intan
TECHNOLOGIES, LLC

RHA1016

Fully Integrated 16-Channel Biopotential Amplifier Array

12 September 2006

Features

- Fully integrated 46 dB (200 V/V) amplifier array; no off-chip capacitors required
- Low input-referred noise: 2 μV_{rms}
- Fully differential architecture from input to output for maximum rejection of interference
- Low power operation: 1.7 – 2.6 mW per channel
- On-chip high-speed analog MUX allows many amplifiers to share one A/D converter
- Lower cutoff frequency below 0.05 Hz allows monitoring of very low frequency signals
- True zero gain at DC rejects large electrode offset voltages
- Upper cutoff frequency of all amplifiers set by two external resistors; tunable from 10 Hz to 10 kHz
- 3rd-order Butterworth low-pass filter at upper cutoff frequency for 60 dB/decade roll-off

Applications

- Miniaturized multi-channel headstages for neural or ECoG recording
- Low-power wireless headstages or backpacks for neurophysiology experiments
- "Smart Petri dish" *in vitro* recording systems
- Simultaneous recording of spikes and local field potentials (LFPs) from microelectrodes
- Portable multi-channel EEG or EMG recording systems
- Wearable EKG monitors

Description

The RHA1016 is an integrated, low-power amplifier array from Intan Technologies. This single-chip device contains 16 fully-differential amplifiers with programmable bandwidths suitable for many bioinstrumentation monitoring and recording applications. Proprietary micropower circuit design allows for portable, battery-powered operation without sacrificing the low input-referred noise levels needed for detection of microvolt level signals.

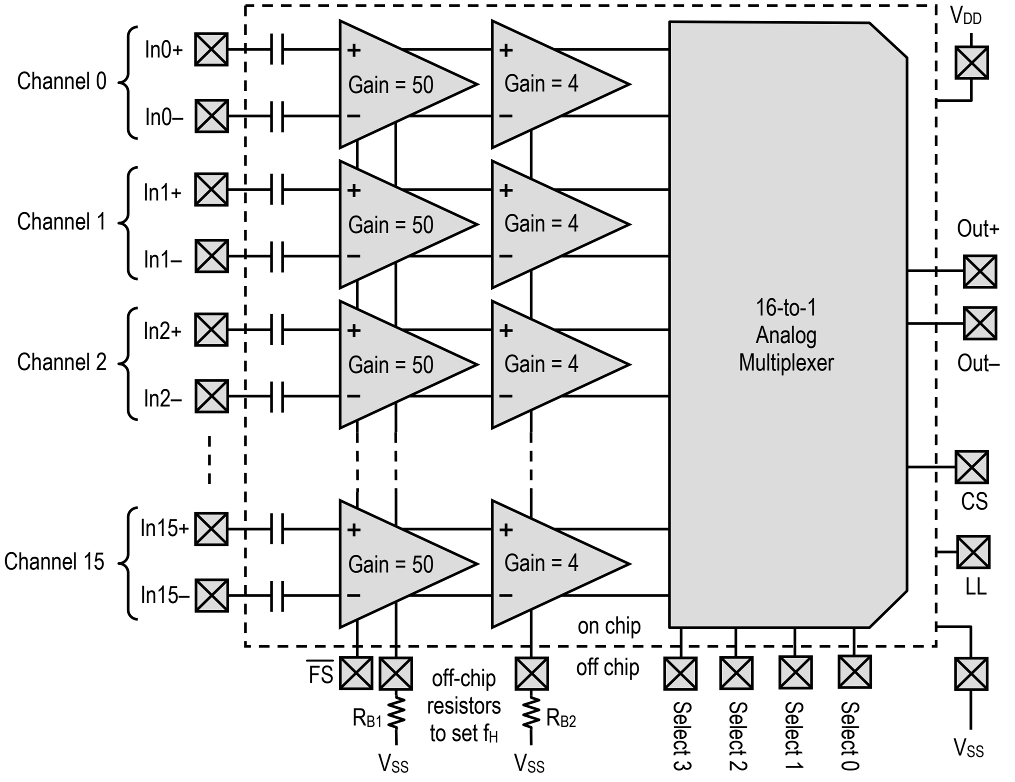
The bandwidths of the amplifiers may be programmed to any value between 10 Hz and 10 kHz by means of two external resistors per chip. This allows a chip to be optimized for different types of biopotential signals (e.g., 100 Hz for EEG or EKG signals, 1 kHz for EMG signals, or 7.5 kHz for neural action potentials). Each amplifier has a 3rd-order Butterworth low-pass filter to reject signals and noise beyond the desired bandwidth and to minimize aliasing.

