

Output impedance matching with fully differential operational amplifiers

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Introduction

Impedance matching is widely used in the transmission of signals in many end applications across the industrial, communications, video, medical, test, measurement, and military markets. Impedance matching is important to reduce reflections and preserve signal integrity. Proper termination results in greater signal integrity with higher throughput of data and fewer errors. Different methods have been employed; the most commonly used are source termination, load termination, and double termination. Double termination is generally recognized as the best method to reduce reflections, while source and load termination have advantages in increased signal swing. With source and load termination, either the source or the load (not both) is terminated with the characteristic impedance of the transmission line. With double termination, both are terminated with this characteristic impedance. No matter what impedance-matching method the designer chooses, the termination impedance to implement must be accurately calculated.

Fully differential operational amplifiers (FDAs) can provide a broadband, DC-coupled amplifier for balanced differential signals. They also have a unique ability to convert broadband, DC-coupled single-ended signals into balanced differential signals.

A common method to provide output impedance matching is to place resistors equal to the desired impedance in series with the amplifier's output. With double termination, this has the drawback that the signal level delivered to the line is reduced by -6 dB (or half) from the signal at the amplifier's output.

Synthetic impedance matching allows lower-value resistors to be used in conjunction with positive feedback around the amplifier. The benefit of doing this is that the output attenuation is reduced. This increases efficiency by lowering the loss and allows support of higher-amplitude signals on the line than can be achieved with standard termination.

Using standard series matching resistors to analyze the output impedance of FDAs is very easy, but

synthetic impedance matching is more complex. So we will first look at the output impedance using only series matching resistors, and then use that as a starting point to consider the more complex synthetic impedance matching.

The fundamentals of FDA operation are presented in Reference 1. Since the principles and terminology presented there will be used throughout this article, please see Reference 1 for definitions and derivations.

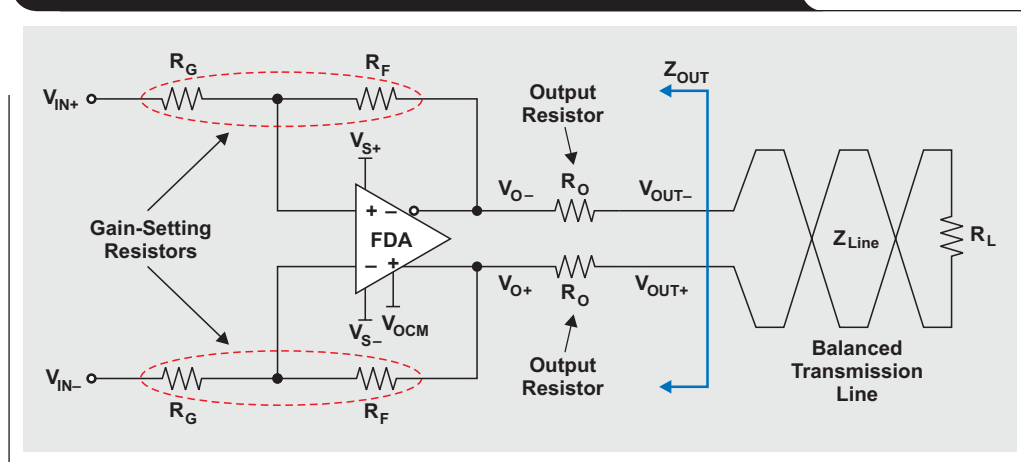
Standard output impedance

An FDA works using negative feedback around the main loop of the amplifier, which tends to drive the impedance at the output terminals, V_{O-} and V_{O+} , to zero, depending on the loop gain. An FDA with equal-value resistors in each output to provide differential output termination is shown in Figure 1. As long as the loop gain is very high, the output impedance, Z_{OUT} , in this circuit is approximately equal to $2 \times R_O$.

Parameter definitions for Figure 1 are as follows:

- R_F and R_G are the gain-setting resistors for the amplifier.
- R_L is the impedance of the load, which should be balanced and, for double termination, equal to Z_{Line} .
- R_O is the output resistor.
- $V_{O\pm}$ is the output terminal.
- V_{OCM} is the output common mode of the FDA.
- $V_{OUT\pm}$ is the differential output signal.
- $V_{S\pm}$ is the power supply to the amplifier.
- Z_{Line} is the characteristic impedance of the balanced transmission line from the amplifier to the load.

