

ISL28134, READ2302G

Composite Amplifier Design for High Gain Applications

Abstract

Industrial signal conditioners with high signal gain often use composite amplifiers. A composite amplifier is an amplifier whose design is composed of a high-precision and a high-speed or fast-slewing operational amplifier (op-amp). Some of the performance improvements of the composite design versus the individual op-amps include low output offset (especially at high gain) high-gain accuracy, increased signal bandwidth, and low-distortion of large output signals.

This application note discusses the design of a composite amplifier using the precision op-amp ISL28134, and the fast slewing op-amp READ2302. The key parameters of both amplifiers are listed in [Table 1](#).

Table 1. Key Parameters

Parameter	Symbol	A1 = ISL28134	A2 = READ2302
Supply Range	V_{CC}	2.25V to 6.0V	2.25V to 6.0V
Operating Temperature Range	T_A	-40°C to +125°C	-40°C to +105°C
Offset Voltage	V_{OS}	0.2μV	6mV
DC Open-Loop Gain	a	174dB	90dB
Slew Rate	SR	1V/μs	8V/μs
Gain Bandwidth	f_c	3.5MHz	6MHz
Phase Margin	Φ_m	75°	65°

Contents

1. Circuit Overview	2
2. Detailed Derivations for the Practical Amplifier	3
2.1 Unity Gain Bandwidth	3
2.2 Compensation Capacitor, CF, for Maximum Bandwidth or Maximum Phase Margin?	3
2.3 Bandwidth Comparison	5
2.4 Output Offset Voltage	6
2.5 Gain Accuracy and Gain Error	6
3. Conclusion	7
4. Revision History	7

List of Figures

Figure 1. Composite Amplifier	2
Figure 2. Frequency Response	2
Figure 3. Composite Unity Gain Bandwidth	3
Figure 4. Loop Gain: $A_{OLC} \cdot \beta$	3
Figure 5. Gain Peaking vs Phase Margin	3
Figure 6. Feedback Phase Compensation	4
Figure 7. $1/\beta$ -Frequency Response and Feedback Factor, β , Phase Response	4
Figure 8. Compensation for Maximum Bandwidth	4
Figure 9. Compensation for Maximum Phase Margin	4
Figure 10. Output Offset Evaluation Model	6
Figure 11. Comparison of 1% Gain Error Bandwidths	7

Related Literature

For a full list of related documents, visit our website:

- [ISL28134](#), [READ2302G](#) device pages

1. Circuit Overview

[Figure 1](#) shows the composite amplifier with the precision op-amp, A1, and the fast switching op-amp, A2. The composite open-loop gain is the product of the individual open-loop gains: $A_{OLc} = A_{OL1} \cdot A_{OL2}$.

