Input impedance matching with fully differential amplifiers

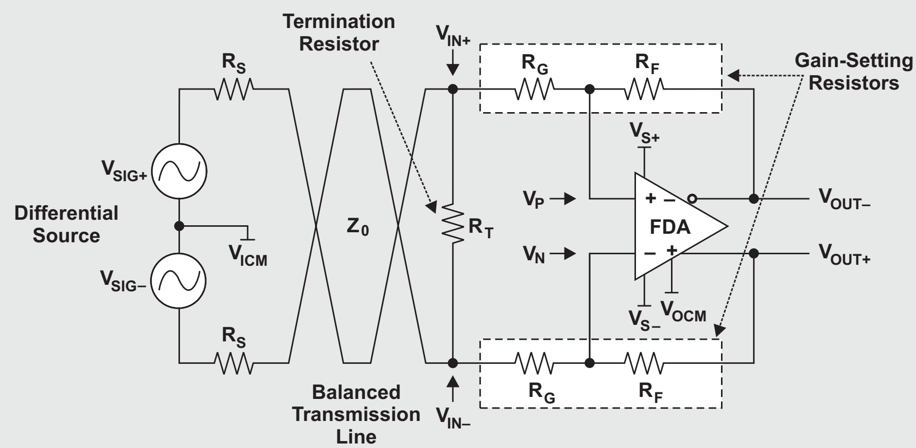
By Jim Karki
Member, Technical Staff, High-Performance Analog

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 schemes have been employed; source termination, load termination, and double termination are the most commonly used. Double termination is generally recognized as the best method to reduce reflections, while source and load termination have the advantage of 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 the source and the load are terminated with that impedance. No matter what impedance-matching scheme is chosen, the termination impedance to implement must be accurately calculated.

In the last few years, fully differential amplifiers (FDAs) have grown in popularity; and, while similar in theory to inverting operational amplifiers, they have important differences that need to be understood when input impedance matching is considered. This article shows how to analyze the input impedance of an FDA. Circuit analysis is performed to aid understanding of the key design points, and a methodology is presented to illustrate how to approach the design variables and calculate component values. A spreadsheet and TINA-TI™ SPICE models are available as design aids.

Figure 1. FDA with differential source



TERM	DEFINITION
R_G, R_F	Gain-setting resistors for the amplifier
R_S	Impedance of the signal source, which should be balanced
R_T	Used when $2R_G$ is higher than the required input termination impedance
V_{ICM}	Common-mode voltage of the signal source
V_{OCM}	Output common mode of the FDA
$V_{S\pm}$	Power supply to the amplifier
$V_{Sig\pm}$	Differential input-signal source
Z_0	Characteristic impedance of the balanced transmission line from the source to the amplifier input

FDA circuit overview

FDAs are broadband, DC-coupled amplifiers for balanced differential signals and have a unique ability to convert broadband, DC-coupled, single-ended signals into balanced differential signals.

The input-impedance analysis of FDAs is very similar to that of two inverting operational amplifiers. The key difference is that with two inverting operational amplifiers, the input common-mode voltage is controlled by the voltage applied to the positive input; while with FDAs, the output common-mode voltage is controlled via a second loop contained within the amplifier. If the input is differential, the analysis is just as easy for an FDA as for an inverting op-amp circuit, but more difficult when the input is single-ended.

For maximum performance, the FDA must be balanced, which again is easier to analyze if the input is differential.

Due to this, we will first look at the input impedance in the differential case and then use that as a starting point to consider the single-ended case.

The fundamentals of FDA operation are presented in Reference 1. Please refer to it for voltage definitions, gain equations, derivations, and terminology.

Analysis of differential-signal input

A differential drive and termination into an FDA is shown in Figure 1. An FDA works using negative feedback around the main loop of the amplifier, which tends to drive the error voltage across the input terminals, V_N and V_P, to zero, depending on the loop gain.