Figure 1. FDA with differential resistors for output termination



For analysis, it is convenient to assume that the FDA is an ideal amplifier with no offset and has infinite gain. Each output of the amplifier can be viewed as a voltage source with an output impedance of r_o . With high loop gain, both r_o and the differential output impedance, Z , of the FDA will be very small; for instance, the output impedance of the Texas Instruments (TI) THS4509 is less than $1\ \Omega$ at frequencies below 40 MHz. For output-impedance analysis, the inputs are grounded so that $V_{IN\pm} = 0\text{ V}$, resulting in $V_{O\pm} = V_{OCM}$. Since we are interested in only the AC response, and since V_{OCM} is a DC voltage, $V_{O\pm}$ is set to 0 V . The differential output impedance can be determined from Figure 2: $Z_{OUT} = 2(r_o + R_O)$; and, since as r_o is nearly $0\ \Omega$, $Z_{OUT} \approx 2 \times R_O$.

For an example of how to select the value of R_O , let's look at driving a twisted pair differentially from the FDA. A value of $Z_{Line} = 100\ \Omega$ is common for twisted-pair cables. For double termination, the source needs to provide $R_O = 50\ \Omega$ on each side for a $100\text{-}\Omega$ differential output impedance, and the line needs to be terminated with $R_L = 100\ \Omega$. It is assumed that the output impedance of the FDA is approximately $0\ \Omega$, so $49.9\text{-}\Omega$ resistors are placed in each series with each output.

In a terminated system, it is common practice to take the gain of the amplifier stage from the source to the load, or from $V_{IN\pm}$ to $V_{OUT\pm}$; so gain is given by

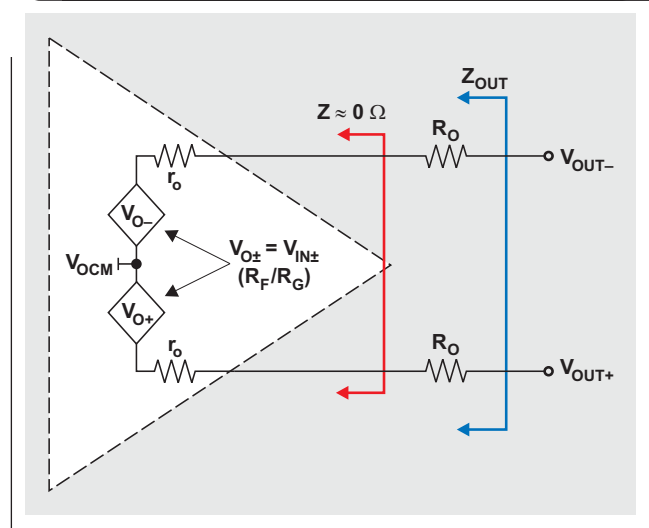
$$\frac{V_{IN\pm}}{V_{OUT\pm}} = \frac{R_L}{R_L + 2R_O} \times \frac{R_F}{R_G} \quad (1)$$

Assuming that the output impedance matches the load impedance,

$$\frac{V_{IN\pm}}{V_{OUT\pm}} = \frac{1}{2} \times \frac{R_F}{R_G} \quad (2)$$

It is recommended that R_F be kept to a range of values for the best performance. Too large a resistance will add excessive noise and will possibly interact with parasitic board capacitance to reduce the bandwidth of the amplifier; and too low a resistance will load the output, causing increased distortion. For example, the THS4509 performs best with R_F in the range of 300 to 500 Ω . In the design process, the designer first selects the value of R_F , then calculates R_O and R_G to match the desired gain. The value of Z_{OUT} is then calculated as $2 \times R_O$.