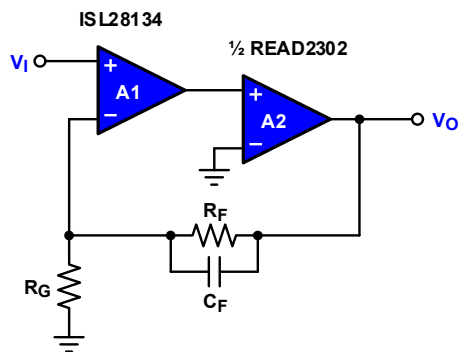


Figure 1. Composite Amplifier

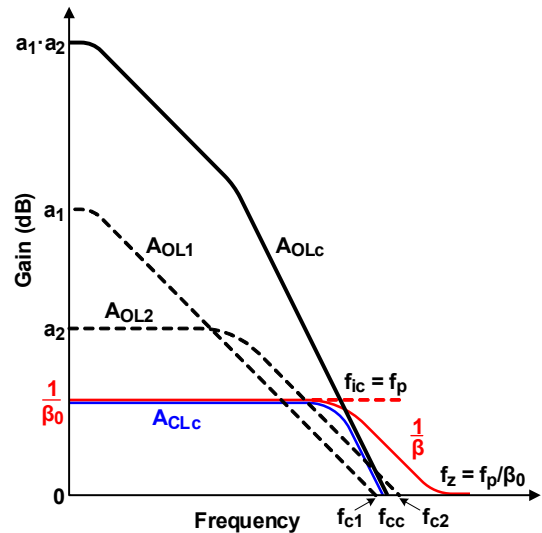


Figure 2. Frequency Response

[Figure 2](#) shows A_{OL1} and A_{OL2} rolling off at a rate of -20dB/decade. A_{OLc} however, starts rolling off at the rate of A_{OL1} , with -20dB/decade, which increases to -40dB/decade, when A_{OL2} starts rolling off. This faster roll-off leads to the crossing of A_{OLc} with A_{OL2} prior to reaching unity gain. The two unity crossover frequencies, f_{c1} and f_{c2} , therefore determine the unity crossover frequency of the composite case, f_{cc} , using: $f_{cc} = \sqrt{f_{c1} \cdot f_{c2}}$.

The single feedback path, using R_G and R_F , sets the ideal gain of the composite amplifier to $1/\beta_0 = 1 + R_F/R_G$. This gain crosses A_{OLc} during its 40dB roll-off, where the composite phase shift is $\Phi = -180^\circ$.

Here the loop-gain $T = |A_{OLc}|e^{-j180^\circ} \cdot \beta_0 = -1$ bears the risk of self-sustaining oscillations.

To ensure circuit stability, capacitor C_F is connected parallel to R_F , which introduces a pole and a zero into the gain function:

$$\frac{1}{\beta} = \frac{1}{\beta_0} \cdot \frac{1 + jf/f_z}{1 + jf/f_p} \quad \text{with} \quad f_p = \frac{1}{2\pi C_F R_F} \quad \text{and} \quad f_z = \frac{1}{2\pi C_F (R_F \parallel R_G)}$$

The now complex $1/\beta$ function generates a positive phase angle that reduces the total phase shift of the loop-gain, T .

However, to fully restore circuit stability while preserving maximum signal bandwidth, the pole and zero frequencies must be sufficiently apart to create enough positive phase angle. This in turn requires that $R_F \gg R_G$. Therefore, feedback phase compensation for maximum bandwidth lends itself to high-gain applications. Here, the optimum C_F value for maximum signal bandwidth is:

$$(EQ. 1) \quad C = \frac{1}{2\pi R_F \sqrt{f_{c1} f_{c2} \beta_0}}$$

The resulting composite closed-loop gain, A_{CLc} , is close to the $1/\beta$ line, up to the A_{OLc} roll-off, and then follows A_{OLc} down to unity.

2. Detailed Derivations for the Practical Amplifier

The following sections derive the equations and key parameters for the practical amplifier design using the ISL28134 as precision amplifier, A1, and the READ2302 as fast slewing, A2.

2.1 Unity Gain Bandwidth

Figure 3 shows A_{OL1} and A_{OL2} approaching unity gain at -20dB/decade, while A_{OLC} is rolling off at -40dB/decade. The unity gain bandwidth of the composite open-loop gain is at the frequency where the product of $1/A_{OL1} \cdot A_{OL2} = 1V/V$.

Denoting these gains as $1/A_x$ and A_x , the gain-bandwidth products of A_{OL1} and A_{OL2} defines them through:

$$A_x = f_{c2}/f_{cc} \quad \text{and} \quad A_x = f_{cc}/f_{c1}. \quad \text{Setting both equations equal and solving for } f_{cc} \text{ gives: } f_{cc} = \sqrt{f_{c1}f_{c2}}.$$

