

# INA191 Low-Power, Zero-Drift, Wide Dynamic Range, Precision Current-Sense Amplifier

## 1 Features

- Low power:
  - Low supply voltage,  $V_S$ : 1.7 V to 5.5 V
  - Low shutdown current: 100 nA (max)
  - Low quiescent current: 43  $\mu$ A at 25°C (typ)
- Low input bias currents: 100 pA (typ) (enables microamp current measurement)
- Accuracy:
  - $\pm 0.25\%$  max gain error (A2 to A5 devices)
  - 7-ppm/°C gain drift (max)
  - $\pm 12$   $\mu$ V (max) offset voltage
  - 0.13- $\mu$ V/°C offset drift (max)
- Wide common-mode voltage:  $-0.2$  V to +40 V
- Gain options:
  - INA191A1: 25 V/V
  - INA191A2: 50 V/V
  - INA191A3: 100 V/V
  - INA191A4: 200 V/V
  - INA191A5: 500 V/V
- Package: 0.895-mm<sup>2</sup> DSBGA

## 2 Applications

- Notebook computers
- Cell phones
- Battery-powered devices
- Telecom equipment
- Power management
- Battery chargers

## 3 Description

The INA191 is a low-power, voltage-output, current-shunt monitor (also called a current-sense amplifier) that is commonly used for overcurrent protection, precision-current measurement for system optimization, or in closed-loop feedback circuits. This device can sense drops across shunts at common-mode voltages from  $-0.2$  V to +40 V, independent of the supply voltage. The low input bias current of the INA191 permits the use of larger current-sense resistors, and thus provides accurate current measurements in the  $\mu$ A range. Five fixed gains are available: 25 V/V, 50 V/V, 100 V/V, 200 V/V, or 500 V/V. The low offset voltage of the zero-drift architecture extends the dynamic range of the current measurement, and allows for smaller sense resistors with lower power loss while still providing accurate current measurements.

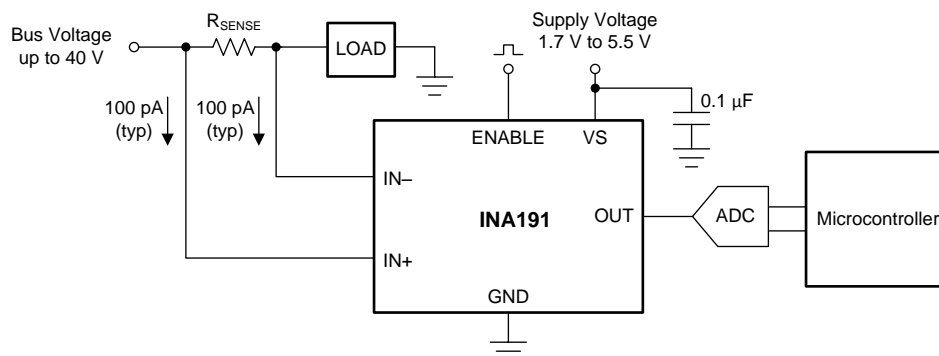
The INA191 operates from a single 1.7-V to 5.5-V power supply, drawing a maximum of 65  $\mu$ A of supply current when enabled and only 100 nA when disabled. The device is specified over the operating temperature range of  $-40^\circ\text{C}$  to  $+125^\circ\text{C}$ , and offered in a DSBGA-6 package.

### Device Information<sup>(1)</sup>

PART NUMBER	PACKAGE	BODY SIZE (NOM)
INA191	DSBGA (6)	1.17 mm x 0.765 mm

(1) For all available packages, see the package option addendum at the end of the datasheet.

### Simplified Schematic



## Table of Contents

<b>1 Features</b> .....	<b>1</b>	7.4 Device Functional Modes.....	<b>15</b>
<b>2 Applications</b> .....	<b>1</b>	<b>8 Application and Implementation</b> .....	<b>16</b>
<b>3 Description</b> .....	<b>1</b>	8.1 Application Information.....	<b>16</b>
<b>4 Revision History</b> .....	<b>2</b>	8.2 Typical Applications .....	<b>21</b>
<b>5 Pin Configuration and Functions</b> .....	<b>3</b>	<b>9 Power Supply Recommendations</b> .....	<b>23</b>
<b>6 Specifications</b> .....	<b>4</b>	<b>10 Layout</b> .....	<b>23</b>
6.1 Absolute Maximum Ratings .....	4	10.1 Layout Guidelines .....	23
6.2 ESD Ratings.....	4	10.2 Layout Example .....	23
6.3 Recommended Operating Conditions .....	4	<b>11 Device and Documentation Support</b> .....	<b>24</b>
6.4 Thermal Information .....	4	11.1 Documentation Support .....	24
6.5 Electrical Characteristics.....	5	11.2 Receiving Notification of Documentation Updates	24
6.6 Typical Characteristics.....	6	11.3 Community Resources.....	24
<b>7 Detailed Description</b> .....	<b>12</b>	11.4 Trademarks .....	24
7.1 Overview .....	12	11.5 Electrostatic Discharge Caution.....	24
7.2 Functional Block Diagram .....	12	11.6 Glossary .....	24
7.3 Feature Description.....	13	<b>12 Mechanical, Packaging, and Orderable Information</b> .....	<b>24</b>

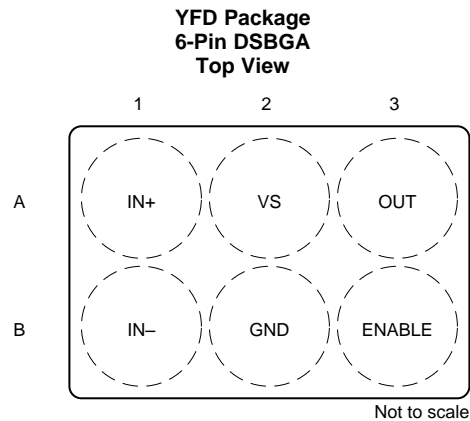
## 4 Revision History

### Changes from Original (February 2019) to Revision A

**Page**

- |  |          |
|--|----------|
| • Changed device from advanced information to production data (active) ..... | <b>1</b> |
|--|----------|

## 5 Pin Configuration and Functions



### Pin Functions

PIN		TYPE	DESCRIPTION
NAME	NO.		
ENABLE	B3	Digital input	Enable pin. When this pin is driven to $V_S$ , the device is on and functions as a current sense amplifier. When this pin is driven to GND, the device is off, the supply current is reduced, and the output is placed in a high-impedance state. This pin must be driven externally, or connected to $V_S$ if not used.
GND	B2	Analog	Ground
IN+	A1	Analog input	Current-shunt monitor positive input. For high-side applications, connect this pin to the bus voltage side of the sense resistor. For low-side applications, connect this pin to the load side of the sense resistor.
IN-	B1	Analog input	Current-shunt monitor negative input. For high-side applications, connect this pin to the load side of the sense resistor. For low-side applications, connect this pin to the ground side of the sense resistor.
OUT	A3	Analog output	This pin provides an analog voltage output that is the amplified voltage difference from the IN+ to the IN- pins.
VS	A2	Analog	Power supply, 1.7 V to 5.5 V

## 6 Specifications

### 6.1 Absolute Maximum Ratings

 over operating free-air temperature range (unless otherwise noted)<sup>(1)</sup>

		MIN	MAX	UNIT
V <sub>S</sub>	Supply voltage		6	V
	Analog inputs, V <sub>IN+</sub> , V <sub>IN-</sub> <sup>(2)</sup>	Differential (V <sub>IN+</sub> ) – (V <sub>IN-</sub> )		V
		Common-mode, V <sub>CM</sub> <sup>(3)</sup>		
V <sub>ENABLE</sub>	ENABLE pin voltage	GND – 0.3	6	V
V <sub>OUT</sub>	OUT pin Voltage <sup>(3)</sup>	GND – 0.3	(V <sub>S</sub> ) + 0.3	V
	Input current into any pin <sup>(3)</sup>		5	mA
T <sub>A</sub>	Operating temperature	–55	150	°C
T <sub>J</sub>	Junction temperature		150	°C
T <sub>stg</sub>	Storage temperature	–65	150	°C

- (1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, which do not imply functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions*. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
- (2) V<sub>IN+</sub> and V<sub>IN-</sub> are the voltages at the IN+ and IN– pins, respectively.
- (3) Input voltage at any pin may exceed the voltage shown if the current at that pin is limited to 5 mA.

### 6.2 ESD Ratings

		VALUE	UNIT
V <sub>(ESD)</sub>	Electrostatic discharge	Human-body model (HBM), per ANSI/ESDA/JEDEC JS-001 <sup>(1)</sup>	
		±2000	V
		Charged-device model (CDM), per JEDEC specification JESD22-C101 <sup>(2)</sup>	
		±1000	

- (1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.
- (2) JEDEC document JEP157 states that 250-V CDM allows safe manufacturing with a standard ESD control process.

### 6.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)

		MIN	NOM	MAX	UNIT
V <sub>CM</sub>	Common-mode input range	–0.2		40	V
V <sub>IN+</sub> , V <sub>IN-</sub>	Input pin voltage range	–0.2		40	V
V <sub>S</sub>	Operating supply voltage	1.7		5.5	V
T <sub>A</sub>	Operating free-air temperature	–40		125	°C

### 6.4 Thermal Information

	THERMAL METRIC <sup>(1)</sup>	INA191	UNIT
		DSBGA	
		6 PINS	
R <sub>θJA</sub>	Junction-to-ambient thermal resistance	141.4	°C/W
R <sub>θJC(top)</sub>	Junction-to-case (top) thermal resistance	1.1	°C/W
R <sub>θJB</sub>	Junction-to-board thermal resistance	45.7	°C/W
ψ <sub>JT</sub>	Junction-to-top characterization parameter	0.4	°C/W
ψ <sub>JB</sub>	Junction-to-board characterization parameter	45.3	°C/W
R <sub>θJC(bot)</sub>	Junction-to-case (bottom) thermal resistance	N/A	°C/W

- (1) For more information about traditional and new thermal metrics, see the [Semiconductor and IC Package Thermal Metrics application report](#).

## 6.5 Electrical Characteristics

at  $T_A = 25^\circ\text{C}$ ,  $V_{\text{SENSE}} = V_{\text{IN}+} - V_{\text{IN}-}$ ,  $V_S = 1.8\text{ V to }5.0\text{ V}$ ,  $V_{\text{IN}+} = 12\text{ V}$ , and  $V_{\text{ENABLE}} = V_S$  (unless otherwise noted)