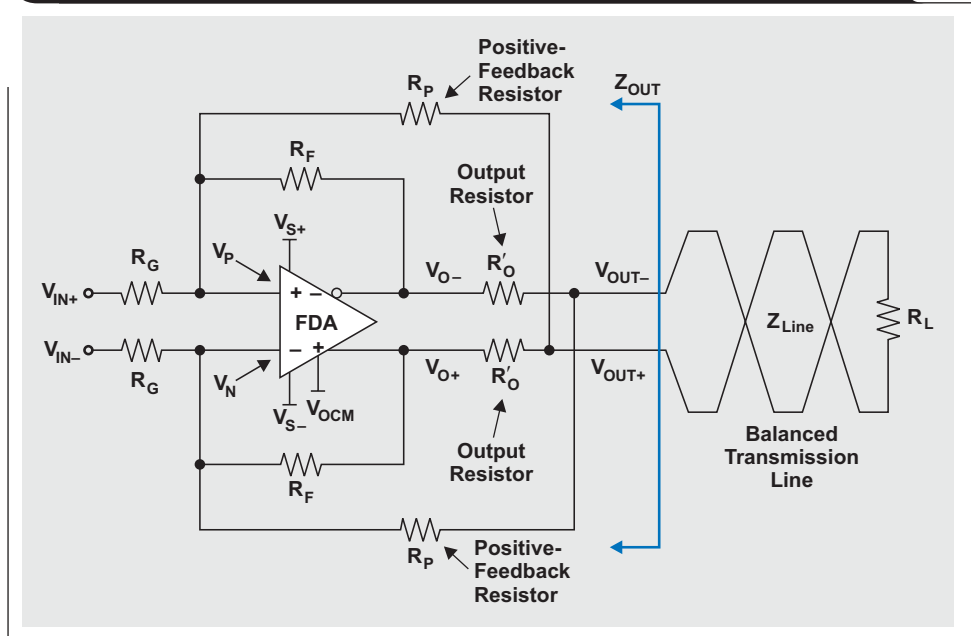
Figure 2. FDA circuit for analysis of balanced output impedance



Synthesized output impedance

In Figure 3, the positive-feedback resistors, R_P , are added from V_{OUT+} to V_P and from V_{OUT-} to V_N . Given a balanced differential system, these resistors provide positive feedback around the amplifier that makes R'_O look larger from the line than the actual value, R_O . The amount of positive feedback used determines the scaling and has an effect on the forward gain of the amplifier.

Figure 3. FDA differential output impedance with synthesized resistors

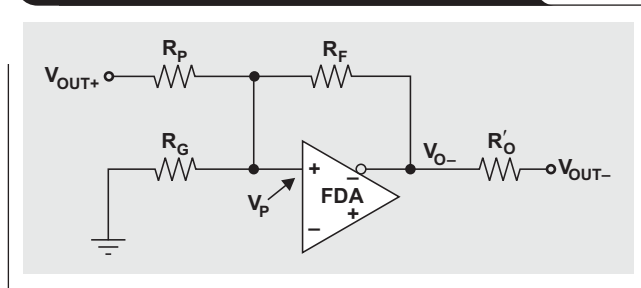


It is convenient to first look at half of this circuit (see Figure 4) to analyze the response of the amplifier to a signal that was applied from the line because resistors R_P were added. To determine the output impedance of the amplifier as seen from the transmission line, a signal is injected at V_{OUT-} with the input at V_{IN+} grounded. The signal from the other side of the line at V_{OUT+} is seen as an input signal to the amplifier, with gain to V_{O-} set by R_F/R_P . Note that the output pins will have a common-mode voltage set by V_{OCM} , which is assumed to be a DC voltage and is set to 0 V for AC analysis as before.

In a balanced system it is assumed that the differential signals are symmetrical and 180° out of phase. Therefore $V_{OUT+} = -V_{OUT-}$, and

$$V_{O-} = -V_{OUT+} \times \frac{R_F}{R_P} = V_{OUT-} \times \frac{R_F}{R_P}.$$

Figure 4. Simplified view for analysis of adding R_P



Thus R_P effectively adds positive feedback to the system, resulting in an in-phase response at V_{O-} to a signal from the line. This in turn makes R'_O appear (from the line) to be a larger-value resistor than it actually is. Inclusion of the other half of the amplifier permits the differential response of the circuit to be shown as

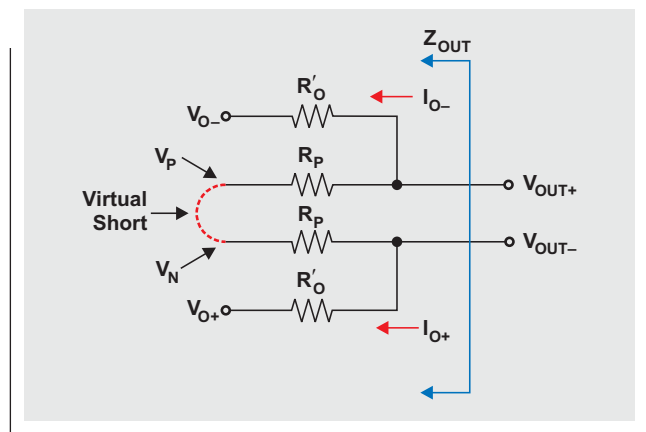
$$V_{O\pm} = V_{OUT\pm} \times \frac{R_F}{R_P}.$$