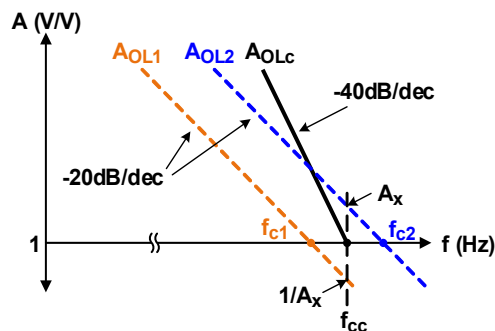


Figure 3. Composite Unity Gain Bandwidth

Therefore, the unity-gain bandwidth of our composite amplifier is $f_{cc} = \sqrt{3.5\text{MHz} \cdot 6\text{MHz}} = 4.58\text{MHz}$.

2.2 Compensation Capacitor, C_F , for Maximum Bandwidth or Maximum Phase Margin?

Figure 4 depicts the loop-gain $T = A_{OLC} \cdot \beta$. From op-amp theory we recall that the phase shift between input voltage, V_I , and feedback voltage, V_{FB} , should never reach -180°, due to the possibility of oscillations. However, long before this angle, gain peaking and signal overshoot occur. A commonly applied reference value for minimum phase margin and therefore, circuit stability, is $\Phi_m = 45^\circ$, as here the gain peaking is still below 3dB (Figure 5).

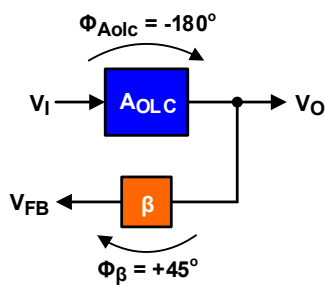


Figure 4. Loop Gain: $A_{OLC} \cdot \beta$

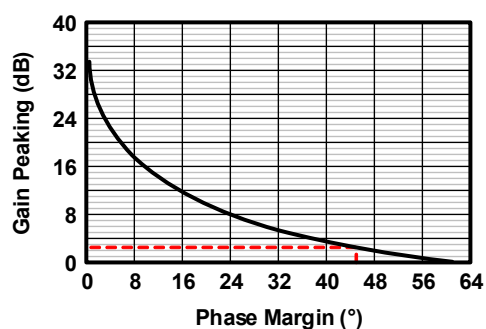


Figure 5. Gain Peaking vs Phase Margin

In the composite amplifier however, the -180° are already consumed by the two open-loop gains. To restore phase margin, the feedback factor must be modified to produce enough positive phase angle (such as 45°) to ensure circuit stability. This is accomplished by connecting a capacitor parallel to R_F and is known as feedback phase compensation (Figure 6 on page 4).

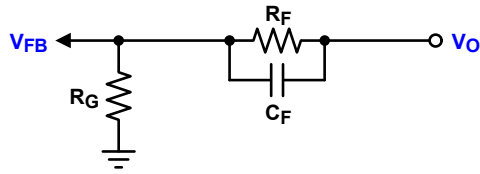
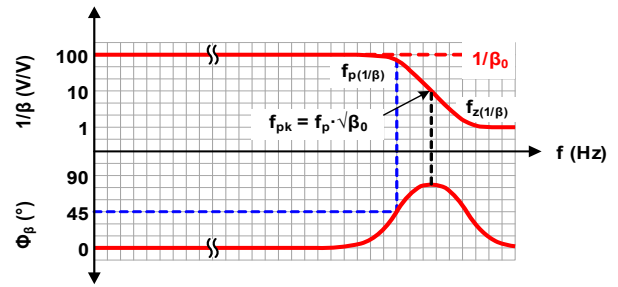


Figure 6. Feedback Phase Compensation

Figure 7. $1/\beta$ -Frequency Response and Feedback Factor, β , Phase Response

The resulting complex feedback factor then becomes:

$$\beta = \frac{R_G}{R_G + R_F \parallel X_C} = \beta_0 \cdot \frac{1 + jf/f_{z(\beta)}}{1 + jf/f_{p(\beta)}} \quad \text{with} \quad \beta_0 = \frac{R_G}{R_G + R_F}, \quad f_{z(\beta)} = \frac{1}{2\pi C_F R_F} \quad \text{and} \quad f_{p(\beta)} = \frac{1}{2\pi C_F R_F \parallel R_G}$$