Internal capacitors completely reject large DC offset voltages at the input pins. This is particularly important for eliminating the effect of built-in potential at electrode-tissue interfaces. The amplifiers are thus AC-coupled with a one-pole high-pass filter below 0.05 Hz. This allows for the monitoring of very low frequency signals such as local field potentials (LFPs) and delta waves.

A low-distortion, high-speed analog multiplexer (MUX) routes a selected amplifier signal off the chip. The MUX permits many amplifiers to share a single A/D converter. The fully-differential output signal is compatible with many modern A/D converters that increasingly use differential signals to reduce interference from external sources. The MUX permits all 16 channels to be sampled at rates as high as 30 kSamples/s per channel.

RHA1016 chips are packaged in standard 48-lead LQFP surface-mount packages (7mm × 7mm × 1.4mm), but are also available as unpackaged die for chip-on-board (COB) assembly. The small footprint and low power consumption of the 16-channel chip enable the miniaturization of front-end electronics for headstages, backpacks, or other wearable or portable biopotential recording systems. This datasheet outlines the measured specifications of the chip.

Simplified Chip Diagram

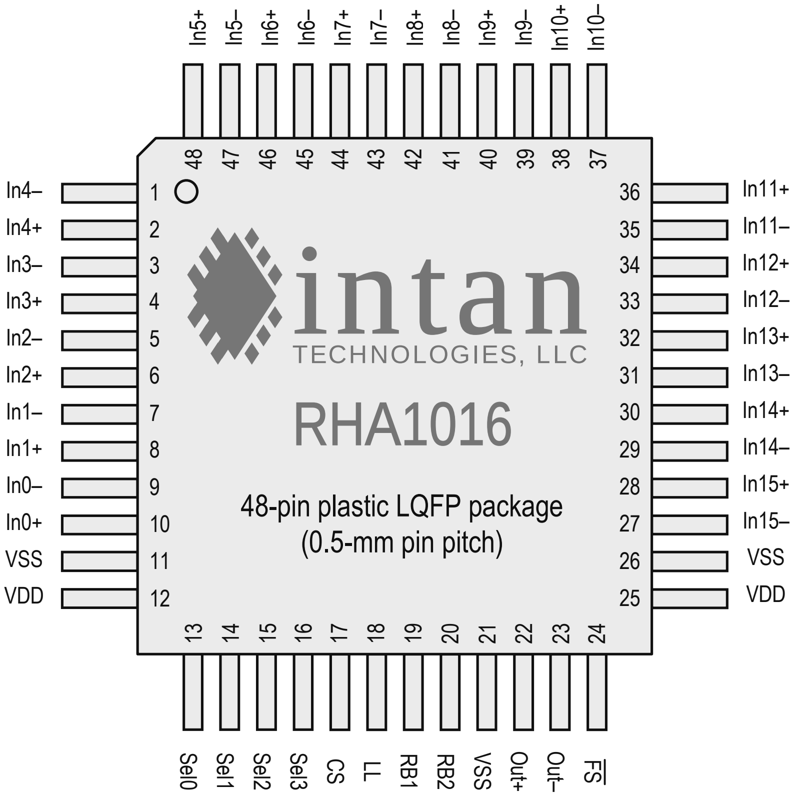


Pin Descriptions

PIN	TYPE	FUNCTION
V_{DD}, V_{SS}	power	Power supply (5 V).
In0+/In0– to In15+/In15–	analog inputs	Differential inputs. (For single-ended inputs, tie In0– to In15– to ground.)
Out+, Out–	analog outputs	Differential output after analog multiplexer.
Select0 – Select3	digital inputs	Channel select for analog multiplexer. Selected amplifier signal appears on output. Select3 is most significant bit (MSB); Select0 is least significant bit (LSB) in 4-bit word.
CS	digital input (active high)	Chip Select. Setting this pin low puts the differential output pins in a high impedance (HI-Z) state. This can be used to allow multiple 16-channel chips to share a single A/D converter by wiring their outputs in parallel. External logic must then be used to ensure that only one chip has CS pulled high at any time. (See Application Notes.)
$\overline{FS}$	digital input (active low)	Fast Settle. Pulsing this pin low resets all amplifiers to baseline levels. This pin can be used for quick recovery from large transient signals.
LL	other	Logic Level select. By default, the chip uses 5V digital logic levels for the Chip Select, Fast Settle, and Select0–Select3 pins. Connecting a resistor to this pin allows the chip to accept 3.3V or 2.5V logic levels. (See text for more details.)
R_{B1}, R_{B2}	other	Connection pins for two off-chips resistors used to set the bandwidth (f_H) of amplifiers.