For analysis, it is convenient to assume that the FDA is an ideal amplifier with no offset and infinite gain. Looking at the input of the amplifier differentially and using the virtual-short concept (Figure 2) from an inverting-amplifier topology, we can express the input impedance as $Z_{IN} = R_T \parallel 2R_G$.

For an example of how to select the value of R_T, let's look at a differential source driving a twisted pair to the FDA. $Z_0 = 100\ \Omega$ is common for twisted-pair cables. For double termination, we want the source to provide $R_S = 50\ \Omega$ on each side for 100-Ω differential output impedance, and we want the input of the FDA to present a 100-Ω differential load. If $R_G = 402\ \Omega$, we then need R_T to be 114.2 Ω; so we select the nearest standard value, 115 Ω, for R_T.

The gain of the circuit from the differential source is

$$\frac{V_{SIG\pm}}{V_{OUT\pm}} = \left(\frac{R_T \parallel 2R_G}{R_T \parallel 2R_G + 2R_S}\right)\left(\frac{R_F}{R_G}\right). \quad (1)$$

If we assume that the input impedance matches the source impedance, then

$$\frac{V_{SIG\pm}}{V_{OUT\pm}} = \left(\frac{1}{2}\right)\left(\frac{R_F}{R_G}\right). \quad (2)$$

It is standard practice to take the gain from the terminated input, in which case

$$\frac{V_{IN\pm}}{V_{OUT\pm}} = \left(\frac{R_F}{R_G}\right). \quad (3)$$

It is recommended that R_F be limited to a range of values for best performance. A resistance value that is too high will add excess noise and possibly interact with parasitic board capacitance to reduce the bandwidth of the amplifier; a value that is too low will load the output, causing increased distortion. Therefore, we need to pick a range of desired values for R_F and calculate R_G for the desired gain. For example, the THS4509 performs best with R_F in the range of 300 to 500 Ω. So, depending on the gain we want from the FDA, there will come a point where $2R_G$ equals the required termination of the transmission line. In this case, no R_T resistor is required.

In design, the target gain and Z_0 are set by the system design. We select the value of R_F first, then calculate R_T and R_G to match the gain and make $Z_{IN} = Z_0$. This is easily done by setting up the equations 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_Input_Impedance.xls, then select the Differential Input worksheet tab.

Figure 2. Balanced input impedance

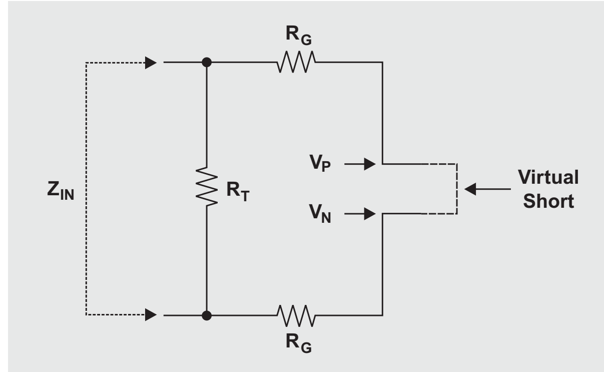
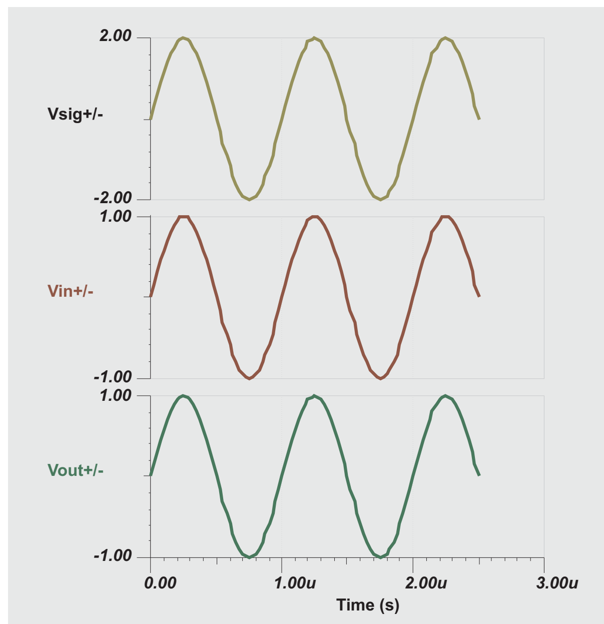


Figure 3. TINA-TI simulation of FDA waveforms with differential input impedance



SPICE simulation is a great way to validate the design. To see a TINA-TI simulation circuit of the example just 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_Diff_Input_Impedance.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.