PARAMETER		CONDITIONS		MIN	TYP	MAX	UNIT
<b>INPUT</b>							
CMRR	Common-mode rejection ratio, RTI <sup>(1)</sup>	$V_{\text{IN}+} = -0.1\text{ V to }40\text{ V}$ , $T_A = -40^\circ\text{C to }+125^\circ\text{C}$		132	150		dB
$V_{\text{OS}}$	Offset voltage, RTI	$V_S = 1.8\text{ V}$			-2.5	$\pm 12$	$\mu\text{V}$
$dV_{\text{OS}}/dT$	Offset drift, RTI	$T_A = -40^\circ\text{C to }+125^\circ\text{C}$			10	130	$\text{nV}/^\circ\text{C}$
PSRR	Power-supply rejection ratio, RTI	$V_S = 1.7\text{ V to }5.5\text{ V}$			-1	$\pm 5$	$\mu\text{V}/\text{V}$
$I_{\text{IB}}$	Input bias current	$V_{\text{SENSE}} = 0\text{ mV}$			0.1	3	nA
$I_{\text{IO}}$	Input offset current	$V_{\text{SENSE}} = 0\text{ mV}$			$\pm 0.07$		nA
<b>OUTPUT</b>							
G	Gain	A1 devices			25		V/V
		A2 devices			50		
		A3 devices			100		
		A4 devices			200		
		A5 devices			500		
$E_G$	Gain error	$V_{\text{OUT}} = 0.1\text{ V to }V_S - 0.1\text{ V}$	A1 device		-0.17%	$\pm 0.35\%$	
			A2, A3, A4, A5 devices		-0.04%	$\pm 0.25\%$	
	Gain error drift	$V_{\text{OUT}} = 0.1\text{ V to }V_S - 0.1\text{ V}$ , $T_A = -40^\circ\text{C to }+125^\circ\text{C}$			2	7	$\text{ppm}/^\circ\text{C}$
	Nonlinearity error	$V_{\text{OUT}} = 0.1\text{ V to }V_S - 0.1\text{ V}$			$\pm 0.01\%$		
	Maximum capacitive load	No sustained oscillation			1		nF
<b>VOLTAGE OUTPUT</b>							
$V_{\text{SP}}$	Swing to $V_S$ power-supply rail	$V_S = 1.8\text{ V}$ , $R_L = 10\text{ k}\Omega$ to GND, $T_A = -40^\circ\text{C to }+125^\circ\text{C}$ , $V_{\text{SENSE}}$ overdrive = 10 mV			$(V_S) - 23$	$(V_S) - 40$	mV
$V_{\text{SN}}$	Swing to GND	$V_S = 1.8\text{ V}$ , $R_L = 10\text{ k}\Omega$ to GND, $T_A = -40^\circ\text{C to }+125^\circ\text{C}$ , $V_{\text{SENSE}} = -10\text{ mV}$			$(V_{\text{GND}}) + 0.05$	$(V_{\text{GND}}) + 1$	mV
$V_{\text{ZL}}$	Zero current output voltage	$V_S = 1.8\text{ V}$ , $R_L = 10\text{ k}\Omega$ to GND, $T_A = -40^\circ\text{C to }+125^\circ\text{C}$ , $V_{\text{SENSE}} = 0\text{ mV}$	A1, A2, A3 devices		$(V_{\text{GND}}) + 1$	$(V_{\text{GND}}) + 3$	mV
			A4 device		$(V_{\text{GND}}) + 2$	$(V_{\text{GND}}) + 4$	
			A5 device		$(V_{\text{GND}}) + 3$	$(V_{\text{GND}}) + 7$	
<b>FREQUENCY RESPONSE</b>							
BW	Bandwidth	$C_{\text{LOAD}} = 10\text{ pF}$	A1 device		45		kHz
			A2 device		37		
			A3 device		35		
			A4 device		33		
			A5 device		27		
SR	Slew rate	$V_S = 5.0\text{ V}$ , $V_{\text{OUT}} = 0.5\text{ V to }4.5\text{ V}$			0.3		$\text{V}/\mu\text{s}$
$t_s$	Settling time	From current step to within 1% of final value			30		$\mu\text{s}$
<b>NOISE, RTI<sup>(1)</sup></b>							
	Voltage noise density				75		$\text{nV}/\sqrt{\text{Hz}}$
<b>ENABLE</b>							
$I_{\text{EN}}$	Leakage input current	$0\text{ V} \leq V_{\text{ENABLE}} \leq V_S$			1	100	nA
$V_{\text{IH}}$	High-level input voltage	$T_A = -40^\circ\text{C to }+125^\circ\text{C}$		1.35		5.5	V
$V_{\text{IL}}$	Low-level input voltage	$T_A = -40^\circ\text{C to }+125^\circ\text{C}$		0		0.4	V
$V_{\text{HYS}}$	Hysteresis				100		mV
$I_{\text{ODIS}}$	Disabled output leakage	$V_S = 1.8\text{ V}$ , $V_{\text{OUT}} = 0\text{ V to }1.8\text{ V}$ , $V_{\text{ENABLE}} = 0\text{ V}$			1	5	$\mu\text{A}$
<b>POWER SUPPLY</b>							
$I_Q$	Quiescent current	$V_{\text{SENSE}} = 0\text{ mV}$ , $V_S = 1.8\text{ V}$			43	65	$\mu\text{A}$
		$V_{\text{SENSE}} = 0\text{ mV}$ , $V_S = 1.8\text{ V}$ , $T_A = -40^\circ\text{C to }+125^\circ\text{C}$				85	
$I_{\text{QDIS}}$	Quiescent current disabled	$V_{\text{ENABLE}} < 0.4$ , $V_{\text{SENSE}} = 0\text{ mV}$			10	100	nA

(1) RTI = referred-to-input.

## 6.6 Typical Characteristics

at  $T_A = 25^\circ\text{C}$ ,  $V_S = 1.8\text{ V}$ ,  $V_{IN+} = 12\text{ V}$ ,  $V_{ENABLE} = V_S$ , and all gain options (unless otherwise noted)

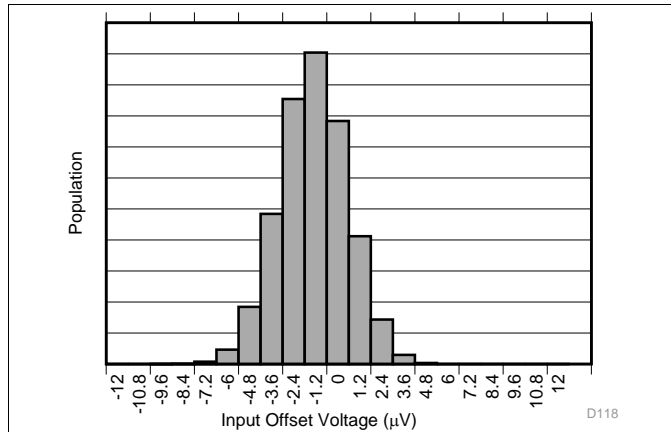


Figure 1. Input Offset Voltage Production Distribution

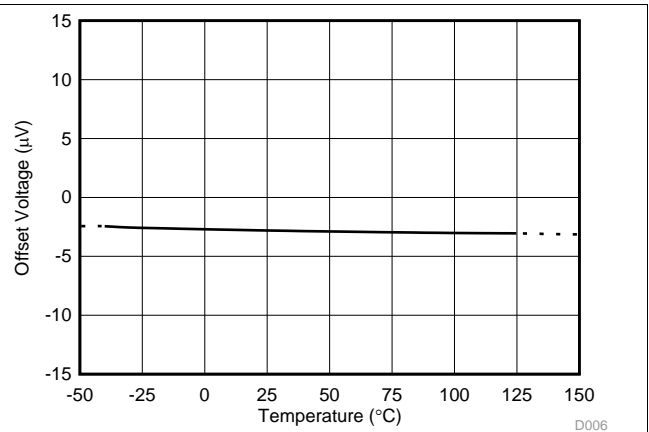


Figure 2. Offset Voltage vs Temperature

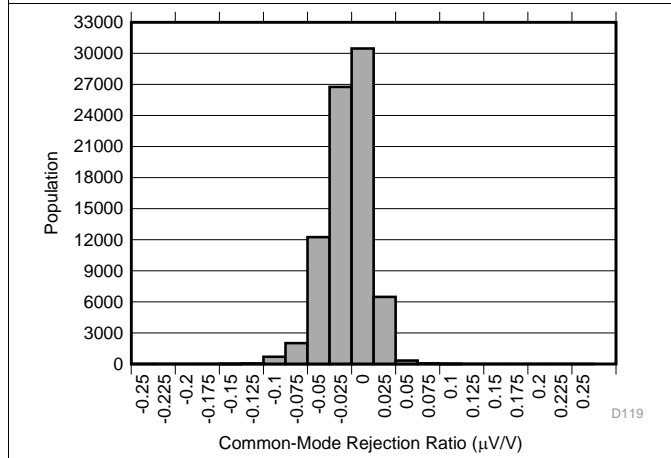


Figure 3. Common-Mode Rejection Production Distribution

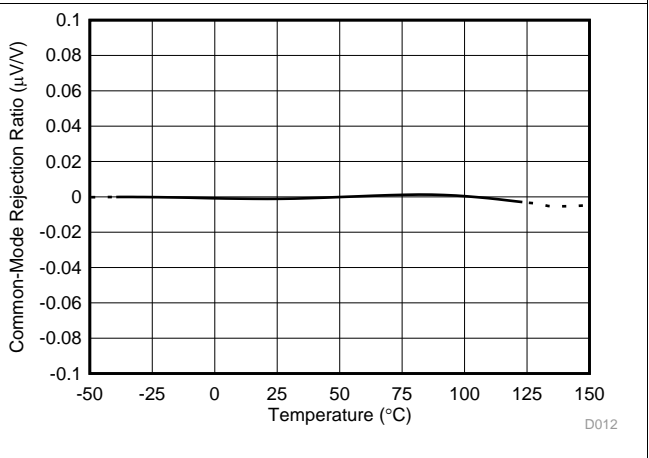


Figure 4. Common-Mode Rejection Ratio vs Temperature

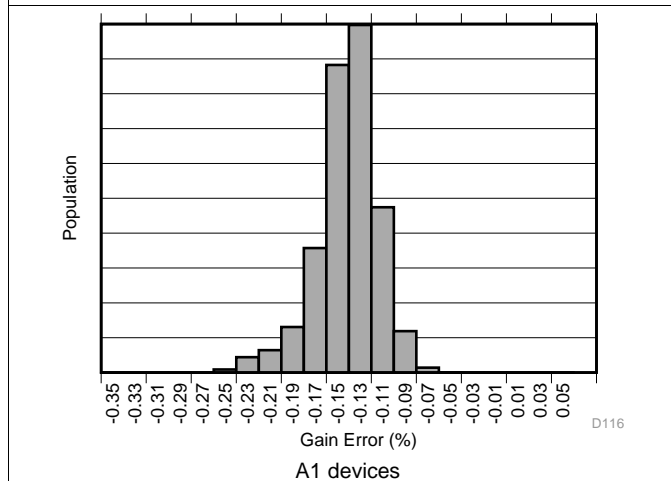


Figure 5. Gain Error Production Distribution  
A1 devices

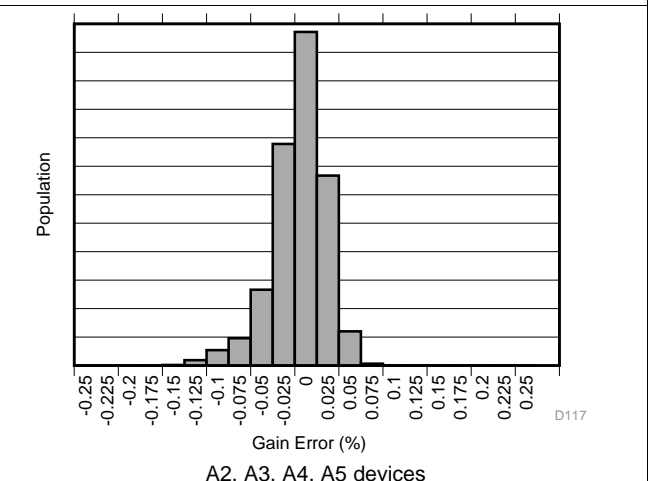


Figure 6. Gain Error Production Distribution  
A2, A3, A4, A5 devices

Typical Characteristics (continued)

at  $T_A = 25^\circ\text{C}$ ,  $V_S = 1.8\text{ V}$ ,  $V_{IN+} = 12\text{ V}$ ,  $V_{ENABLE} = V_S$ , and all gain options (unless otherwise noted)