To complete the analysis, this result is used in conjunction with a virtual short* to construct a simplified view of the impedance seen from the line with this architecture; the diagram is shown in Figure 5. This figure shows that the differential output equals $2 \times R_P$ in parallel with the effective value of $R'_O = 2(V_{OUT\pm} - V_{O\pm})/I_{O\pm}$. With the expressions for $V_{O\pm}$ from before and some algebra, an equation to calculate the output impedance of the circuit can be derived:

$$Z_{OUT} = 2 \times \left(\frac{R'_O}{1 - \frac{R_F}{R_P}} \parallel R_P \right) \quad (3)$$

*The term "virtual short" means that while an op amp is in linear operation with negative feedback and the loop gain is high, the input terminals are driven to the same voltage and appear to be "virtually" shorted together.

Figure 5. Simplified view for analysis of impedance seen from the line



The positive feedback from adding resistors R_P affects the forward gain of the amplifier and adds another load in parallel with R_L . Accounting for this effect and the voltage divider between R'_O and $R_L \parallel 2R_P$, the gain from $V_{IN\pm}$ to $V_{OUT\pm}$ is given by

$$\frac{V_{OUT\pm}}{V_{IN\pm}} = \frac{R_F}{R_G} \times \frac{1}{\frac{2R'_O + R_L \parallel 2R_P}{R_L \parallel 2R_P} - \frac{R_F}{R_P}}. \quad (4)$$

The derivation of this equation is left to the interested reader.

Design is best accomplished by first choosing the values of R_F and R'_O . Next, the required value of R_P is calculated to arrive at the desired Z_{OUT} . Then R_G is calculated for the required gain. These equations are easy to solve when set up in a spreadsheet. To see an example Excel® worksheet, click on the Attachments tab or icon on the left side of the Adobe® Reader® window. Open the file FDA_Output_Impedance_Wksht.xls, then select the Synthesized Output Resistor worksheet tab.

As an example of the design method, let's say a twisted pair is driven differentially from the THS4509 FDA with $Z_{OUT} = 100 \Omega$, and a gain of 1.58 (4 dB) to the load is desired. Values of $R_F = 402 \Omega$ and $R'_O = 25 \Omega$ are chosen. R_P can then be calculated by rearranging Equation 3 and substituting the chosen values:

$$R_P = \frac{R_F - R'_O}{1 - \frac{2R'_O}{Z_{OUT}}} = \frac{402 - 25}{1 - \frac{50}{100}} = 754.0 \Omega$$

The nearest standard value, 750 Ω , should be used.

R_G can be found by rearranging Equation 4 and substituting the known values:

$$R_G = R_F \times \frac{1}{\frac{2R'_O + R_L \parallel 2R_P}{R_L \parallel 2R_P} - \frac{R_F}{R_P}} \times \frac{V_{IN\pm}}{V_{OUT\pm}}$$

$$= 402 \times \frac{1}{\frac{50 + 100 \parallel 1500}{100 \parallel 1500} - \frac{402}{750}} \times 1.58 = 255.1 \Omega.$$

The nearest standard value, 255 Ω , should be used.

SPICE simulation of standard and synthesized output impedance matching

SPICE simulation is a great way to compare expected circuit performance from standard versus synthesized output impedance matching. There are numerous ways to

find the output impedance in SPICE. An easy way is to drive the output from a differential source with output impedance equal to Z_{OUT} and with $V_{IN\pm}$ grounded. Then verify that half the differential source amplitude is seen at $V_{OUT\pm}$, which is expected for double termination with equal impedances.

To see a TINA-TI™ simulation circuit of the two examples given, click on the Attachments tab or icon on the left side of the Adobe Reader window. If you have the TINA-TI software installed, you can open the file FDA_Output_Impedance_Standard_vs_Synthesized_Resistors.TSC to view the examples. To download and install the free TINA-TI software, visit www.ti.com/tina-ti and click the Download button.

For clarity, the simulation circuits and expected waveforms are shown as separate circuits in Figures 6 and 7, which show that the termination is correct.