There are numerous ways to find the input impedance in SPICE, but from the simulation waveforms shown in Figure 3, we see the expected input and output voltages for double termination with equal impedances.

Analysis of single-ended signal input

In Figure 4, the differential source circuit shown in Figure 1 is modified for a single-ended, DC-coupled source. To keep balance in the circuit, the source is converted to a single-ended source referenced to V_{ICM}; R_T is split into two resistors of equal value with the center point tied to ground; and the negative input is tied to V_{ICM} via R_S.

Another scenario is when the source is an RF, IF, or CATV-type class-A amplifier that is designed with intrinsic output impedance. With this type of amplifier, AC coupling of the outputs is usually required via a DC-blocking capacitor to avoid disturbing the DC bias point of the amplifier. In this case, R_T on the positive side and $R_{EQ} = R_G + R_S \parallel R_T$ on the negative side (where R_S is the output impedance of the RF/IF/CATV amplifier) should be tied to ground via a DC-blocking capacitor of the same size. This is shown in Figure 5. Note that in this configuration the FDA will self-bias input and output pins to the common-mode voltage set by the V_{OCM}.

In actual implementation, the source may be DC-coupled (Figure 4) and have a common-mode reference that is not ground. In this case, care must be taken to tie R_S to the same common reference for balance. Also note that DC current will flow in R_T when tied to ground. When a source is DC-coupled with a ground-referenced source, R_S and R_T on the negative side should be tied to ground.

The last scenario makes the circuit analysis easier and will provide the solution for the other scenarios as well.