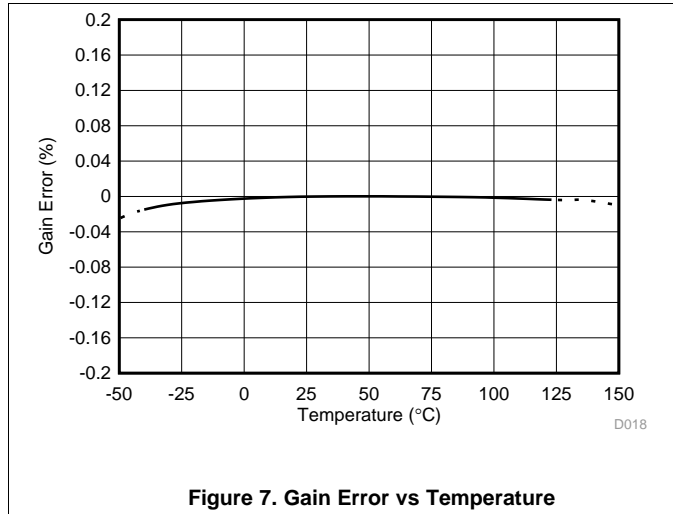


Figure 7. Gain Error vs Temperature

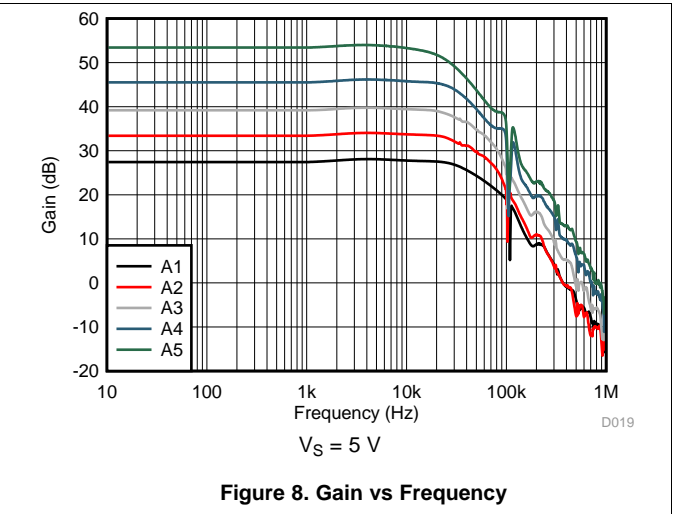


Figure 8. Gain vs Frequency

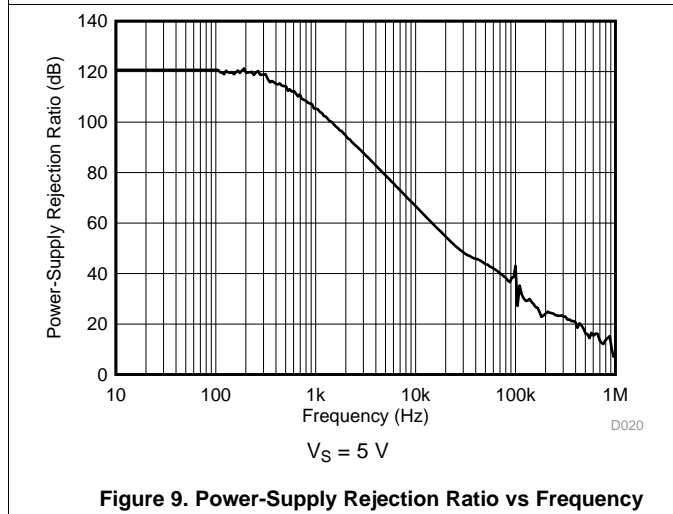


Figure 9. Power-Supply Rejection Ratio vs Frequency

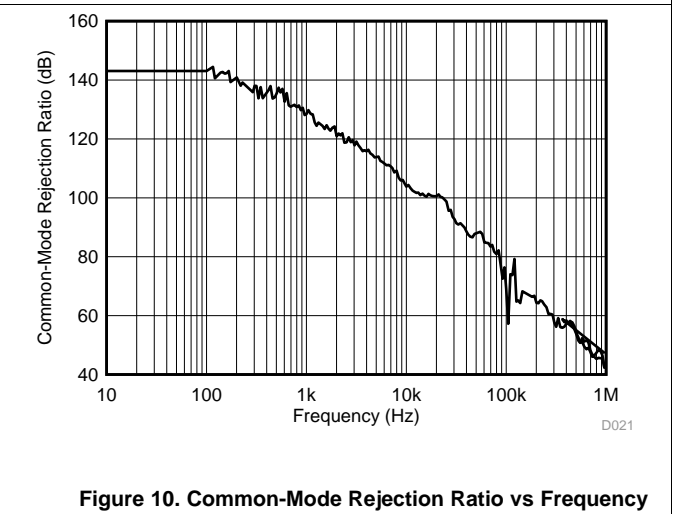


Figure 10. Common-Mode Rejection Ratio vs Frequency

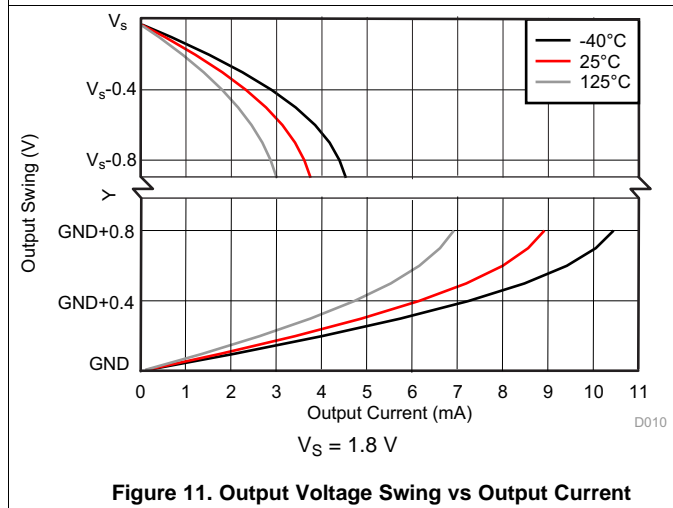


Figure 11. Output Voltage Swing vs Output Current

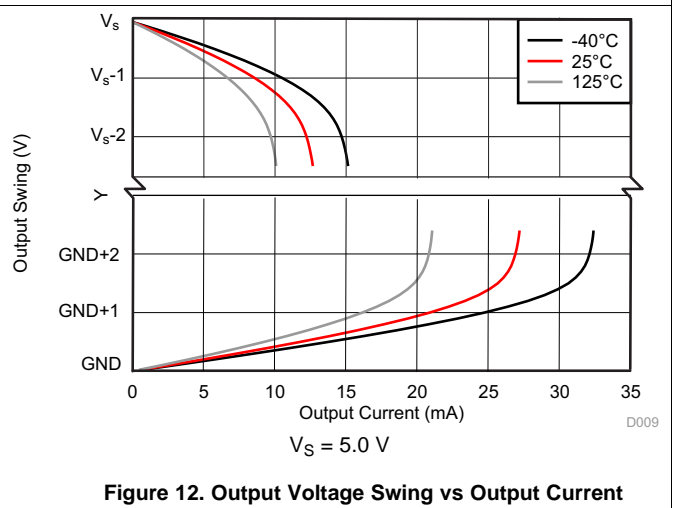


Figure 12. Output Voltage Swing vs Output Current

### Typical Characteristics (continued)

at  $T_A = 25^\circ\text{C}$ ,  $V_S = 1.8\text{ V}$ ,  $V_{IN+} = 12\text{ V}$ ,  $V_{ENABLE} = V_S$ , and all gain options (unless otherwise noted)

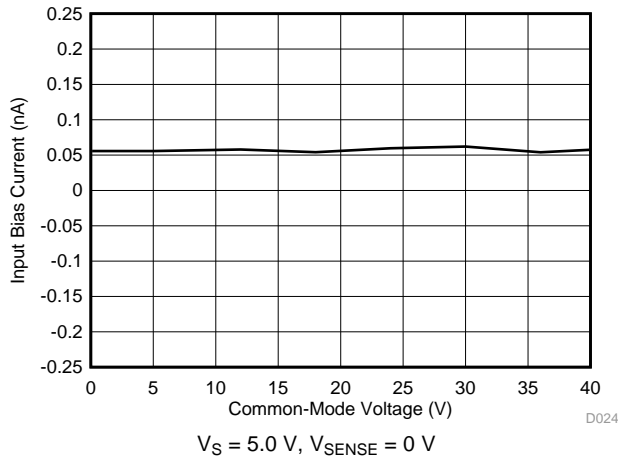


Figure 13. Input Bias Current vs Common-Mode Voltage

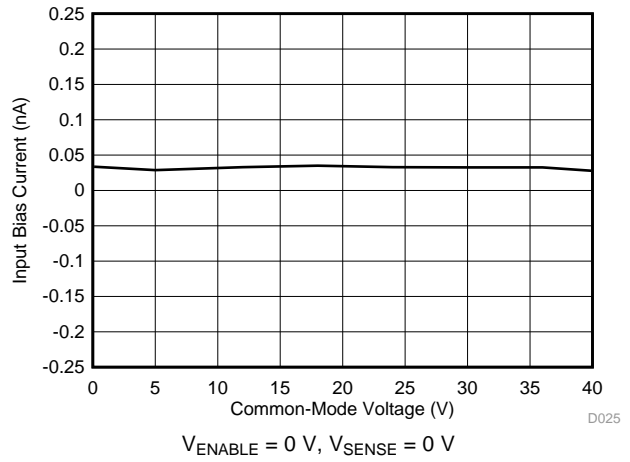


Figure 14. Input Bias Current vs Common-Mode Voltage (Shutdown)

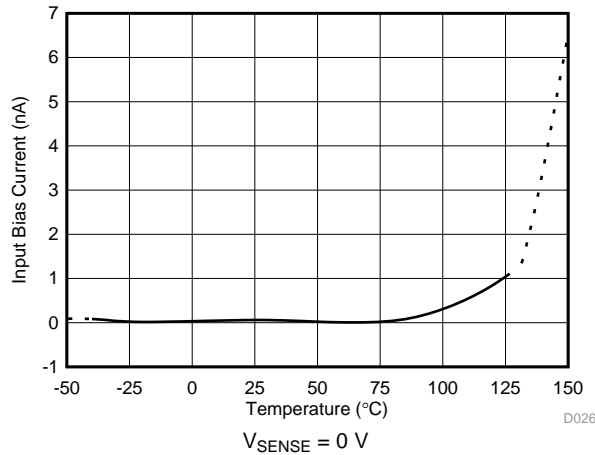


Figure 15. Input Bias Current vs Temperature

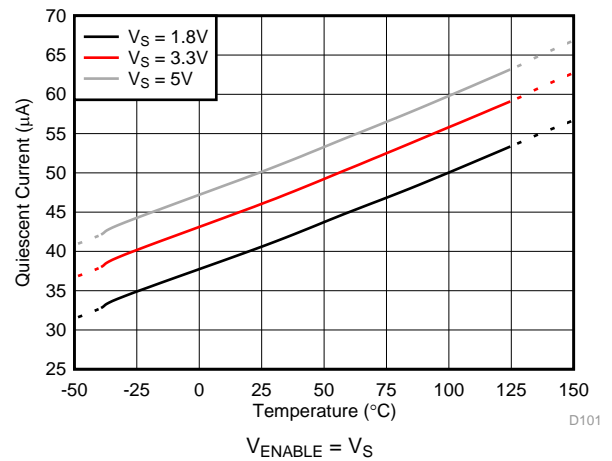


Figure 16. Quiescent Current vs Temperature (Enabled)

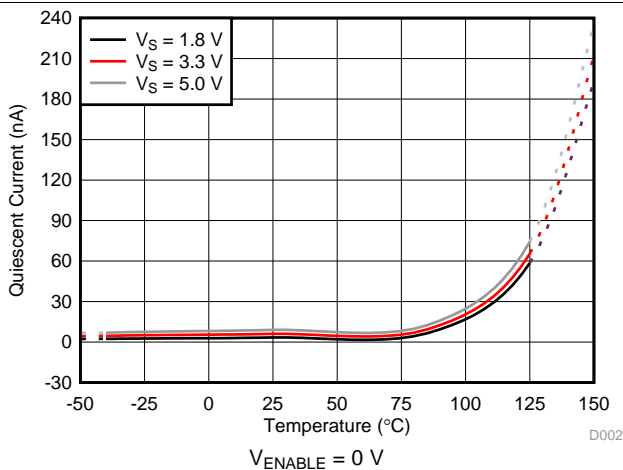


Figure 17. Quiescent Current vs Temperature (Disabled)

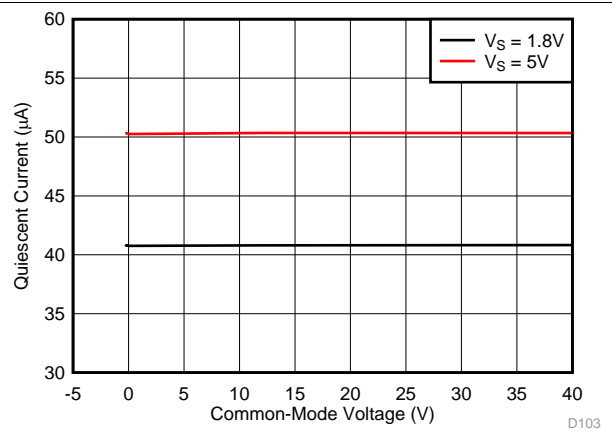


Figure 18. Quiescent Current vs Common Mode Voltage

Typical Characteristics (continued)

at  $T_A = 25^\circ\text{C}$ ,  $V_S = 1.8\text{ V}$ ,  $V_{IN+} = 12\text{ V}$ ,  $V_{ENABLE} = V_S$ , and all gain options (unless otherwise noted)

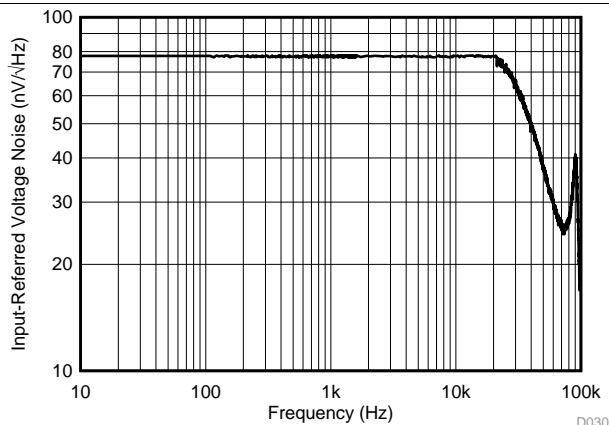


Figure 19. Input-Referred Voltage Noise vs Frequency

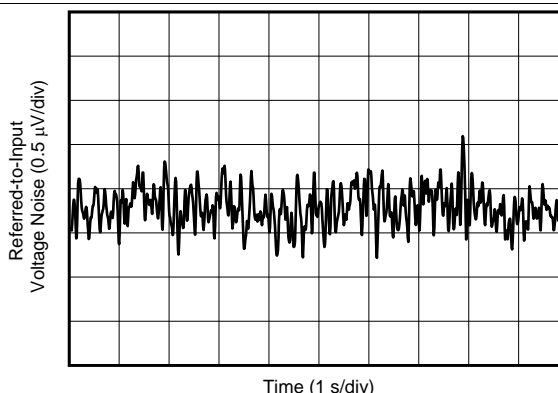
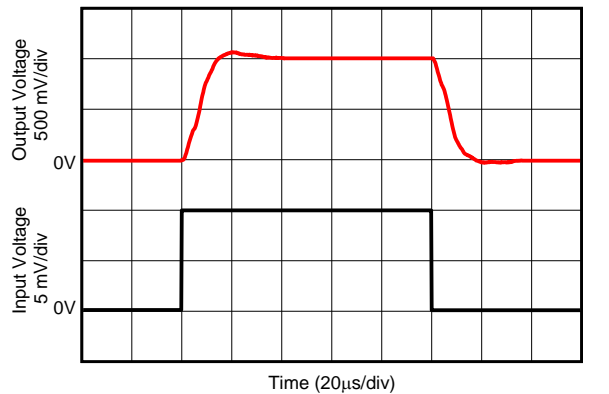