Because Bode plots use the $1/\beta$ rather than the β representation, we establish the reciprocal of β with:

$$\frac{1}{\beta} = \frac{1}{\beta_0} \cdot \frac{1 + jf/f_{p(\beta)}}{1 + jf/f_{z(\beta)}} \quad \text{with} \quad \frac{1}{\beta_0} = 1 + \frac{R_F}{R_G}, \quad f_{p(1/\beta)} = \frac{1}{2\pi C_F R_F} \quad \text{and} \quad f_{z(1/\beta)} = \frac{1}{2\pi C_F R_F \parallel R_G}$$

Note: The zero pole and zero frequencies of the β response reverse for the $1/\beta$ response:

$f_{z(\beta)} \rightarrow f_{p(1/\beta)}$ and $f_{p(\beta)} \rightarrow f_{z(1/\beta)}$. Figure 7 shows the frequency response of $1/\beta$ and the corresponding phase response of β . From the previous equation for $f_{p(1/\beta)}$ and $f_{z(1/\beta)}$, we find that $f_{z(1/\beta)} / f_{p(1/\beta)} = 1 + R_F/R_G = 1/\beta_0$ so $f_{z(1/\beta)} = f_{p(1/\beta)} / \beta_0$. Therefore, for $R_F = 100 R_G$, $1/\beta_0 = 101$ and $f_{z(1/\beta)} = 101 \cdot f_{p(1/\beta)}$.

With f_p and f_z being two frequency decades apart, Φ_β , which is also the phase margin Φ_m , is 45° at f_p . The maximum phase margin however, occurs at f_{pk} , which is the geometric mean of f_p and f_z :

$$f_{pk} = \sqrt{f_{p(1/\beta)} \cdot f_{z(1/\beta)}}$$

Substituting $f_{z(1/\beta)}$ with $f_{p(1/\beta)} / \beta_0$ then makes Equation 2.

$$(EQ. 2) \quad f_{pk} = f_{p(1/\beta)} / (\sqrt{\beta_0})$$

These frequency-phase relations of Figure 7 therefore allow for two options of phase compensation: one aiming for maximum bandwidth, and a second one establishing maximum phase margin. Both options are shown in Figures 8 and 9.

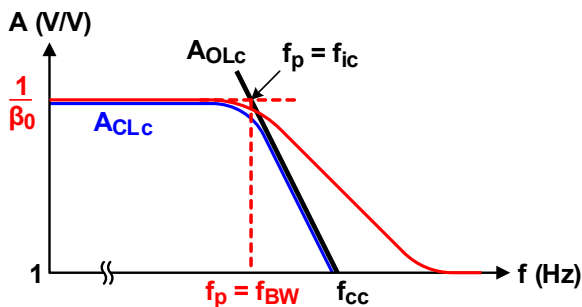


Figure 8. Compensation for Maximum Bandwidth

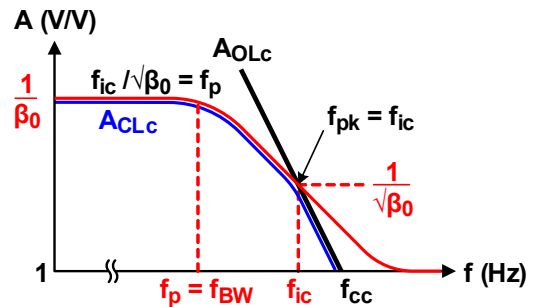


Figure 9. Compensation for Maximum Phase Margin

2.2.1 Phase Compensation for Maximum Bandwidth, f_{BW-max}

Placing the pole frequency at the intercept of $1/\beta_0$ and A_{OLC} generates the minimum phase margin of 45° . The frequency at the intercept, f_{ic} , is defined by the second order roll-off of A_{OLC} and its unit crossover frequency as: $f_{ic} = f_{cc} \cdot \sqrt{\beta_0}$. Therefore, expressing f_p = f_{ic} through their detailed equations:

$\frac{1}{2\pi C_F R_F} = f_{cc} \cdot \sqrt{\beta_0}$, and solving for C_F , gives the capacitor value for maximum bandwidth:

$$(EQ. 3) \quad C_{F(BW-max)} = \frac{1}{2\pi R_F f_{cc} \cdot \sqrt{\beta_0}} = \frac{1}{2\pi R_F \sqrt{f_{c1} f_{c2} \beta_0}}$$

therefore, confirming [Equation 1 on page 2](#).

The -3dB signal bandwidth is the actual pole frequency:

$$(EQ. 4) \quad f_{BW} = \frac{1}{2\pi R_F C_{F(BW-max)}}$$

For a practical amplifier circuit with $R_F = 10k\Omega$ and $R_G = 100\Omega$, $C_{F(BW-max)} = 35pF$. Selecting the standard value of 39pF, results in a signal bandwidth of $f_{BW} = 408kHz$.

2.2.2 Phase Compensation for Maximum Phase Margin, Φ_{m-max}

To ensure maximum phase margin at the intercept of $1/\beta$ and A_{OLC} , the $1/\beta$ function is moved left towards lower frequencies, until f_{pk} , the frequency at maximum phase margin, coincides with f_{ic} , the frequency at which A_{OLC} equals half the $1/\beta_0$ value in dB, or $\sqrt{1/\beta_0}$ in V/V. Here, f_{ic} is defined by the second order roll-off of A_{OLC} , the unit crossover frequency, f_{cc} , and the gain $\sqrt{1/\beta_0}$ as: $f_{ic} = f_{cc} \cdot \sqrt{\beta_0} = f_{cc} \cdot 4\sqrt{\beta_0}$.

With [Equation 4](#), making $f_{pk} = f_{ic}$ results in $f_p / \sqrt{\beta_0} = f_{cc} \cdot 4\sqrt{\beta_0}$.

Further substitution of f_p yields $1/(2\pi R_F C_F \sqrt{\beta_0}) = f_{cc} \cdot 4\sqrt{\beta_0}$, and solving for C_F gives the capacitor value for maximum phase margin:

$$(EQ. 5) \quad C_{F(\Phi_{max})} = \frac{1}{2\pi R_F f_{cc} \cdot \sqrt{\beta_0} \cdot 4\sqrt{\beta_0}} = \frac{1}{2\pi R_F \sqrt{f_{c1} f_{c2} \beta_0} \cdot 4\sqrt{\beta_0}}$$

Again, the -3dB signal bandwidth is the actual pole frequency:

$$(EQ. 6) \quad f_{BW} = \frac{1}{2\pi R_F C_{F(\Phi_{max})}}$$

For a practical amplifier circuit with $R_F = 10k\Omega$ and $R_G = 100\Omega$, $C_{F(BW-max)} = 111pF$. Selecting the standard value of 100pF, results in a signal bandwidth of $f_{BW} = 161kHz$.

2.3 Bandwidth Comparison

When using the READ2302 in a normal, non-inverting amplifier configuration, its gain-bandwidth product of 6MHz limits the signal bandwidth to 60kHz, when operating at a gain of 100V/V. In strong contrast, the composite amplifier, which is designed for maximum bandwidth extends this bandwidth by a factor of almost 7 to about 408kHz. Even when optimized for maximum phase margin, the composite almost triples the bandwidth to about 160kHz. We can therefore conclude that the composite amplifier significantly increases signal bandwidth over the standard configuration.