Figure 4. FDA with single-ended source

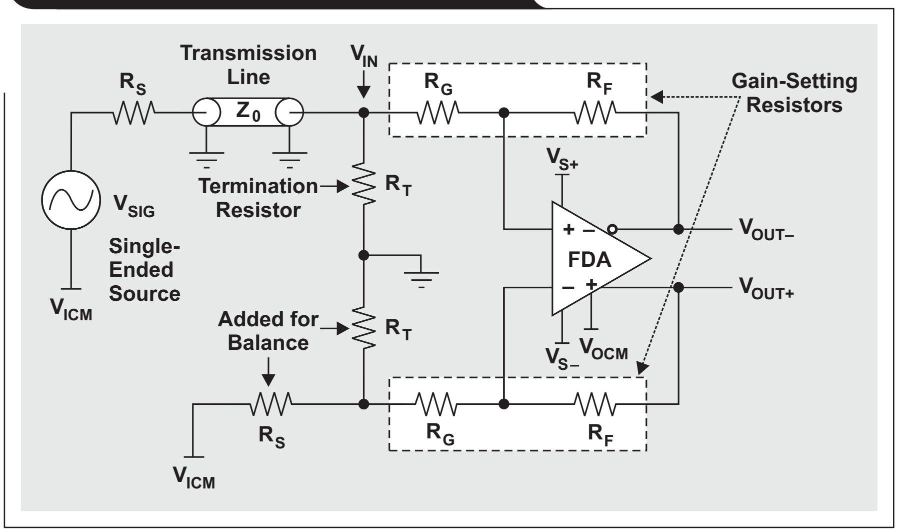


Figure 5. FDA with AC-coupled RF/IF/CATV amplifier input

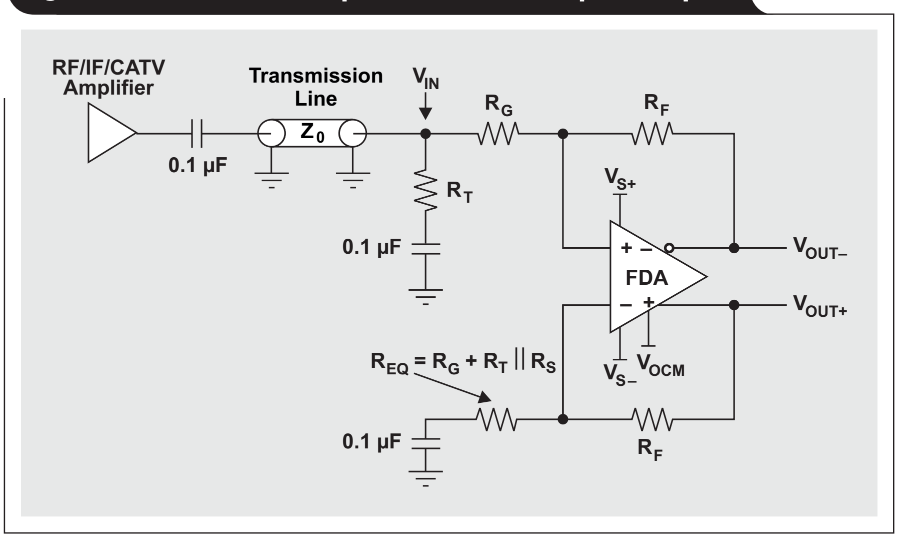


Figure 6 shows the case where the source is ground-referenced and R_S and R_T are combined with R_G into one resistor of equivalent value, $R_{EQ} = R_G + R_T \parallel R_S$, which is tied to ground. We will base the analysis of the input impedance on this circuit.

With single-ended input, only one side of the FDA is actively driven, and the other side is grounded (or tied to some reference as discussed earlier). With this scenario, the input pins of the amplifier are not fixed at a DC voltage but will have an AC component. So even though the error voltage across the inputs is driven to zero by the action of the amplifier, we can no longer use the virtual-short concept to derive the input impedance. Instead we must use an alternate, more complex method.

The first step in analyzing the circuit is to break it along the center vertical axis into positive and negative input sides. Then the positive side is converted to its Thevenin equivalent so the circuit can be analyzed and a solution can be developed. Finally, the components on the negative side are balanced to make sure the amplifier gives balanced output. In the positive side of the circuit shown in Figure 7,

$$Z_{IN} = \frac{V_{IN}}{I_{IN}} \parallel R_T = Z_A \parallel R_T. \qquad (4)$$

The Thevenin equivalent of the positive side is shown in Figure 8. In this circuit,

$$I_{IN} = \frac{V_{IN} - V_{OUT-}}{R_F + R_G}. \qquad (5)$$

We can treat V_{IN} as a summing node, or solve the node equation to get

$$V_{IN} = \frac{V_{SIG}\left(\frac{R_T}{R_S + R_T}\right)(R_G + R_F) + V_{OUT-}(R_S \parallel R_T)}{R_G + R_F + R_S \parallel R_T}. \qquad (6)$$

At this point we make use of Equation 12 for output voltage from page 10 of Reference 1, with simplification and some slight changes in nomenclature. In the analysis we need to find V_{OUT-} in relation to V_{IN}, so β_+ will be used here in place of β_1 for the feedback factor in the Thevenin equivalent of the positive side. For the feedback factor of the negative side, β_- will be used in place of β_2. To clarify, the different terms that arise for the feedback factors are artifacts of the analysis, and in reality the circuit will have balanced feedback factors as long as $R_{EQ} = R_G + R_T \parallel R_S$. Let's also zero out V_{OCM} because it is a DC level, and zero out $V_{IN}-$ because we grounded the input to the negative side of the amplifier.