Figure 6. TINA-TI simulation of FDA output impedance with standard impedance-matching resistors

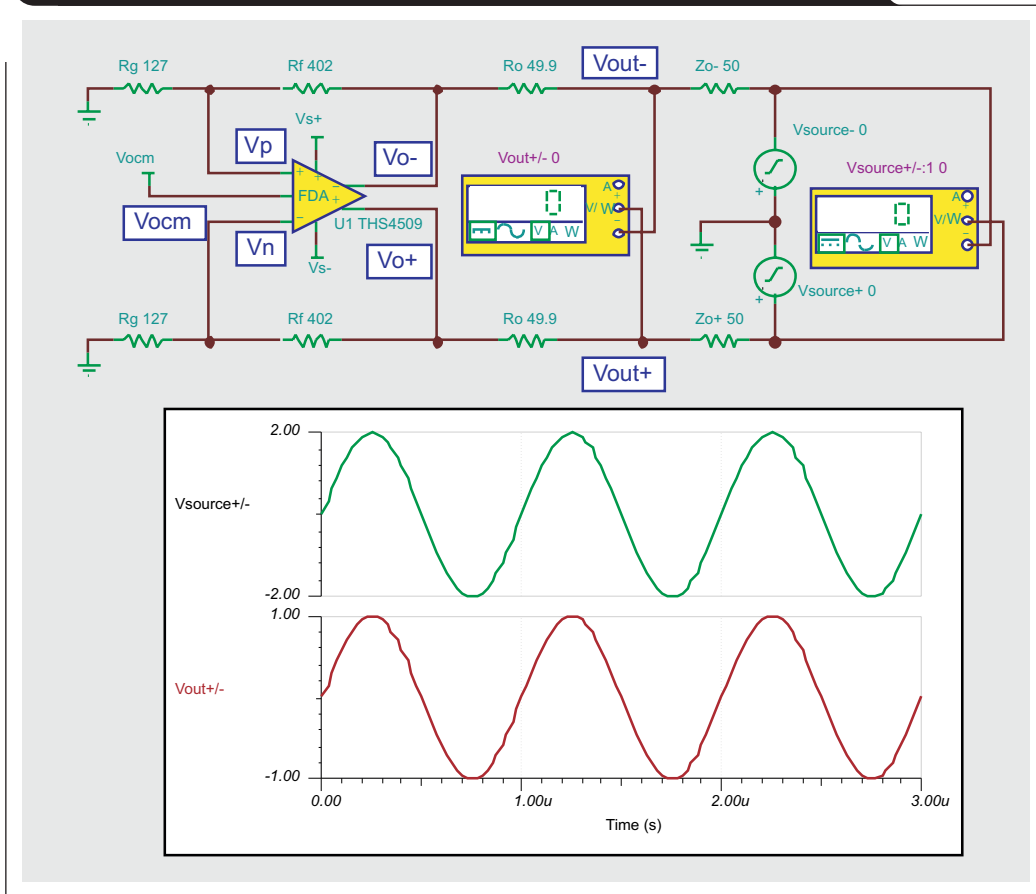


Figure 7. TINA-TI simulation of FDA output impedance with synthesized impedance-matching resistors