2.4 Output Offset Voltage

In a non-inverting $G = 100$ amplifier application, the READ2302 rather large input offset of 6mV generates a 600mV output offset. In comparison, analysis of the composite amplifier output offset in [Figure 10](#) defines the output voltage with:

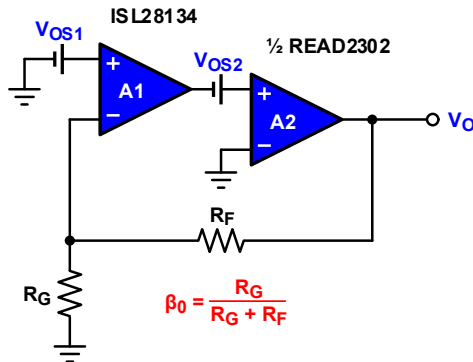


Figure 10. Output Offset Evaluation Model

$$V_O = a_2[V_{OS2} + a_1(V_{OS1} - V_O \cdot \beta_0)]$$

Multiplying and collecting terms gives:

$$V_O = \frac{V_{OS1}}{\frac{1}{a_1 a_2} + \beta} + \frac{V_{OS2}}{\frac{1}{a_2} + a_1 \beta}$$

Because the DC open-loop gains of both op-amps are much larger than 1 ($a_1, a_2 \gg 1$), the output voltage due to offset is:

$$V_O = \frac{1}{\beta} \left(V_{OS1} + \frac{V_{OS2}}{a_1} \right)$$

In practical terms, $V_{OS1} = \pm 4\mu\text{V}$, $V_{OS2} = \pm 6\text{mV}$, $a_1 = 5 \cdot 10^8 \text{ V/V}$ (174dB), and $1/\beta = 101\text{V/V}$, therefore generating an output offset of about only $400\mu\text{V}$ at a gain of 100. This shows that in the composite design the DC shortcomings of the high-speed amplifier, A2, are reduced by the open-loop gain of the precision amplifier, A1, which is beneficial in high-gain applications.

2.5 Gain Accuracy and Gain Error

The closed-loop gain, A_{CL} , can be expressed through the product of the ideal gain, $1/\beta$, and the gain accuracy, $1/(1+1/T)$.

$$A_{CL} = \frac{1}{\beta} \cdot \frac{1}{1+1/T} \quad \text{with } T = A_{OL}\beta$$

The gain error is defined as the difference between ideal and actual gain, referred to the ideal gain:

$$E_G = \frac{1/\beta - A_{CL}}{1/\beta} = 1 - \frac{1}{1+1/T}$$

Because both functions contain loop gain T , and therefore A_{OL} , in their denominators, gain accuracy and gain error are frequency dependent. Rather than calculating the complex equations for a complex and composite A_{OL} , it is easier to approximate the gain error if loop-gain $T \gg 1$. The following steps simplify the gain error expression to:

$$E_G = 1 - \frac{1}{1+1/T} = 1 - \frac{T}{1+T} = \frac{1+T-T}{1+T} = \frac{1}{1+T}$$

Then for $T \gg 1$ follows: $E_G \approx \frac{1}{T}$ and $E_G(\%) \approx \frac{100}{T}$

In a Bode plot, loop-gain is the difference in dB between the open-loop gain and the ideal gain:

$T(\text{dB}) = A_{OL}(\text{dB}) - 1/\beta(\text{dB})$. Therefore, to determine the bandwidth for 1% gain error, we identify the frequency where the difference between A_{OL} and $1/\beta$ is 40dB (100V/V).

This procedure is applied to A_{OL2} and A_{OLc} in [Figure 11 on page 7](#). It clearly shows that the large open-loop gain of the composite amplifier ensures gain errors of $\leq 1\%$ up to 47kHz, which is almost 80 times the 600Hz range of the non-inverting amplifier using a single READ2303 op-amp.