With these changes in nomenclature, and substituting the Thevenin equivalent shown earlier, we can derive the equation for only the amplifier's AC or signal response to V_{OUT-}, which we will call $V_{OUT-\,(AC\ only)}$:

$$V_{OUT-\ (AC\ only)} = \frac{-\left[V_{SIG}\left(\frac{R_T}{R_S + R_T}\right)\right](1 - \beta_+)}{\beta_+ + \beta_-}, \qquad (7)$$

where

$$\beta_+ = \frac{R_G}{R_F + R_G}, \text{ and } \beta_- = \frac{R_G + (R_S \parallel R_T)}{R_F + R_G + (R_S \parallel R_T)}.$$

Figure 6. FDA with DC-coupled, single-ended source referenced to ground

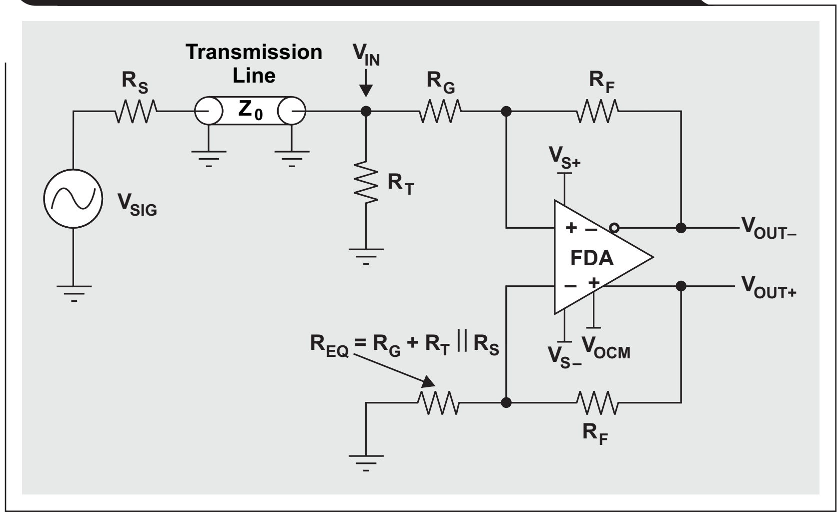


Figure 7. Positive side of FDA circuit

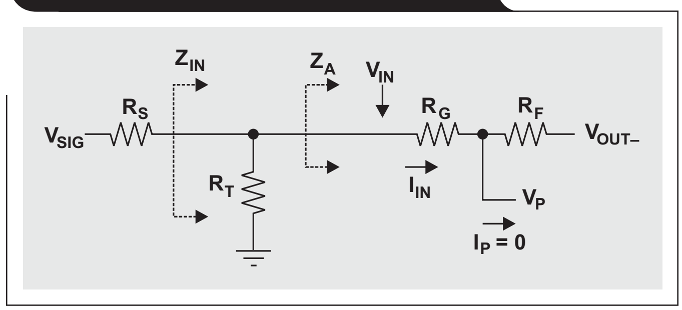
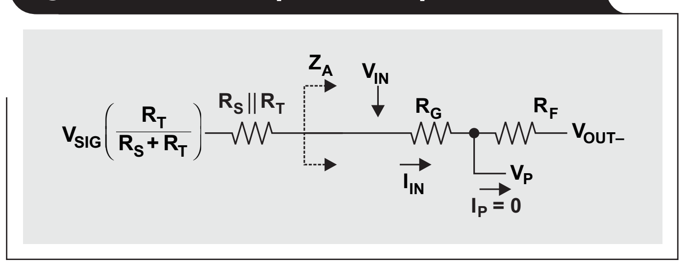


Figure 8. Thevenin equivalent of positive side



With a significant amount of algebra and substitution, we solve for Z_A and then use Equation 4 to find Z_{IN}:

$$Z_A = \frac{(R_G + R_F)(\beta_+ + \beta_-)}{\beta_- + 1} \quad \textbf{(8)}$$

The gain from the terminated input to the differential output, assuming the circuit is balanced, is

$$\frac{V_{OUT\ (Differential)}}{V_{IN}} = 2\left(\frac{R_F}{R_G + R_S \parallel R_T}\right)\left(\frac{R_T}{R_S + R_T}\right). \quad \textbf{(9)}$$

The output DC common mode is set by the input to V_{OCM}.