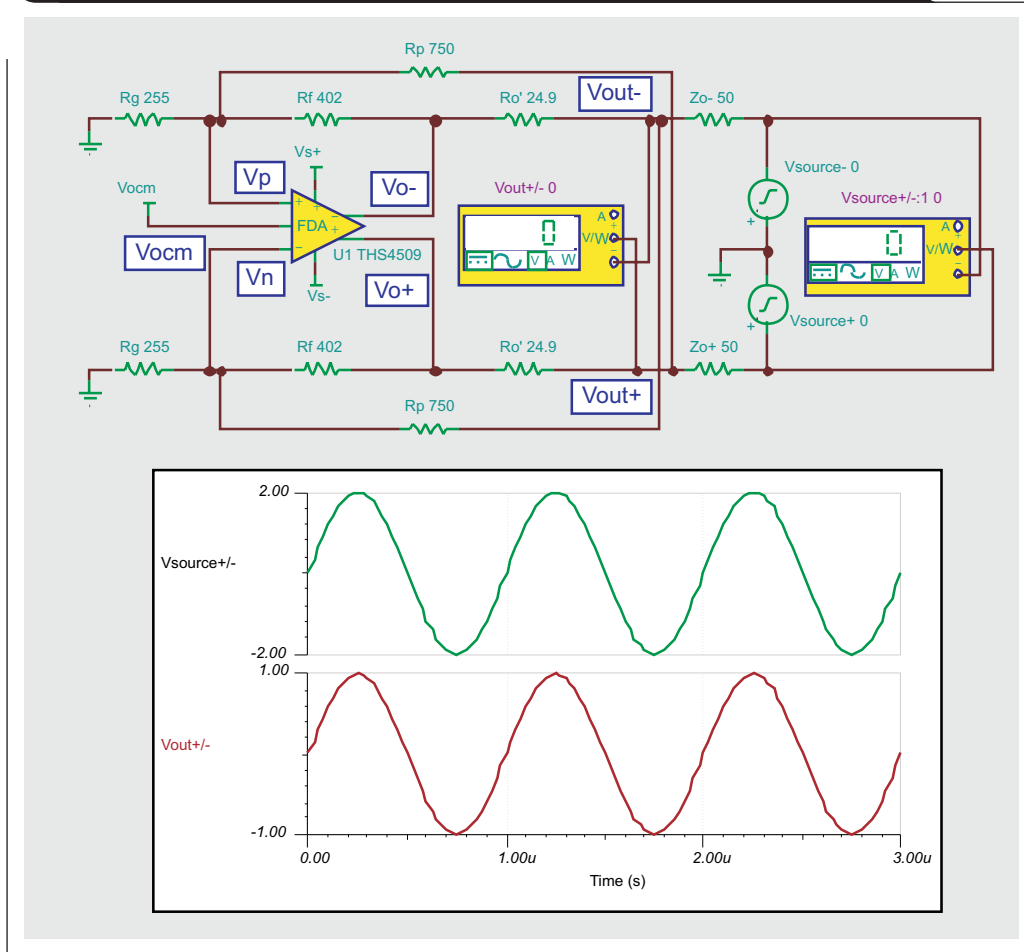


Figure 8 shows the amplifier's expected signal amplitudes at the input, at the output, and at the load for the two scenarios. To see a TINA-TI simulation circuit of the gain and signal amplitudes, click on the Attachments tab or icon on the left side of the Adobe Reader window. If you have the TINA-TI software installed, you can open the file `FDA_Gain_and_Voltages_with_Synthesized_vs_Standard_Resistors.TSC` to view the circuit example. To download and install the free TINA-TI software, visit www.ti.com/tina-ti and click the Download button.

Figure 8. TINA-TI simulation of FDA output voltages with standard and synthesized impedance matching

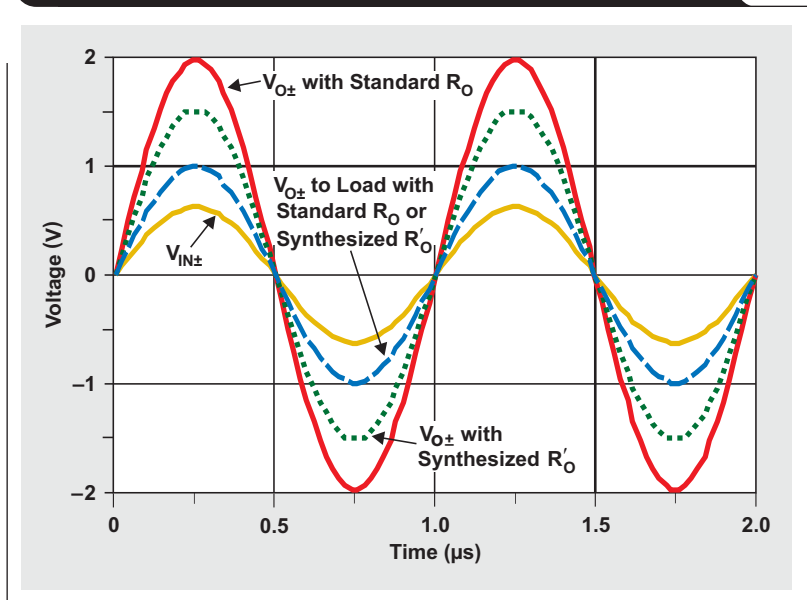
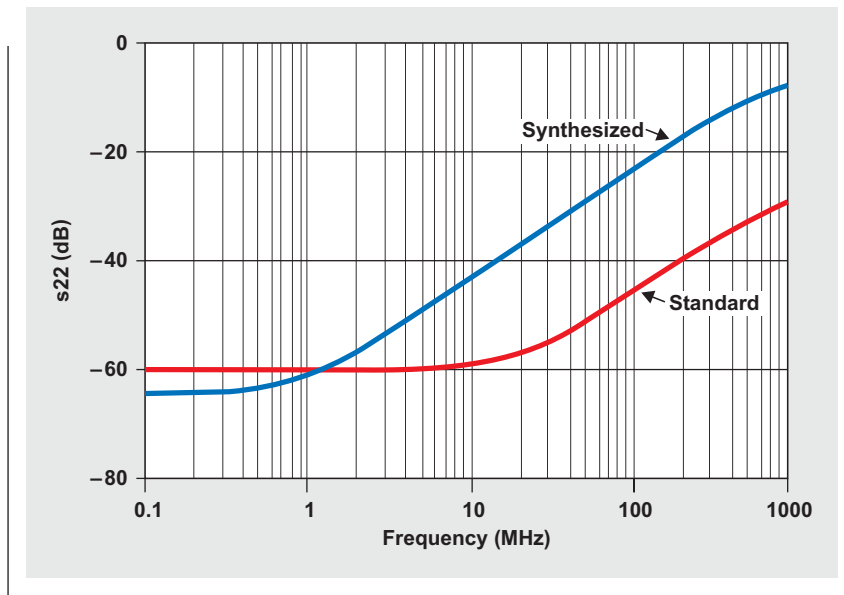