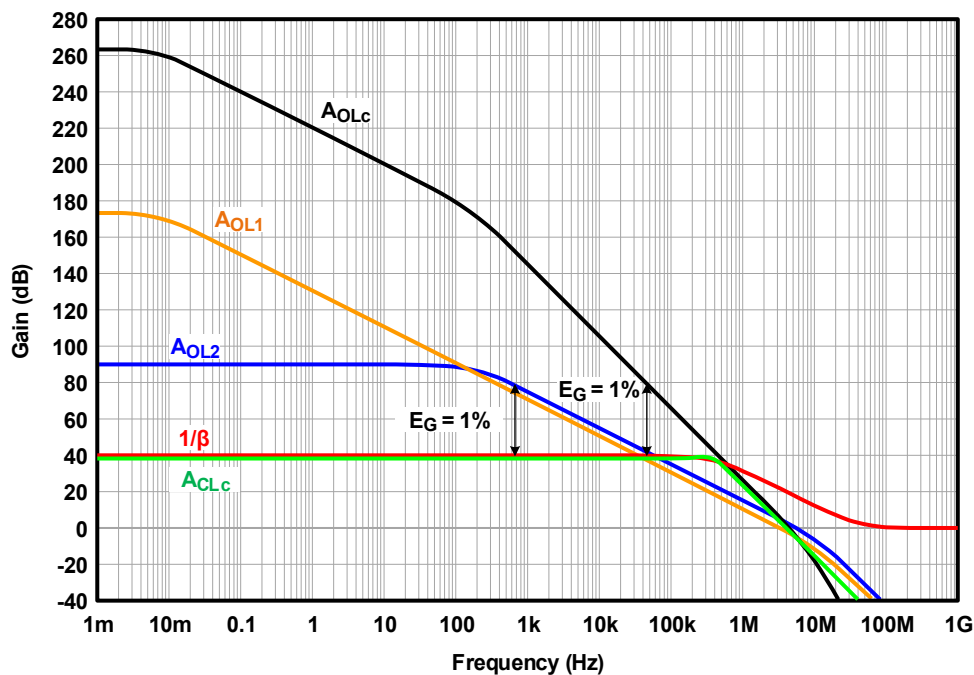


Figure 11. Comparison of 1% Gain Error Bandwidths

3. Conclusion

While there is a variety of composite amplifier designs using different stabilizing techniques, the design discussed here uses feedback phase compensation. It is one of the simpler compensation techniques and mainly applied in high-gain applications.

Composite amplifiers combine the DC performance of a precision op-amp with the AC performance of a fast-slewing or high-speed op-amp.

4. Revision History

Rev.	Date	Description
1.00	Oct.2.19	Initial release

Notice

1. Descriptions of circuits, software and other related information in this document are provided only to illustrate the operation of semiconductor products and application examples. You are fully responsible for the incorporation or any other use of the circuits, software, and information in the design of your product or system. Renesas Electronics disclaims any and all liability for any losses and damages incurred by you or third parties arising from the use of these circuits, software, or information.
2. Renesas Electronics hereby expressly disclaims any warranties against and liability for infringement or any other claims involving patents, copyrights, or other intellectual property rights of third parties, by or arising from the use of Renesas Electronics products or technical information described in this document, including but not limited to, the product data, drawings, charts, programs, algorithms, and application examples.
3. No license, express, implied or otherwise, is granted hereby under any patents, copyrights or other intellectual property rights of Renesas Electronics or others.
4. You shall not alter, modify, copy, or reverse engineer any Renesas Electronics product, whether in whole or in part. Renesas Electronics disclaims any and all liability for any losses or damages incurred by you or third parties arising from such alteration, modification, copying or reverse engineering.
5. Renesas Electronics products are classified according to the following two quality grades: "Standard" and "High Quality". The intended applications for each Renesas Electronics product depends on the product's quality grade, as indicated below.

"Standard": Computers; office equipment; communications equipment; test and measurement equipment; audio and visual equipment; home electronic appliances; machine tools; personal electronic equipment; industrial robots; etc.