Figure 20. 0.1-Hz to 10-Hz Input-Referred Voltage Noise



$V_S = 5.0\text{ V}$ , 10-mV<sub>PP</sub> input step

Figure 21. Step Response

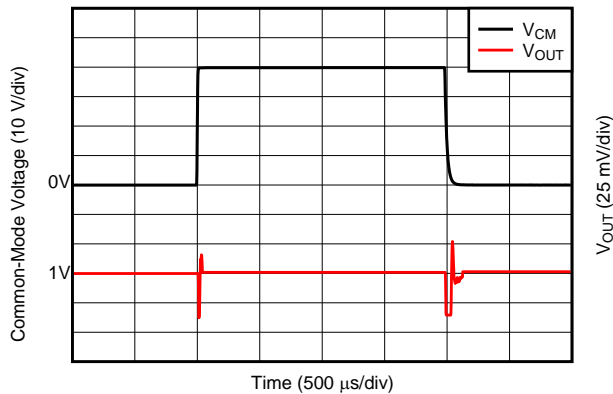


Figure 22. Common-Mode Voltage Transient Response

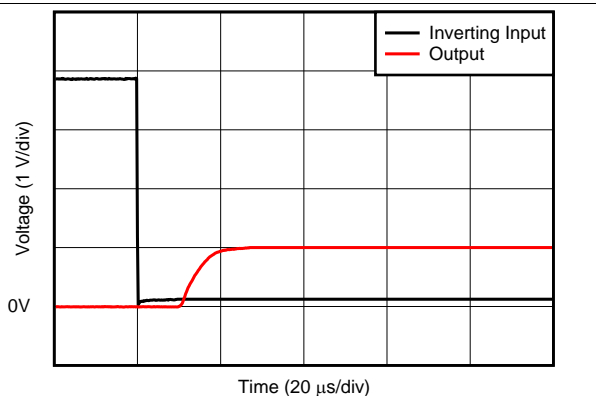
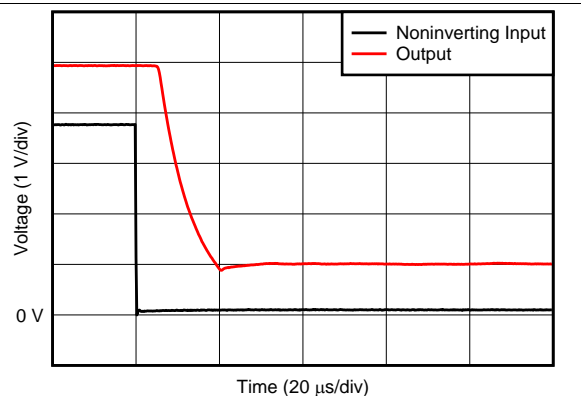


Figure 23. Inverting Differential Input Overload Recovery

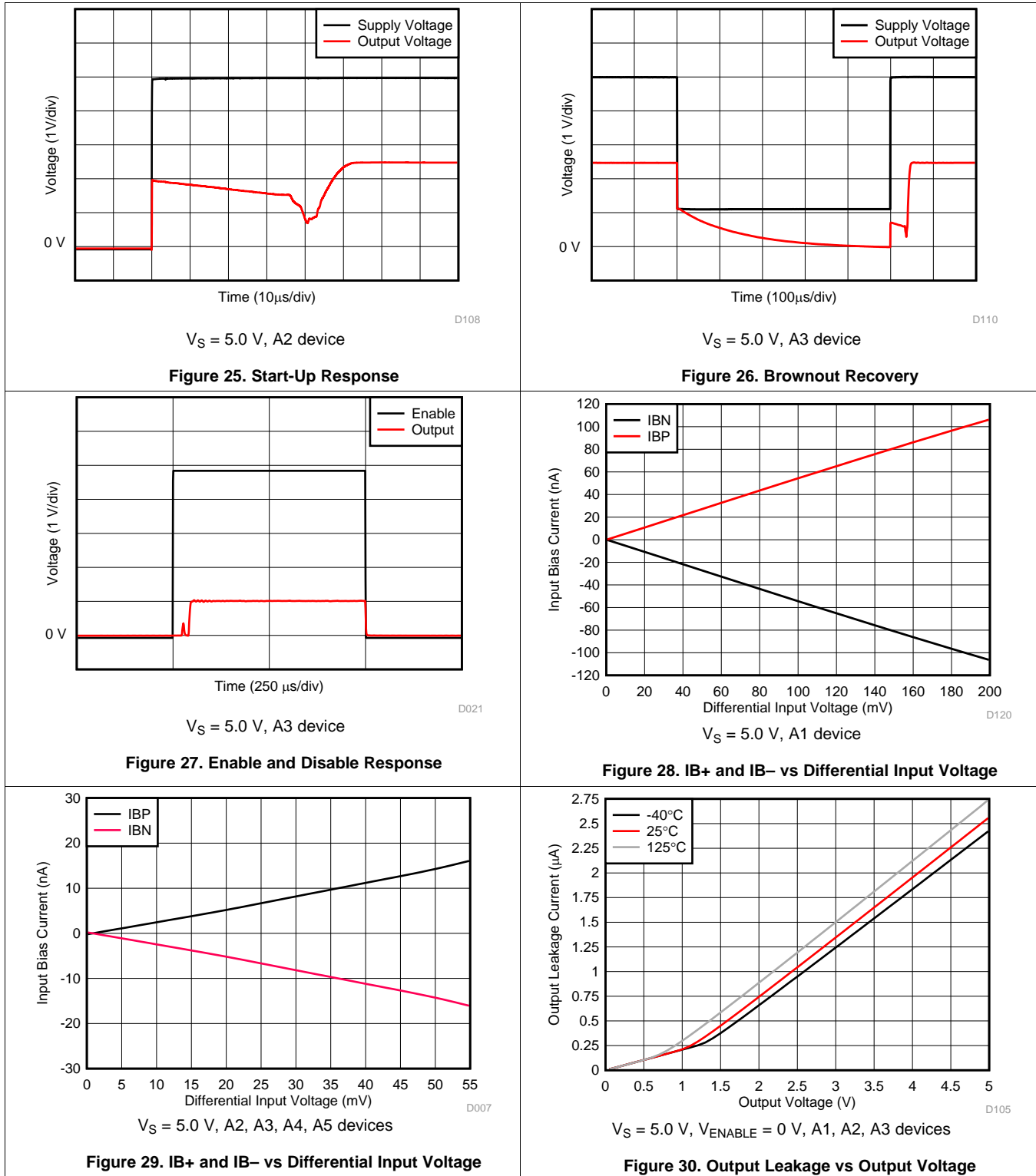


$V_S = 5.0\text{ V}$

Figure 24. Noninverting Differential Input Overload Recovery

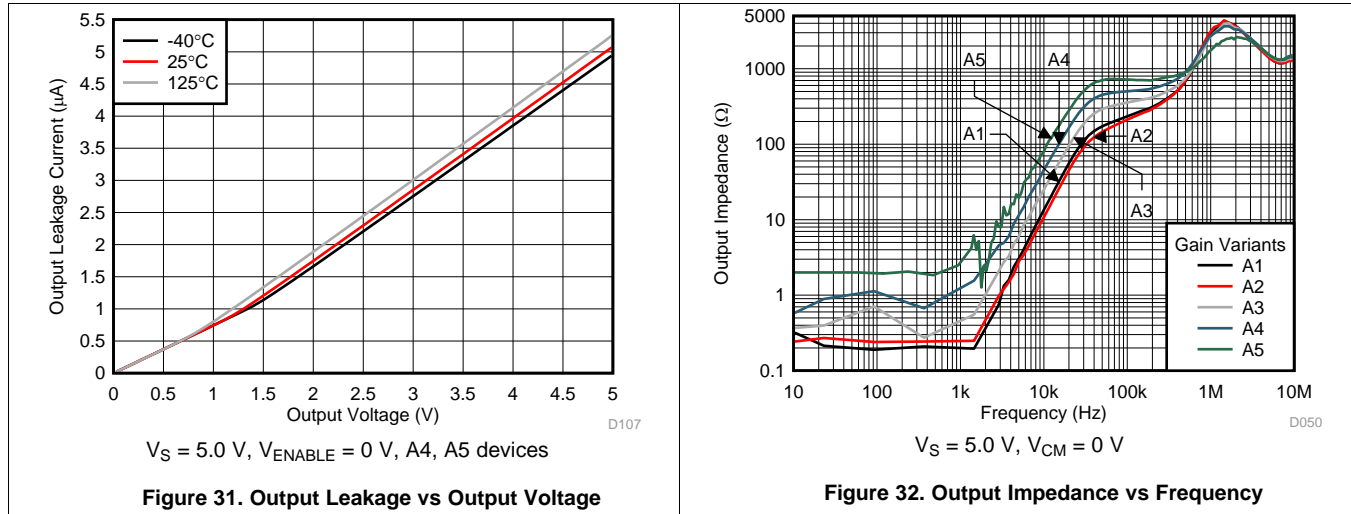
### Typical Characteristics (continued)

at  $T_A = 25^\circ\text{C}$ ,  $V_S = 1.8\text{ V}$ ,  $V_{IN+} = 12\text{ V}$ ,  $V_{ENABLE} = V_S$ , and all gain options (unless otherwise noted)



Typical Characteristics (continued)

at  $T_A = 25^\circ\text{C}$ ,  $V_S = 1.8\text{ V}$ ,  $V_{IN+} = 12\text{ V}$ ,  $V_{ENABLE} = V_S$ , and all gain options (unless otherwise noted)

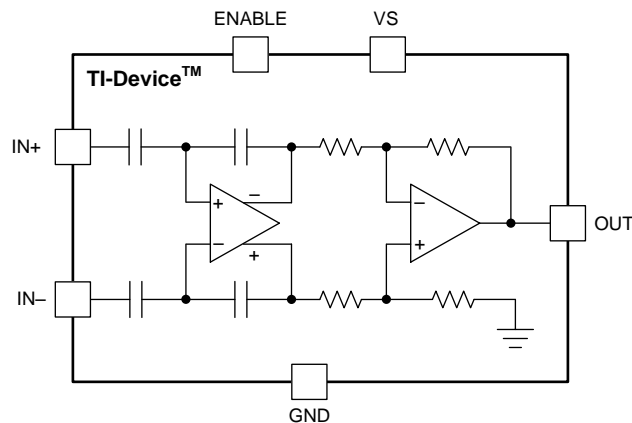


## 7 Detailed Description

### 7.1 Overview

The INA191 is a low bias current, 40-V common-mode, current-sensing amplifier with an enable pin. When disabled, the output goes to a high-impedance state, and the supply current draw is reduced to less than 0.1  $\mu\text{A}$ . The INA191 is intended for use in either low-side and high-side current-sensing configurations where high accuracy and low current consumption are required. The INA191 is a specially designed, current-sensing amplifier that accurately measure voltages developed across current-sensing resistors on common-mode voltages that far exceed the supply voltage. Current can be measured on input voltage rails as high as 40 V, with a supply voltage as low as 1.7 V.

### 7.2 Functional Block Diagram



## 7.3 Feature Description

### 7.3.1 Precision Current Measurement

The INA191 provides accurate current measurements over a wide dynamic range. The high accuracy of the device is attributable to the low gain error and offset specifications. The offset voltage of the INA191 is less than 12  $\mu\text{V}$ . In this case, the low offset improves the accuracy at light loads when  $V_{\text{IN}+}$  approaches  $V_{\text{IN}-}$ .

Another advantage of low offset is the ability to use a lower-value shunt resistor that reduces the power loss in the current-sense circuit, and improves the power efficiency of the end application.

The maximum gain error of the INA191 is specified to be within 0.25% for most gain options. As the sensed voltage becomes much larger than the offset voltage, the gain error becomes the dominant source of error in the current-sense measurement. When the device monitors currents near the full-scale output range, the total measurement error approaches the value of the gain error.