Figure 9. Simulated s22 of FDA with standard and synthesized impedance matching



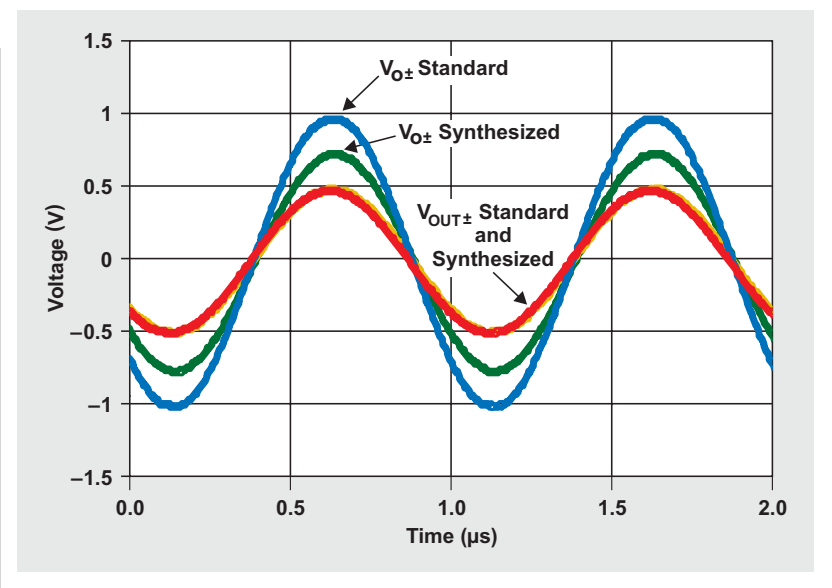
Lab testing of standard and synthesized output impedance matching

Using a network analyzer to measure the output return loss, or scattering parameter s_{22} ,** is a common way to show the performance of impedance matching in the lab. Figure 9 shows the simulated s_{22} of the FDA with standard and synthesized output impedance matching.

To further validate the design equations, test circuits using the THS4509 FDA were built and tested on the bench. The lab equipment used for testing had single-ended, 50-Ω inputs and outputs; so the circuits presented earlier were redesigned to match $Z_{OUT} = 50 \Omega$. The circuits were also modified to convert the output differential signal to single-ended (and vice versa) by adding a Mini-Circuits ADT1-1WT 1:1 transformer on the output.

First, the signal swings were tested by connecting a signal generator to the input and using an oscilloscope with a 50-Ω input to look at the output waveforms. The results, shown in Figure 10, demonstrate that the performance matches the simulations.

Figure 10. Bench test of signal voltages with standard and synthesized impedance matching



** A common two-port method to show performance uses scattering parameters, or s-parameters. The standard nomenclature used is “s” followed by the incident port number and then the measurement port number. The notation “s22” means the signal is injected to the output port of the device and the reflection is measured. A lower value indicates less reflection and a better impedance match.