"High Quality": Transportation equipment (automobiles, trains, ships, etc.); traffic control (traffic lights); large-scale communication equipment; key financial terminal systems; safety control equipment; etc.

Unless expressly designated as a high reliability product or a product for harsh environments in a Renesas Electronics data sheet or other Renesas Electronics document, Renesas Electronics products are not intended or authorized for use in products or systems that may pose a direct threat to human life or bodily injury (artificial life support devices or systems; surgical implantations; etc.), or may cause serious property damage (space system; undersea repeaters; nuclear power control systems; aircraft control systems; key plant systems; military equipment; etc.). Renesas Electronics disclaims any and all liability for any damages or losses incurred by you or any third parties arising from the use of any Renesas Electronics product that is inconsistent with any Renesas Electronics data sheet, user's manual or other Renesas Electronics document.
6. When using Renesas Electronics products, refer to the latest product information (data sheets, user's manuals, application notes, "General Notes for Handling and Using Semiconductor Devices" in the reliability handbook, etc.), and ensure that usage conditions are within the ranges specified by Renesas Electronics with respect to maximum ratings, operating power supply voltage range, heat dissipation characteristics, installation, etc. Renesas Electronics disclaims any and all liability for any malfunctions, failure or accident arising out of the use of Renesas Electronics products outside of such specified ranges.
7. Although Renesas Electronics endeavors to improve the quality and reliability of Renesas Electronics products, semiconductor products have specific characteristics, such as the occurrence of failure at a certain rate and malfunctions under certain use conditions. Unless designated as a high reliability product or a product for harsh environments in a Renesas Electronics data sheet or other Renesas Electronics document, Renesas Electronics products are not subject to radiation resistance design. You are responsible for implementing safety measures to guard against the possibility of bodily injury, injury or damage caused by fire, and/or danger to the public in the event of a failure or malfunction of Renesas Electronics products, such as safety design for hardware and software, including but not limited to redundancy, fire control and malfunction prevention, appropriate treatment for aging degradation or any other appropriate measures. Because the evaluation of microcomputer software alone is very difficult and impractical, you are responsible for evaluating the safety of the final products or systems manufactured by you.
8. Please contact a Renesas Electronics sales office for details as to environmental matters such as the environmental compatibility of each Renesas Electronics product. You are responsible for carefully and sufficiently investigating applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive, and using Renesas Electronics products in compliance with all these applicable laws and regulations. Renesas Electronics disclaims any and all liability for damages or losses occurring as a result of your noncompliance with applicable laws and regulations.
9. Renesas Electronics products and technologies shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable domestic or foreign laws or regulations. You shall comply with any applicable export control laws and regulations promulgated and administered by the governments of any countries asserting jurisdiction over the parties or transactions.
10. It is the responsibility of the buyer or distributor of Renesas Electronics products, or any other party who distributes, disposes of, or otherwise sells or transfers the product to a third party, to notify such third party in advance of the contents and conditions set forth in this document.
11. This document shall not be reprinted, reproduced or duplicated in any form, in whole or in part, without prior written consent of Renesas Electronics.
12. Please contact a Renesas Electronics sales office if you have any questions regarding the information contained in this document or Renesas Electronics products.

(Note1) "Renesas Electronics" as used in this document means Renesas Electronics Corporation and also includes its directly or indirectly controlled subsidiaries.

(Note2) "Renesas Electronics product(s)" means any product developed or manufactured by or for Renesas Electronics.

(Rev.4.0-1 November 2017)

Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu,
Koto-ku, Tokyo 135-0061, Japan
www.renesas.com

Trademarks

Renesas and the Renesas logo are trademarks of Renesas Electronics Corporation. All trademarks and registered trademarks are the property of their respective owners.

Contact Information

For further information on a product, technology, the most up-to-date version of a document, or your nearest sales office, please visit:
www.renesas.com/contact/