### 7.3.2 Low Input Bias Current

The INA191 is different from many current-sense amplifiers because this device offers very low input bias current. The low input bias current of the INA191 has three primary benefits.

The first benefit is the reduction of the current consumed by the device in both the enabled and disabled states. Classical current-sense amplifier topologies typically consume tens of microamps of current at the inputs. For these amplifiers, the input current is the result of the resistor network that sets the gain and additional current to bias the input amplifier. To reduce the bias current to near zero, the INA191 uses a capacitively coupled amplifier on the input stage, followed by a difference amplifier on the output stage.

The second benefit of low bias current is the ability to use input filters to reject high-frequency noise before the signal is amplified. In a traditional current-sense amplifier, the addition of input filters comes at the cost of reduced accuracy. However, as a result of the low bias currents, input filters have little effect on the measurement accuracy of the INA191.

The third benefit of low bias current is the ability to use a larger current-sense resistor. This ability allows the device to accurately monitor currents as low as 1  $\mu\text{A}$ .

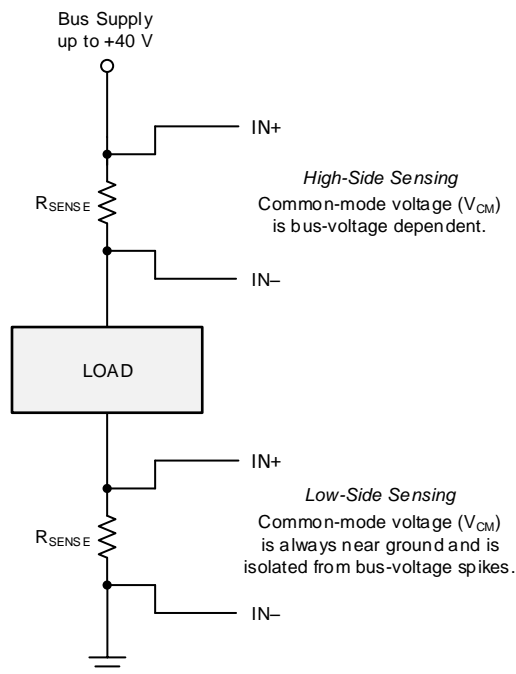
### 7.3.3 Low Quiescent Current With Output Enable

The device features low quiescent current ( $I_Q$ ), while still providing sufficient small-signal bandwidth to be usable in most applications. The quiescent current of the INA191 is only 43  $\mu\text{A}$  (typ), while providing a small-signal bandwidth of 35 kHz in a gain of 100. The low  $I_Q$  and good bandwidth allow the device to be used in many portable electronic systems without excessive drain on the battery. Because many applications only need to periodically monitor current, the INA191 features an enable pin that turns off the device until needed. When in the disabled state, the INA191 typically draws 10 nA of total supply current.

## Feature Description (continued)

### 7.3.4 High-Side and Low-Side Current Sensing

The INA191 supports input common-mode voltages from  $-0.2\text{ V}$  to  $+40\text{ V}$ . Because of the internal topology, the common-mode range is not restricted by the power-supply voltage ( $V_S$ ). The ability to operate with common-mode voltages greater or less than  $V_S$  allows the INA191 to be used in high-side and low-side current-sensing applications, as shown in [Figure 33](#).



**Figure 33. High-Side and Low-Side Sensing Connections**

### 7.3.5 High Common-Mode Rejection

The INA191 uses a capacitively coupled amplifier on the front end. Therefore, dc common-mode voltages are blocked from downstream circuits, resulting in very high common-mode rejection. Typically, the common-mode rejection of the INA191 is approximately 150 dB. The ability to reject changes in the dc common-mode voltage allows the INA191 to monitor both high- and low-voltage rail currents with very little change in the offset voltage.

### 7.3.6 Rail-to-Rail Output Swing

The INA191 supports linear current-sensing operation with the output close to the supply rail and ground. The maximum specified output swing to the positive rail is  $V_S - 40\text{ mV}$ , and the maximum specified output swing to GND is only  $GND + 1\text{ mV}$  with  $-10\text{ mV}$  of differential overdrive. For cases where the sense current is zero, the swing to ground is determined by the zero current output specification. The value of the zero current output voltage can differ from the specified value depending on the common mode voltage, supply voltage, and output load. The close-to-rail output swing maximizes the usable output range, particularly when operating the device from a 1.8-V supply.

## 7.4 Device Functional Modes

### 7.4.1 Normal Operation

The INA191 is in normal operation when the following conditions are met:

- The power-supply voltage ( $V_S$ ) is between 1.7 V and 5.5 V.
- The common-mode voltage ( $V_{CM}$ ) is within the specified range of  $-0.2$  V to  $+40$  V.
- The maximum differential input signal times the gain is less than  $V_S$  minus the output voltage swing to  $V_S$ .
- The ENABLE pin is driven or connected to  $V_S$ .
- The minimum differential input signal times the gain is greater than the swing to GND (see the [Rail-to-Rail Output Swing](#) section).

During normal operation, this device produces an output voltage that is the *amplified* representation of the difference voltage from  $IN+$  to  $IN-$ .

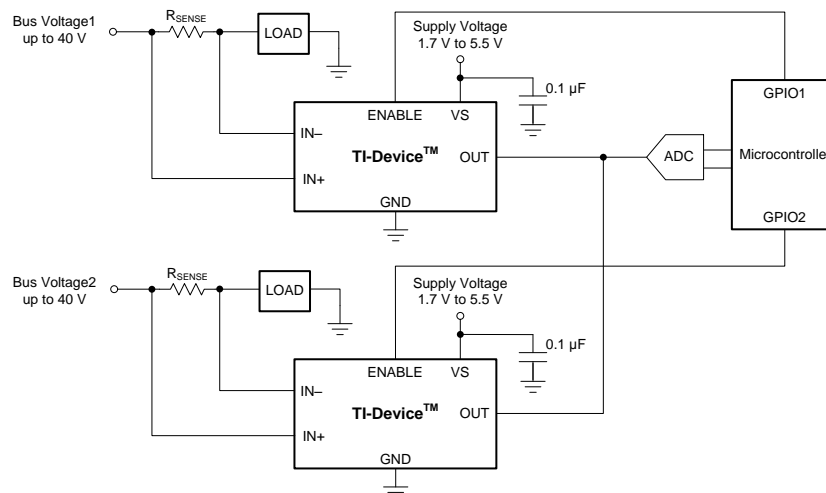
### 7.4.2 Input Differential Overload

If the differential input voltage ( $V_{IN+} - V_{IN-}$ ) times gain exceeds the voltage swing specification, the INA191 drives the output as close as possible to the positive supply or ground, and does not provide accurate measurement of the differential input voltage. If this input overload occurs during normal circuit operation, then reduce the value of the shunt resistor or use a lower-gain version with the chosen sense resistor to avoid this mode of operation. If a differential overload occurs in a fault event, then the output of the INA191 returns to the expected value approximately 40  $\mu$ s after the fault condition is removed. When the differential voltage exceeds approximately 300 mV, the differential input impedance reduces to 3.3 k $\Omega$ , and results in a rapid increase in bias currents as the differential voltage increases. A 3.3-k $\Omega$  resistance exists between  $IN+$  and  $IN-$  during a differential overload condition; therefore, currents flowing into the  $IN+$  pin flow out of the  $IN-$  pin. An increase in bias currents during a input differential overload occurs even with the device is powered down. Input differential overloads less than the absolute maximum voltage rating do not damage the device or result in an output inversion.

### 7.4.3 Shutdown

The INA191 features an active-high ENABLE pin that shuts down the device when pulled to ground. When the device is shut down, the quiescent current is reduced to 10 nA (typ), the input bias currents are further reduced, and the output goes to a high-impedance state. When disabled, the low quiescent and input currents extend the battery lifetime when the current measurement is not needed. When the ENABLE pin is driven to the supply voltage, the device turns back on. When enabled, the typical output settling time is 130  $\mu$ s.

The output of the INA191 goes to a high-impedance state when disabled; therefore, it is possible to connect multiple outputs of the INA191 together to a single ADC or measurement device, as shown in [Figure 34](#). When connected in this way, enable only one INA191 at a time, and make sure both devices have the same supply voltage.



**Figure 34. Multiplexing Multiple Devices With the ENABLE Pin**

## 8 Application and Implementation

### NOTE

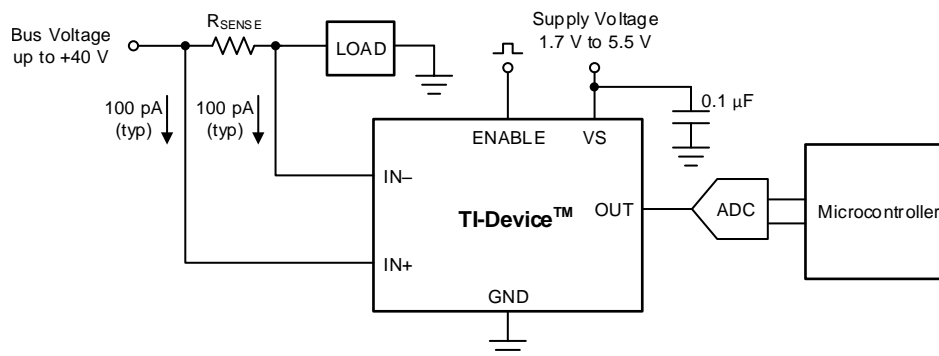
Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes. Customers should validate and test their design implementation to confirm system functionality.

### 8.1 Application Information

The INA191 amplifies the voltage developed across a current-sensing resistor as current flows through the resistor to the load or ground.

#### 8.1.1 Basic Connections

Figure 35 shows the basic connections of the INA191. Connect the input pins (IN+ and IN–) as closely as possible to the shunt resistor to minimize any resistance in series with the shunt resistor. The ENABLE pin must be controlled externally or connected to VS if not used.



**Figure 35. Basic Connections for the INA191**

A power-supply bypass capacitor of at least 0.1  $\mu\text{F}$  is required for proper operation. Applications with noisy or high-impedance power supplies may require additional decoupling capacitors to reject power-supply noise. Connect bypass capacitors close to the device pins.

## Application Information (continued)

### 8.1.2 R<sub>SENSE</sub> and Device Gain Selection

The accuracy of any current-sense amplifier is maximized by choosing the current-sense resistor to be as large as possible. A large sense resistor maximizes the differential input signal for a given amount of current flow and reduces the error contribution of the offset voltage. However, there are practical limits as to how large the current-sense resistor can be in a given application because of the resistor size and maximum allowable power dissipation. [Equation 1](#) gives the maximum value for the current-sense resistor for a given power dissipation budget:

$$R_{\text{SENSE}} < \frac{PD_{\text{MAX}}}{I_{\text{MAX}}^2}$$

where:

- PD<sub>MAX</sub> is the maximum allowable power dissipation in R<sub>SENSE</sub>.
- I<sub>MAX</sub> is the maximum current that flows through R<sub>SENSE</sub>. (1)

An additional limitation on the size of the current-sense resistor and device gain is due to the power-supply voltage, V<sub>S</sub>, and device swing-to-rail limitations. In order to make sure that the current-sense signal is properly passed to the output, both positive and negative output swing limitations must be examined. [Equation 2](#) provides the maximum values of R<sub>SENSE</sub> and GAIN to keep the device from hitting the positive swing limitation.

$$I_{\text{MAX}} \times R_{\text{SENSE}} \times \text{GAIN} < V_{\text{SP}}$$

where:

- I<sub>MAX</sub> is the maximum current that flows through R<sub>SENSE</sub>.
- GAIN is the gain of the current-sense amplifier.
- V<sub>SP</sub> is the positive output swing as specified in the data sheet. (2)

To avoid positive output swing limitations when selecting the value of R<sub>SENSE</sub>, there is always a trade-off between the value of the sense resistor and the gain of the device under consideration. If the sense resistor selected for the maximum power dissipation is too large, then it is possible to select a lower-gain device in order to avoid positive swing limitations.

The zero current output voltage places a limit on how small of a sense resistor can be used in a given application. [Equation 3](#) provides the limit on the minimum size of the sense resistor.

$$I_{\text{MIN}} \times R_{\text{SENSE}} \times \text{GAIN} > V_{\text{ZL}}$$

where:

- I<sub>MIN</sub> is the minimum current flows through R<sub>SENSE</sub>.
- GAIN is the gain of the current-sense amplifier.
- V<sub>ZL</sub> is the zero current output voltage of the device (see the [Rail-to-Rail Output Swing](#) section for more information). (3)

## Application Information (continued)

### 8.1.3 Signal Conditioning

When performing accurate current measurements in noisy environments, the current-sensing signal is often filtered. The INA191 features low input bias currents. Therefore, it is possible to add a differential mode filter to the input without sacrificing the current-sense accuracy. Filtering at the input is advantageous because this action attenuates differential noise before the signal is amplified. Figure 36 provides an example of how to use a filter on the input pins of the device.