Next, the s_{22} was measured with a network analyzer to show the quality of the impedance match over frequency. The results are shown in Figure 11. The performance was limited by the transformer, which was to be expected based upon a review of the Mini-Circuits ADT1-1WT 1:1 datasheet. Up to about 40 MHz, the test showed the performance of the transformer for both the standard and synthesized impedance-matching circuits.

With standard impedance-matching resistors, the output impedance of the amplifier starts to degrade the impedance match above 40 MHz, up to the frequency limit of the transformer. With synthesized impedance-matching resistors, the impedance match shows the transformer performance up to about 200 MHz. At higher frequencies, the impedance match degrades significantly faster than with standard resistors due to the amplitude imbalance of the transformer.

Finally, the two-tone, third-order intermodulation distortion performance was tested to see if it would improve with the lower losses of synthetic impedance matching. Test signals $f_1 = 70$ MHz and $f_2 = 71$ MHz were used, along with a $2-V_{PP}$ envelope signal level ($1 V_{PP}$ for each tone) delivered to the load. The test showed no significant difference between the two impedance-matching approaches for the near frequencies in third-order intermodulation terms; in fact, the results were actually better than what the datasheet shows for similar loading (see Table 1).

These results may seem contrary to expectations because lower signal amplitude is associated with better distortion performance. However, even though the impedance seen by the line looking into the amplifier with synthesized output-impedance resistors is the same as with standard resistors, the amplifier sees the actual resistance in both cases. Therefore, due to the lower-output resistors and the

Table 1. Two-tone, third-order intermodulation distortion performance at 70 MHz

CIRCUIT	LOW-SIDE IMD3 Spur (69 MHz)	HIGH-SIDE IMD3 SPUR (71 MHz)
Standard (dBc)	-91	-88
Synthesized (dBc)	-94	-86

added parallel load of the R_P resistors, the amplifier with synthesized output impedance sees a heavier load. In this case the effects of the lower voltage and the higher load basically offset one another.

Note that positive feedback can lead to oscillation. When I tested the synthesized output impedance circuit, it worked as designed as long as the load was connected, but it oscillated when the load was disconnected. This is a drawback to consider if the application calls for supporting a wide load range that includes an open-circuit condition.

Reference

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Document Title	TI Lit. #
1. Jim Karki, “Fully Differential Amplifiers,” Application Report.	sloa054

Related Web sites

- amplifier.ti.com
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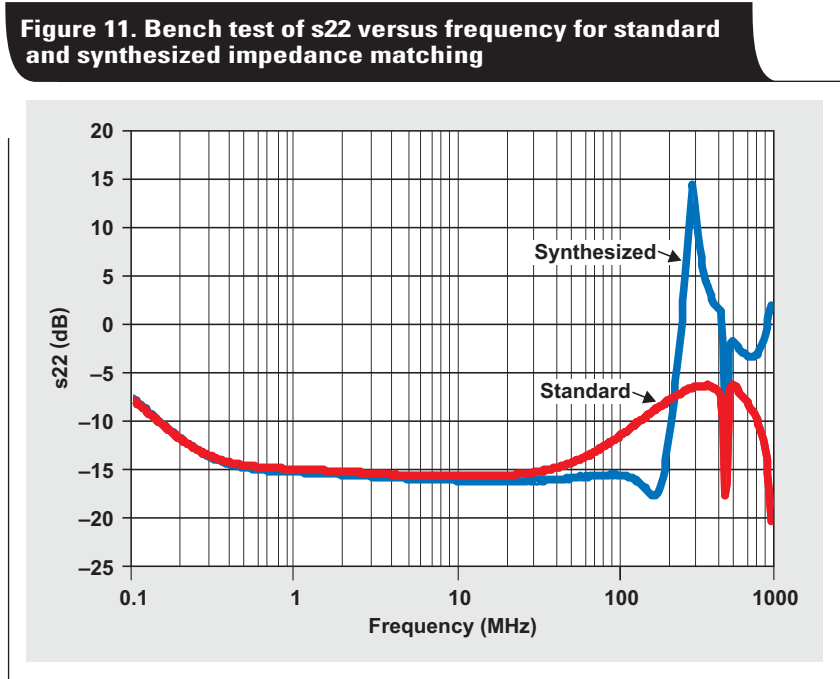


Figure 11. Bench test of s_{22} versus frequency for standard and synthesized impedance matching

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