop gain.
	Low Zo output, post filter design very flexible	
	Can save space and cost of Balun	

Summary tips and tricks for high-speed signal path design using FDAs

- One of the most critical decision points in the design flow is if the channel can be AC-coupled or if DC coupling is required
- If AC coupled, wideband baluns are widely used in ADC and DAC interfaces
  - Combining a balun with an FDA provides a low noise figure, flexible design flow that has shown very high SFDR at much lower power dissipation vs. an RF LNA followed by a balun solution
- FDAs offer a solution using the active balun approach for where the smallest area ADC input interface is required (no balun but single-to-differential operation – DC coupled if desired)
- TI provides simulation models in TINA-TI that correctly predict the AC response shape in these newer design options
  - Models do not predict the harmonic distortion terms

Additional information

All of the following fully differential amplifiers are available on EVM boards:

- THS4541, 850Mhz gain gandwidth product, best DC precision
  - EVM orderable → THS4541RGTEVM
  - http://www.ti.com/tool/ths4541rgtevm
- LMH6554, 2GHz current feedback
  - EVM orderable → LMH6554LE-EVAL/NOPB
  - http://www.ti.com/tool/lmh6554le-eval
- THS4509, 3GHz gain bandwidth product
  - EVM orderable → THS4509EVM
  - http://www.ti.com/tool/ths4509evm
- LMH3401, 7GHz fixed gain of 16dB FDA
  - EVM orderable → LMH3401EVM
  - http://www.ti.com/tool/lmh3401evm
- LMH5401, 8GHz Gain BW Product FDA
  - EVM orderable → LMH5401EVM
  - http://www.ti.com/tool/lmh5401evm