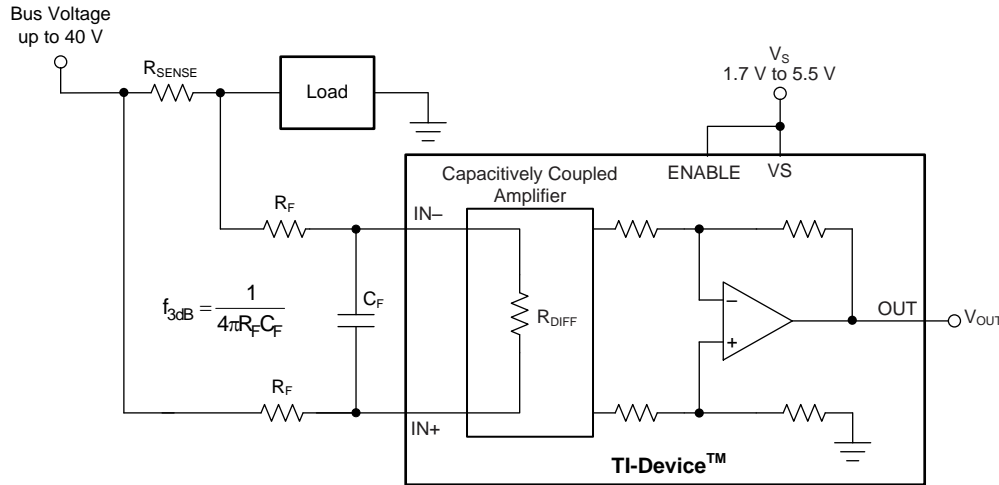


Figure 36. Filter at the Input Pins

The differential input impedance ( $R_{DIFF}$ ) shown in Figure 36 limits the maximum value for  $R_F$ . The value of  $R_{DIFF}$  is a function of the device temperature and gain option, as shown in Figure 37.

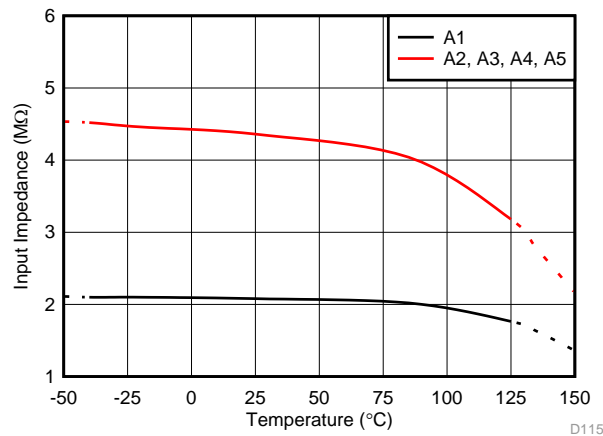


Figure 37. Differential Input Impedance vs Temperature

## Application Information (continued)

As the voltage drop across the sense resistor ( $V_{\text{SENSE}}$ ) increases, the amount of voltage dropped across the input filter resistors ( $R_F$ ) also increases. The increased voltage drop results in additional gain error. The error caused by these resistors is calculated by the resistor divider equation shown in [Equation 4](#).

$$\text{Error(\%)} = \left( 1 - \frac{R_{\text{DIFF}}}{R_{\text{SENSE}} + R_{\text{DIFF}} + (2 \times R_F)} \right) \times 100$$

where:

- $R_{\text{SENSE}}$  is the current sense resistor, as defined in [Equation 1](#).
- $R_{\text{DIFF}}$  is the differential input impedance.
- $R_F$  is the added value of the series filter resistance. (4)

The input stage of the INA191 uses a capacitive feedback amplifier topology in order to achieve high dc precision. As a result, periodic high-frequency shunt voltage (or current) transients of significant amplitude (10 mV or greater) and duration (hundreds of nanoseconds or greater) may be amplified by the INA191, even though the transients are greater than the device bandwidth. Use a differential input filter in these applications to minimize disturbances at the INA191 output.

The high input impedance and low bias current of the INA191 provides flexibility in the input filter design without impacting the accuracy of current measurement. For example, set  $R_F = 100 \, \Omega$  and  $C_F = 22 \, \text{nF}$  to achieve a low-pass filter corner frequency of 36.2 kHz. These filter values significantly attenuate most unwanted high-frequency signals at the input without severely impacting the current-sensing bandwidth or precision. If a lower corner frequency is desired, increase the value of  $C_F$ .

Filtering the input filters out differential noise across the sense resistor. If high-frequency, common-mode noise is a concern, add an RC filter from the OUT pin to ground. The RC filter helps filter out both differential and common mode noise, as well as internally generated noise from the device. The value for the resistance of the RC filter is limited by the impedance of the load. Any current drawn by the load manifests as an external voltage drop from the INA191 OUT pin to the load input. To select the optimal values for the output filter, use [Figure 32](#) and see the [Closed-Loop Analysis of Load-Induced Amplifier Stability Issues Using ZOUT Application Report](#)

## Application Information (continued)

### 8.1.4 Common-Mode Voltage Transients

With a small amount of additional circuitry, the INA191 can be used in circuits subject to transients that exceed the absolute maximum voltage ratings. The most simple way to protect the inputs from negative transients is to add resistors in series to the IN<sup>-</sup> and IN<sup>+</sup> pins. Use resistors that are 1 kΩ or less, and limit the current in the ESD structures to less than 5 mA. For example, using 1-kΩ resistors in series with the INA191 allows voltages as low as -5 V, while limiting the ESD current to less than 5 mA. If protection from high-voltage or more-negative, common-voltage transients is needed, use the circuits shown in Figure 38 and Figure 39. When implementing these circuits, use only Zener diodes or Zener-type transient absorbers (sometimes referred to as *transzorb*s); any other type of transient absorber has an unacceptable time delay. Start by adding a pair of resistors as a working impedance for the Zener diode, as shown in Figure 38. Keep these resistors as small as possible; most often, use around 100 Ω. Larger values can be used with an effect on gain that is discussed in the [Signal Conditioning](#) section. This circuit limits only short-term transients; therefore, many applications are satisfied with a 100-Ω resistor along with conventional Zener diodes of the lowest acceptable power rating. This combination uses the least amount of board space. These diodes can be found in packages as small as SOT-523 or SOD-523.

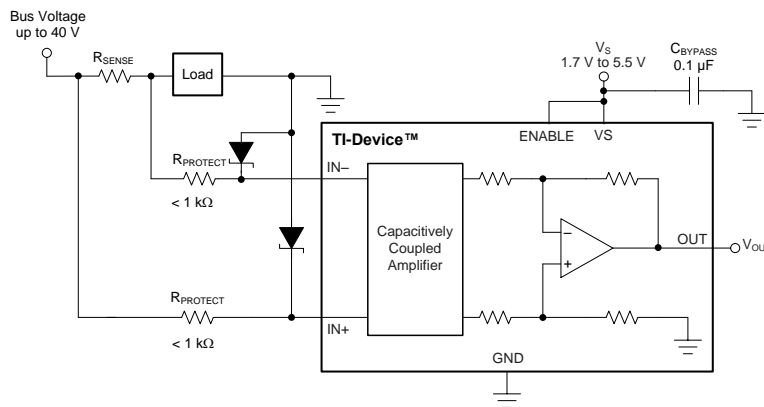


Figure 38. Transient Protection Using Dual Zener Diodes

In the event that low-power Zener diodes do not have sufficient transient absorption capability, a higher-power transzorb must be used. The most package-efficient solution involves using a single transzorb and back-to-back diodes between the device inputs, as shown in Figure 39. The most space-efficient solutions are dual, series-connected diodes in a single SOT-523 or SOD-523 package. In either of the examples shown in Figure 38 and Figure 39, the total board area required by the INA191 with all protective components is less than that of an SO-8 package, and only slightly greater than that of an VSSOP-8 package.

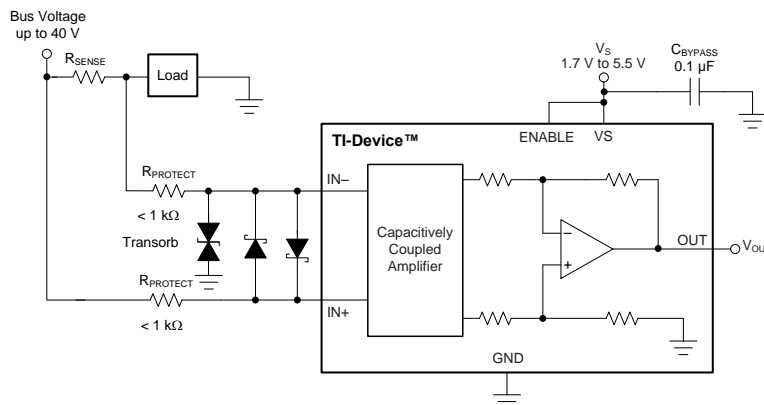


Figure 39. Transient Protection Using a Single Transzorb and Input Clamps

For more information, see [Current Shunt Monitor With Transient Robustness Reference Design](#).

## 8.2 Typical Applications

### 8.2.1 Microamp Current Measurement

The low input bias current of the INA191 provides accurate monitoring of small-value currents. To accurately monitor currents in the microamp range, increase the value of the sense resistor to increase the sense voltage so that the error introduced by the offset voltage is small. The circuit configuration to monitor low-value currents is shown in Figure 40. As a result of the differential input impedance of the INA191, limit the value of  $R_{SENSE}$  to 1 k $\Omega$  or less for best accuracy.

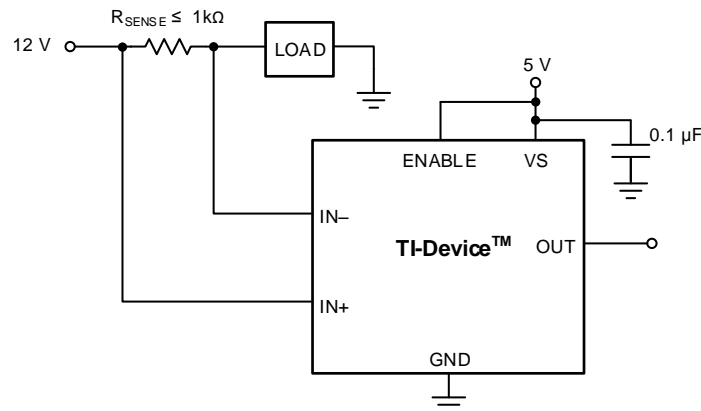


Figure 40. Measuring Microamp Currents

#### 8.2.1.1 Design Requirements

The design requirements for the circuit shown in Figure 40, are listed in Table 1

Table 1. Design Parameters

DESIGN PARAMETER	EXAMPLE VALUE
Power-supply voltage ( $V_S$ )	5 V
Bus supply rail ( $V_{CM}$ )	12 V
Minimum sense current ( $I_{MIN}$ )	1 $\mu$ A
Maximum sense current ( $I_{MAX}$ )	150 $\mu$ A
Device gain (GAIN)	25 V/V

#### 8.2.1.2 Detailed Design Procedure

The maximum value of the current-sense resistor is calculated based choice of gain, value of the maximum current the be sensed ( $I_{MAX}$ ), and the power supply voltage ( $V_S$ ). When operating at the maximum current, the output voltage must not exceed the positive output swing specification,  $V_{SP}$ . Using Equation 5, for the given design parameters the maximum value for  $R_{SENSE}$  is calculated to be 1.321 k $\Omega$ .

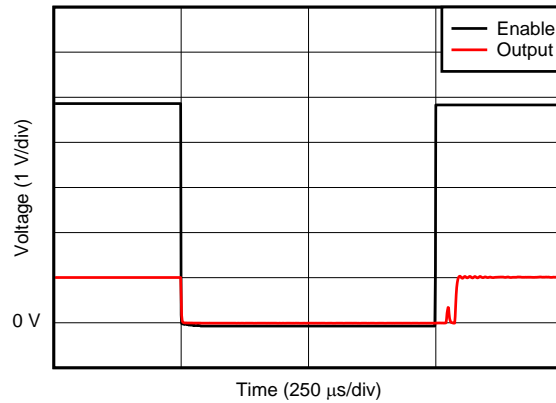
$$R_{SENSE} < \frac{V_{SP}}{I_{MAX} \times GAIN} \quad (5)$$

However, because this value exceeds the maximum recommended value for  $R_{SENSE}$ , a resistance value of 1 k $\Omega$  must be used. When operating at the minimum current value,  $I_{MIN}$  the output voltage must be greater than the swing to GND ( $V_{SN}$ ), specification. For this example, the output voltage at the minimum current is calculated using Equation 6 to be 25 mV, which is greater than the value for  $V_{SN}$ .

$$V_{OUTMIN} = I_{MIN} \times R_{SENSE} \times GAIN \quad (6)$$

**8.2.1.3 Application Curve**

Figure 41 shows the output of the device when disabled and enabled while measuring a 40- $\mu$ A load current. When disabled, the current draw from the device supply and inputs is less than 106 nA.