It would be useful to have a closed-form equation to solve for R_T to satisfy both Equations 8 and 9, but none could be found. One solution is to guess values and iterate, but sometimes that fails to find a solution. A more practical approach is to modify the equations and solve using Equations 10 and 11.

$$\frac{1}{R_T} = \frac{1}{Z_0} - \left[\frac{1-GF}{2(1+GF)}\right]\left(\frac{2GF}{2R_F - Z_0 GF}\right), \quad \textbf{(10)}$$

where Z_0 is the desired termination, G is the target gain from terminated input to output, and F is a factor less than 1 that depends on the gain and value of R_F. The result is fed into Equation 11 to solve for R_G:

$$R_G = \left[\frac{2R_T R_F}{G(Z_0 + R_T)}\right] - Z_0 \parallel R_T \quad \textbf{(11)}$$

In design, the target gain and Z_0 are set by the system design; and, as noted earlier, it is recommended that R_F be limited to a range of values for best performance. So we select the value of R_F first and then try values for F until $Z_{IN} = Z_0$. This is easily done by setting up the equations in a spreadsheet that can simultaneously calculate with incremental values, and then selecting the appropriate values. 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_Input_Impedance.xls, then select the Single-Ended Input worksheet tab.

For an example of how to select the value of R_T, let's look at a single-ended source driving a coax to the FDA with $Z_0 = 50\ \Omega$. For double termination, we want the source to provide $R_S = 50\text{-}\Omega$ output impedance, and we want the input of the FDA to present a 50-Ω single-ended load. Assuming that we want a gain of 1 from the terminated input and that $R_F = 402\ \Omega$, we can use the spreadsheet to calculate the nearest standard values for $R_G = 392\ \Omega$, $R_T = 54.9\ \Omega$, and $R_{EQ} = 422\ \Omega$, which gives us $Z_{IN} = 49.73\ \Omega$ and a gain of 1.006 V/V.

Again we use SPICE simulation to validate the design. To see a TINA-TI simulation circuit of the example just 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_Single_Ended_Input_Impedance.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.

There are numerous ways to find the input impedance in SPICE, but from the simulation waveforms shown in Figure 9, we see the expected input and output voltages for double termination with equal impedances.

Reference

For more information related to this article, you can download an Acrobat Reader file at www-s.ti.com/sc/techlit/*litnumber* and replace "*litnumber*" with the **TI Lit. #** for the materials listed below.

Document Title **TI Lit. #**

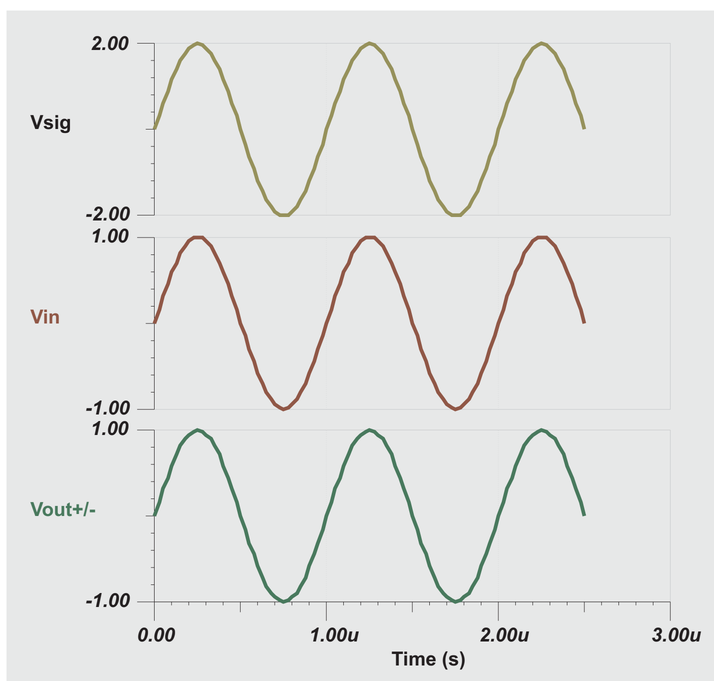
1. Jim Karki, "Fully Differential Amplifiers," Application Report. sloa054