D030

**Figure 41. Output Disable and Enable Response**

## 9 Power Supply Recommendations

The input circuitry of the INA191 accurately measures beyond the power-supply voltage,  $V_S$ . For example,  $V_S$  can be 5 V, whereas the bus supply voltage at IN+ and IN– can be as high as 40 V. However, the output voltage range of the OUT pin is limited by the voltage on the VS pin. The INA191 also withstands the full differential input signal range up to 40 V at the IN+ and IN– input pins, regardless of whether or not the device has power applied at the VS pin. There is no sequencing requirement for  $V_S$  and  $V_{IN+}$  or  $V_{IN-}$ .

## 10 Layout

### 10.1 Layout Guidelines

- Connect the input pins to the sensing resistor using a Kelvin or 4-wire connection. This connection technique makes sure that only the current-sensing resistor impedance is detected between the input pins. Poor routing of the current-sensing resistor commonly results in additional resistance present between the input pins. Given the very low ohmic value of the current resistor, any additional high-current carrying impedance can cause significant measurement errors.
- Place the power-supply bypass capacitor as close as possible to the device power supply and ground pins. The recommended value of this bypass capacitor is 0.1  $\mu\text{F}$ . To compensate for noisy or high-impedance power supplies, add more decoupling capacitance.
- When routing the connections from the current-sense resistor to the device, keep the trace lengths as short as possible. Place input filter capacitor  $C_F$  as close as possible to the input pins of the device.

### 10.2 Layout Example

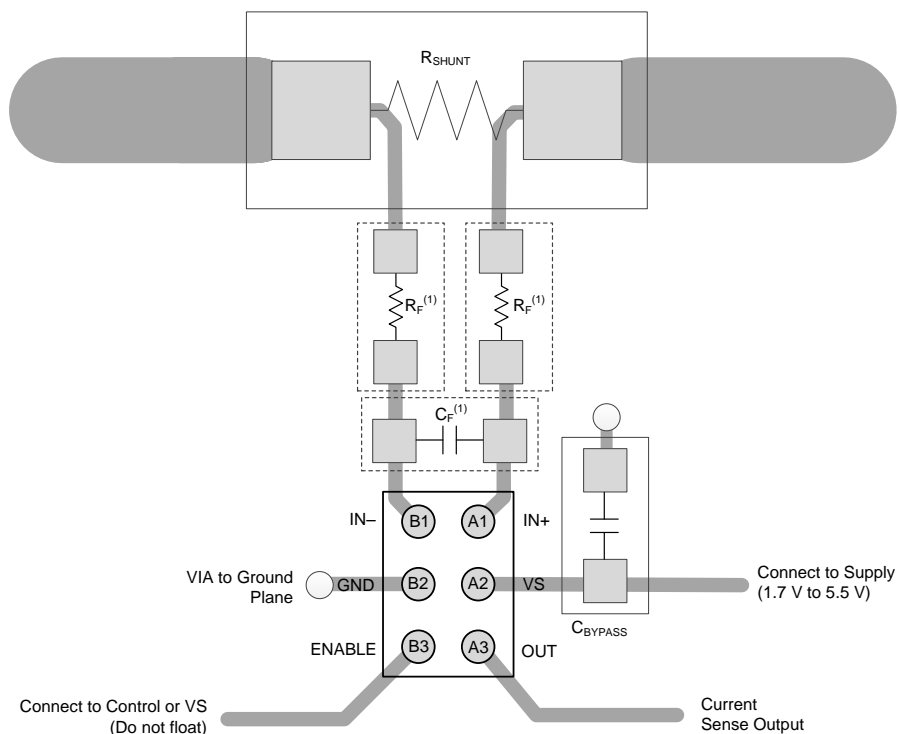


Figure 42. Recommended Layout DSBGA (YFD) Package

## 11 Device and Documentation Support

### 11.1 Documentation Support

#### 11.1.1 Related Documentation

For related documentation see the following:

Texas Instruments, [INA191EVM user's guide](#)

### 11.2 Receiving Notification of Documentation Updates

To receive notification of documentation updates, navigate to the device product folder on ti.com. In the upper right corner, click on *Alert me* to register and receive a weekly digest of any product information that has changed. For change details, review the revision history included in any revised document.

### 11.3 Community Resources

The following links connect to TI community resources. Linked contents are provided "AS IS" by the respective contributors. They do not constitute TI specifications and do not necessarily reflect TI's views; see TI's [Terms of Use](#).

**TI E2E™ Online Community** *TI's Engineer-to-Engineer (E2E) Community*. Created to foster collaboration among engineers. At e2e.ti.com, you can ask questions, share knowledge, explore ideas and help solve problems with fellow engineers.

**Design Support** *TI's Design Support* Quickly find helpful E2E forums along with design support tools and contact information for technical support.

### 11.4 Trademarks

E2E is a trademark of Texas Instruments.

All other trademarks are the property of their respective owners.

### 11.5 Electrostatic Discharge Caution



This integrated circuit can be damaged by ESD. Texas Instruments recommends that all integrated circuits be handled with appropriate precautions. Failure to observe proper handling and installation procedures can cause damage.

ESD damage can range from subtle performance degradation to complete device failure. Precision integrated circuits may be more susceptible to damage because very small parametric changes could cause the device not to meet its published specifications.

### 11.6 Glossary

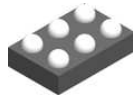
[SLYZ022](#) — *TI Glossary*.

This glossary lists and explains terms, acronyms, and definitions.

## 12 Mechanical, Packaging, and Orderable Information

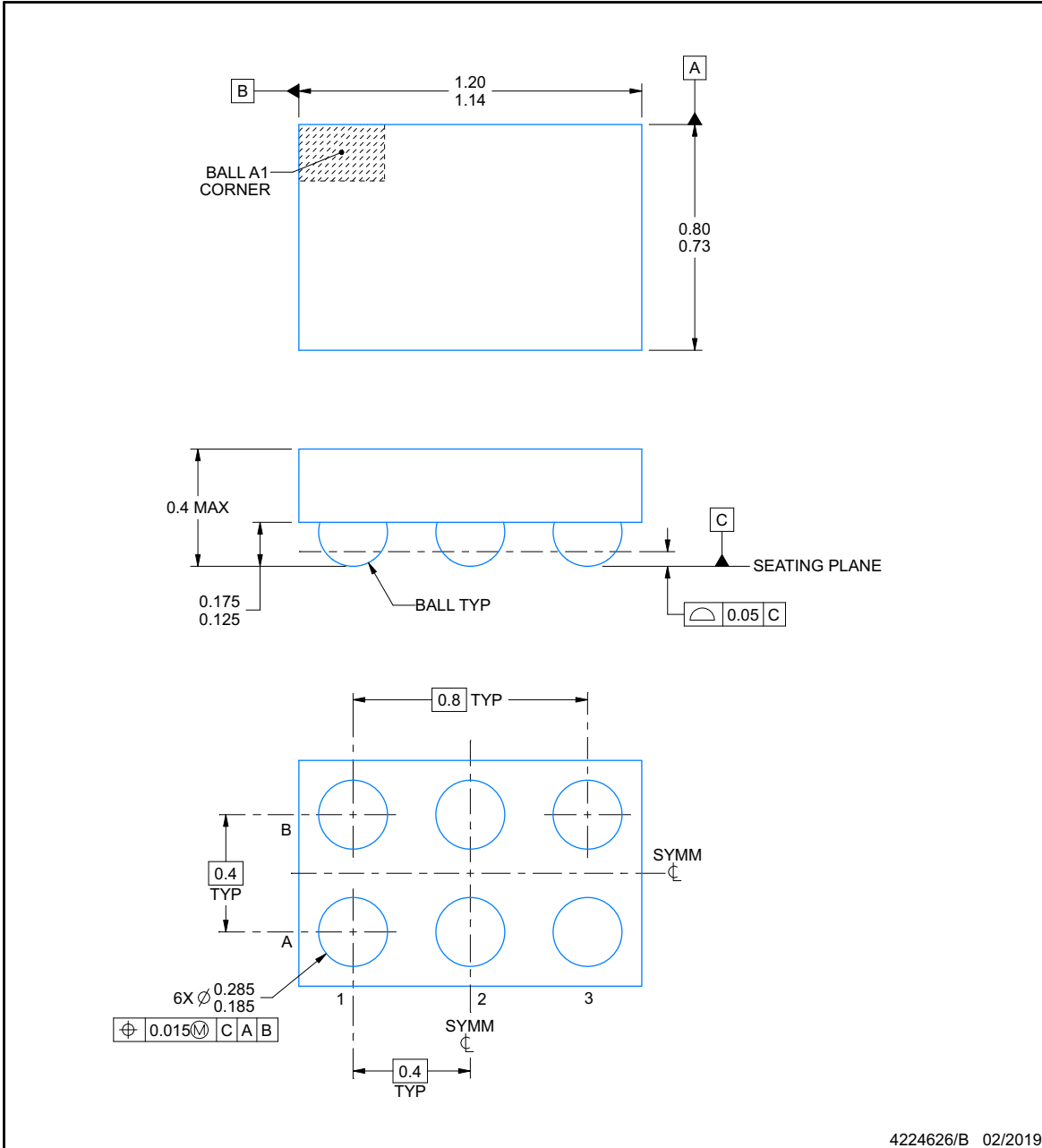
The following pages include mechanical, packaging, and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

**INA191AxIYFD  
YFD0006-C02**



**PACKAGE OUTLINE  
DSBGA - 0.4 mm max height**

DIE SIZE BALL GRID ARRAY



**NOTES:**

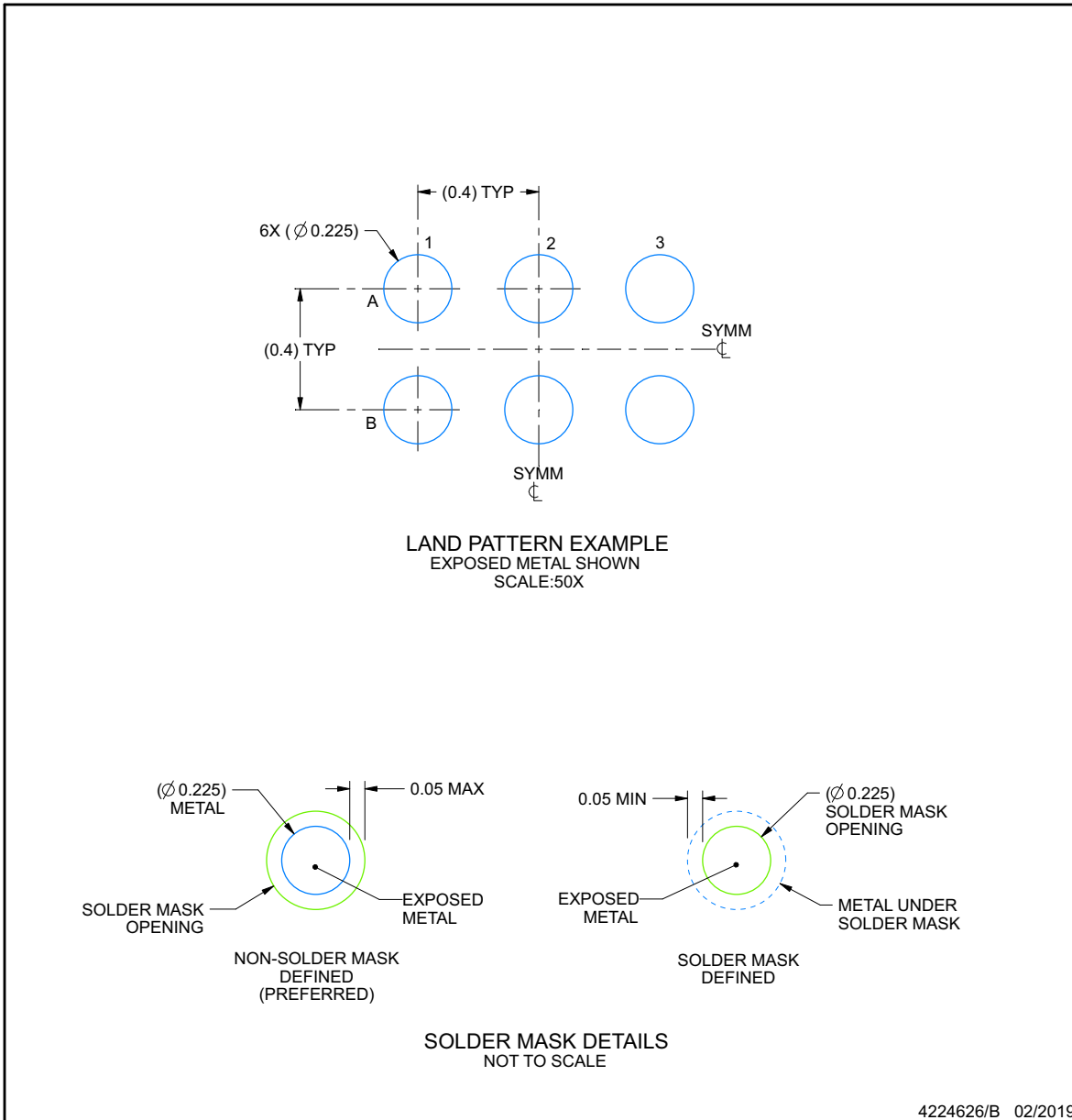
1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.

**INA191AxIYFD  
YFD0006-C02**

**EXAMPLE BOARD LAYOUT**

**DSBGA - 0.4 mm max height**

DIE SIZE BALL GRID ARRAY



NOTES: (continued)

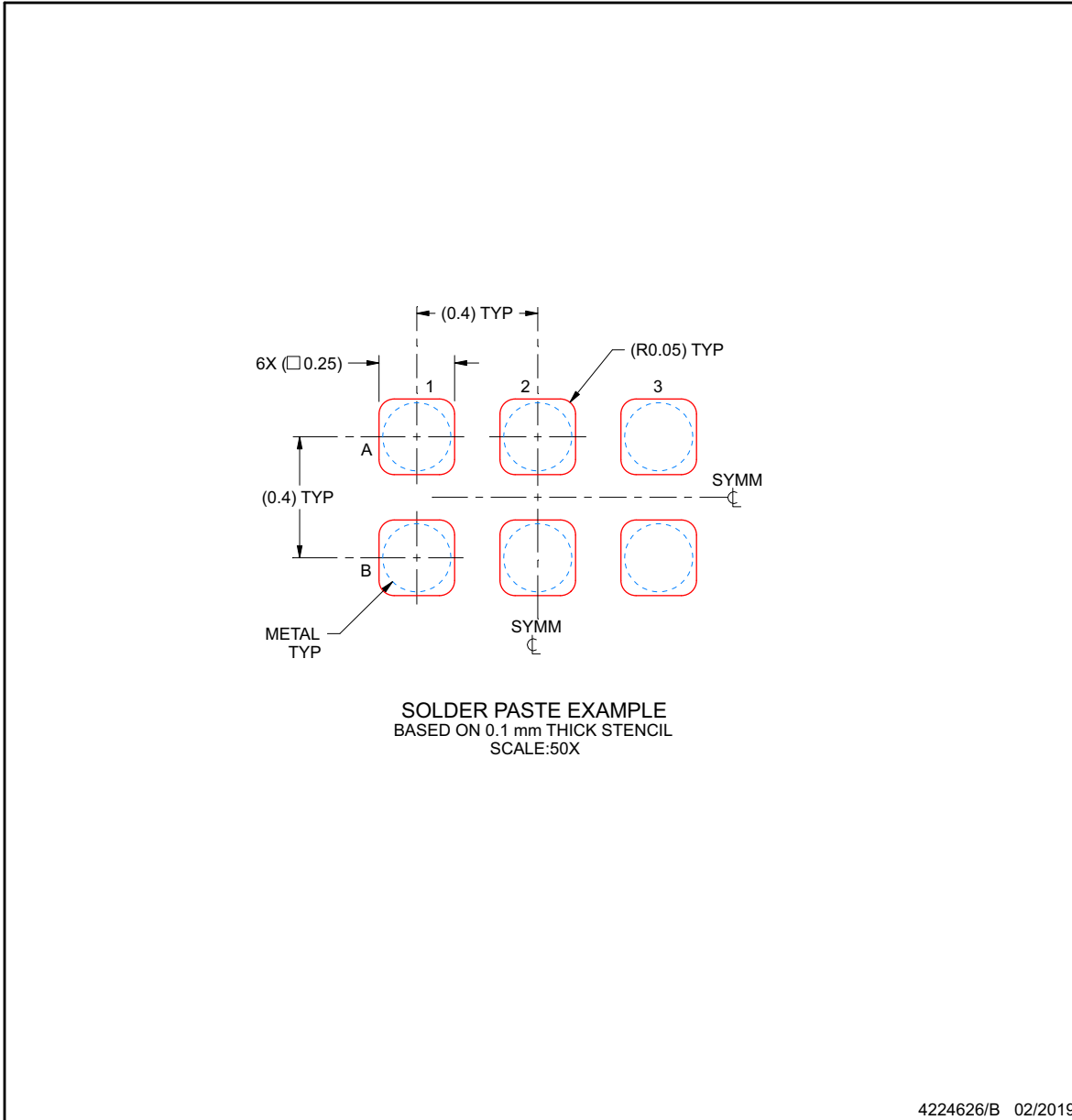
- Final dimensions may vary due to manufacturing tolerance considerations and also routing constraints. Refer to Texas Instruments Literature No. SNVA009 ([www.ti.com/lit/snva009](http://www.ti.com/lit/snva009)).

**INA191AxIYFD  
YFD0006-C02**

**EXAMPLE STENCIL DESIGN**

**DSBGA - 0.4 mm max height**

DIE SIZE BALL GRID ARRAY



NOTES: (continued)

4. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release.

**PACKAGING INFORMATION**

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead/Ball Finish (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
INA191A1IYFDR	ACTIVE	DSBGA	YFD	6	3000	Green (RoHS & no Sb/Br)	SNAGCU	Level-1-260C-UNLIM	-40 to 125	1E3	<a href="#">Samples</a>
INA191A2IYFDR	ACTIVE	DSBGA	YFD	6	3000	Green (RoHS & no Sb/Br)	SNAGCU	Level-1-260C-UNLIM	-40 to 125	1E2	<a href="#">Samples</a>
INA191A3IYFDR	ACTIVE	DSBGA	YFD	6	3000	Green (RoHS & no Sb/Br)	SNAGCU	Level-1-260C-UNLIM	-40 to 125	1E4	<a href="#">Samples</a>
INA191A4IYFDR	ACTIVE	DSBGA	YFD	6	3000	Green (RoHS & no Sb/Br)	SNAGCU	Level-1-260C-UNLIM	-40 to 125	1E5	<a href="#">Samples</a>
INA191A5IYFDR	ACTIVE	DSBGA	YFD	6	3000	Green (RoHS & no Sb/Br)	SNAGCU	Level-1-260C-UNLIM	-40 to 125	1E6	<a href="#">Samples</a>

(1) The marketing status values are defined as follows:

**ACTIVE:** Product device recommended for new designs.

**LIFEBUY:** TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.

**NRND:** Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.

**PREVIEW:** Device has been announced but is not in production. Samples may or may not be available.

**OBSELETE:** TI has discontinued the production of the device.

(2) **RoHS:** TI defines "RoHS" to mean semiconductor products that are compliant with the current EU RoHS requirements for all 10 RoHS substances, including the requirement that RoHS substance do not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, "RoHS" products are suitable for use in specified lead-free processes. TI may reference these types of products as "Pb-Free".

**RoHS Exempt:** TI defines "RoHS Exempt" to mean products that contain lead but are compliant with EU RoHS pursuant to a specific EU RoHS exemption.

**Green:** TI defines "Green" to mean the content of Chlorine (Cl) and Bromine (Br) based flame retardants meet JS709B low halogen requirements of <=1000ppm threshold. Antimony trioxide based flame retardants must also meet the <=1000ppm threshold requirement.

(3) MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

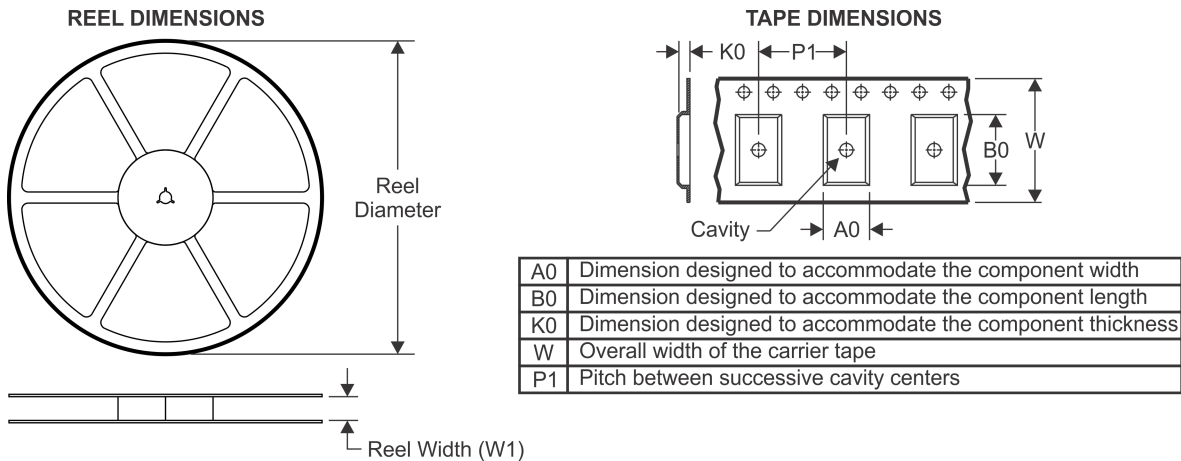
(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "-" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

(6) Lead/Ball Finish - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.

**Important Information and Disclaimer:** The information provided on this page represents TI's knowledge and belief as of the date that it is provided. TI bases its knowledge and belief on information provided by third parties, and makes no representation or warranty as to the accuracy of such information. Efforts are underway to better integrate information from third parties. TI has taken and continues to take reasonable steps to provide representative and accurate information but may not have conducted destructive testing or chemical analysis on incoming materials and chemicals. TI and TI suppliers consider certain information to be proprietary, and thus CAS numbers and other limited information may not be available for release.

In no event shall TI's liability arising out of such information exceed the total purchase price of the TI part(s) at issue in this document sold by TI to Customer on an annual basis.

## TAPE AND REEL INFORMATION



### QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



\*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
INA191A1IYFDR	DSBGA	YFD	6	3000	180.0	8.4	0.86	1.26	0.56	4.0	8.0	Q2
INA191A1IYFDR	DSBGA	YFD	6	3000	178.0	8.4	0.84	1.27	0.46	4.0	8.0	Q2
INA191A2IYFDR	DSBGA	YFD	6	3000	178.0	8.4	0.84	1.27	0.46	4.0	8.0	Q2
INA191A2IYFDR	DSBGA	YFD	6	3000	180.0	8.4	0.86	1.26	0.56	4.0	8.0	Q2
INA191A3IYFDR	DSBGA	YFD	6	3000	180.0	8.4	0.86	1.26	0.56	4.0	8.0	Q2
INA191A3IYFDR	DSBGA	YFD	6	3000	178.0	8.4	0.84	1.27	0.46	4.0	8.0	Q2
INA191A4IYFDR	DSBGA	YFD	6	3000	178.0	8.4	0.84	1.27	0.46	4.0	8.0	Q2
INA191A4IYFDR	DSBGA	YFD	6	3000	180.0	8.4	0.86	1.26	0.56	4.0	8.0	Q2
INA191A5IYFDR	DSBGA	YFD	6	3000	178.0	8.4	0.84	1.27	0.46	4.0	8.0	Q2
INA191A5IYFDR	DSBGA	YFD	6	3000	180.0	8.4	0.86	1.26	0.56	4.0	8.0	Q2

**TAPE AND REEL BOX DIMENSIONS**


\*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
INA191A11YFDR	DSBGA	YFD	6	3000	182.0	182.0	20.0
INA191A11YFDR	DSBGA	YFD	6	3000	220.0	220.0	35.0
INA191A21YFDR	DSBGA	YFD	6	3000	220.0	220.0	35.0
INA191A21YFDR	DSBGA	YFD	6	3000	182.0	182.0	20.0
INA191A31YFDR	DSBGA	YFD	6	3000	182.0	182.0	20.0
INA191A31YFDR	DSBGA	YFD	6	3000	220.0	220.0	35.0
INA191A41YFDR	DSBGA	YFD	6	3000	220.0	220.0	35.0
INA191A41YFDR	DSBGA	YFD	6	3000	182.0	182.0	20.0
INA191A51YFDR	DSBGA	YFD	6	3000	220.0	220.0	35.0
INA191A51YFDR	DSBGA	YFD	6	3000	182.0	182.0	20.0

## IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to TI's Terms of Sale ([www.ti.com/legal/termsofsale.html](http://www.ti.com/legal/termsofsale.html)) or other applicable terms available either on [ti.com](http://ti.com) or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265  
Copyright © 2020, Texas Instruments Incorporated