Related Web sites

amplifier.ti.com

www.ti.com/tina-ti

Figure 9. TINA-TI simulation of FDA waveforms with single-ended input impedance



IMPORTANT NOTICE

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Amplifiers	amplifier.ti.com	Audio	www.ti.com/audio
Data Converters	dataconverter.ti.com	Automotive	www.ti.com/automotive
Clocks and Timers	www.ti.com/clocks	Broadband	www.ti.com/broadband
DSP	dsp.ti.com	Digital control	www.ti.com/digitalcontrol
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Military	www.ti.com/military
Power Mgmt	power.ti.com	Optical Networking	www.ti.com/opticalnetwork
Microcontrollers	microcontroller.ti.com	Security	www.ti.com/security
RFID	www.ti-rfid.com	Telephony	www.ti.com/telephony
RF/IF and ZigBee® Solutions	www.ti.com/lprf	Video and Imaging	www.ti.com/video
		Wireless	www.ti.com/wireless

Mailing Address: Texas Instruments
Post Office Box 655303
Dallas, Texas 75265

TI Worldwide Technical Support

Internet

TI Semiconductor Product Information Center Home Page
support.ti.com

TI Semiconductor KnowledgeBase Home Page
support.ti.com/sc/knowledgebase

Product Information Centers

Americas	Phone	+1(972) 644-5580
Brazil	Phone	0800-891-2616
Mexico	Phone	0800-670-7544
	Fax	+1(972) 927-6377
	Internet/Email	support.ti.com/sc/pic/americas.htm

Europe, Middle East, and Africa

Phone

European Free Call	00800-ASK-TEXAS (00800 275 83927)
International	+49 (0) 8161 80 2121
Russian Support	+7 (4) 95 98 10 701

Note: The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

Fax	+(49) (0) 8161 80 2045
Internet	support.ti.com/sc/pic/euro.htm

Japan

Fax	International	+81-3-3344-5317
	Domestic	0120-81-0036
Internet/Email	International	support.ti.com/sc/pic/japan.htm
	Domestic	www.tij.co.jp/pic

Asia

Phone

International	+91-80-41381665
Domestic	Toll-Free Number
Australia	1-800-999-084
China	800-820-8682
Hong Kong	800-96-5941
India	1-800-425-7888
Indonesia	001-803-8861-1006
Korea	080-551-2804
Malaysia	1-800-80-3973
New Zealand	0800-446-934
Philippines	1-800-765-7404
Singapore	800-886-1028
Taiwan	0800-006800
Thailand	001-800-886-0010

Fax	+886-2-2378-6808
Email	tiasia@ti.com or ti-china@ti.com
Internet	support.ti.com/sc/pic/asia.htm

IMPORTANT NOTICE

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Amplifiers	amplifier.ti.com	Audio	www.ti.com/audio
Data Converters	dataconverter.ti.com	Automotive	www.ti.com/automotive
DSP	dsp.ti.com	Broadband	www.ti.com/broadband
Clocks and Timers	www.ti.com/clocks	Digital Control	www.ti.com/digitalcontrol
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Military	www.ti.com/military
Power Mgmt	power.ti.com	Optical Networking	www.ti.com/opticalnetwork
Microcontrollers	microcontroller.ti.com	Security	www.ti.com/security
RFID	www.ti-rfid.com	Telephony	www.ti.com/telephony
RF/IF and ZigBee® Solutions	www.ti.com/lprf	Video & Imaging	www.ti.com/video
		Wireless	www.ti.com/wireless

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265