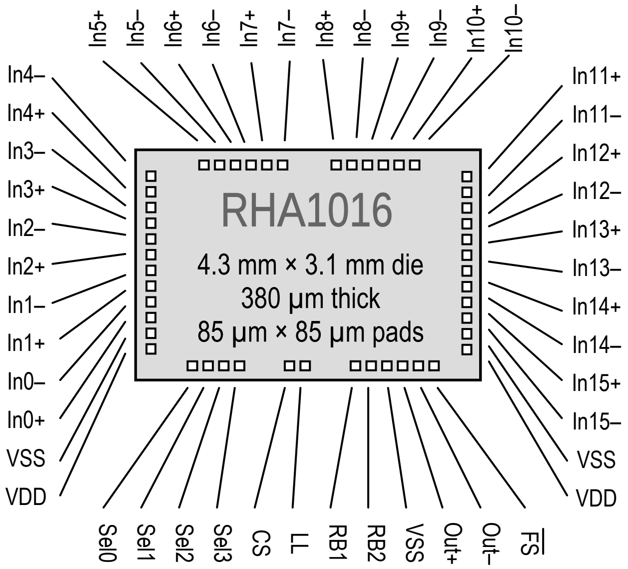
Package Description

48-Lead LQFP (Low-Profile Quad Flat Package)



Unpackaged Silicon Die

Exact pad placement not shown to scale; contact Intan Technologies for precise pad locations.



RHA1016 in packaged and bare die form

Electrical Characteristics

T_A = 25ºC, V_{SUPPLY} = 5V, V_{CM} = 0V unless otherwise noted.

SYMBOL	PARAMETER	CONDITIONS	VALUE	UNITS	COMMENTS
A_D	Differential Gain	In midband region between f_L and f_H	200 46	V/V dB	Linear response for inputs up to ±5 mV in AC amplitude.
A_0	DC Differential Gain		0	V/V	Complete DC rejection, unlike amplifiers that have A_0 = 1 V/V.
f_L	Low-Frequency 3-dB Cutoff Frequency (High-Pass Filter)		< 0.05	Hz	1-pole roll-off below f_L.
f_H	High-Frequency 3-dB Cutoff Frequency (Low-Pass Filter)	Set by two off-chip resistors; tunable from 10 Hz to 10 kHz	10 – 10000	Hz	3-pole 3rd-order Butterworth filter roll-off above f_H.
$\Delta f_H/\Delta T$	Temperature Dependence of High-Frequency 3-dB Cutoff		+0.4	%/°C	
V_{OUT}	Output Voltage Swing		±1.0	V	$V_{OUT} = V_{OUT+} - V_{OUT-}$
$V_{IN\text{-}AC}$	Distortion-Free Differential Input Voltage AC Swing	THD < 1 %	±5	mV	
$V_{IN\text{-}DC}$	Allowable Input Voltage DC Offset		±2.5	V	Advantageous for microelectrode applications.
V_{CM}	Allowable Common Mode Input Voltage Range		±2.5	V	
CMRR	Common Mode Rejection Ratio	f = 50 or 60 Hz f = 1 kHz (f_H = 10 kHz)	84 84	dB dB	Average measured value. CMRR of individual amplifiers varies from 70 dB – 105 dB.
PSRR	Power Supply Rejection Ratio	f = 50 or 60 Hz f = 1 kHz (f_H = 10 kHz)	75 75	dB dB	Average measured value. PSRR of individual amplifiers varies from 65 dB – 95 dB.
	Crosstalk	f = 0.05 Hz to 10 kHz	< -90	dB	Measured between adjacent amplifiers on chip.
V_{OS}	Input Offset Voltage		< ±0.6	mV	
$\Delta V_{OS}/\Delta T$	Temperature Coefficient of Input Offset Voltage		-1.0	μV/°C	
I_B	Input Bias Current	$V_{SS} < V_{IN} < V_{DD}$ $V_{SS} - 2.5\text{ V} < V_{IN} < V_{SS}$	< 50 < 200	pA pA	Typical input bias current is approximately 3 pA.
R_{in}	Input Resistance		10^{12}	Ω	
C_{in}	Input Capacitance		40	pF	
v_{ni}	Input-Referred Noise		2	μV_{rms}	Noise stays nearly constant as f_H varies from 10 Hz to 10 kHz.
THD	Total Harmonic Distortion	f = 1 kHz, f_H = 10 kHz V_{IN} = 2 $mV_{P\text{-}P}$ V_{IN} = 10 $mV_{P\text{-}P}$	0.1 < 1.0	% %	Includes any nonlinearity in MUX.

Electrical Characteristics

$T_A = 25ºC$, $V_{SUPPLY} = 5V$, $V_{CM} = 0V$ unless otherwise noted.

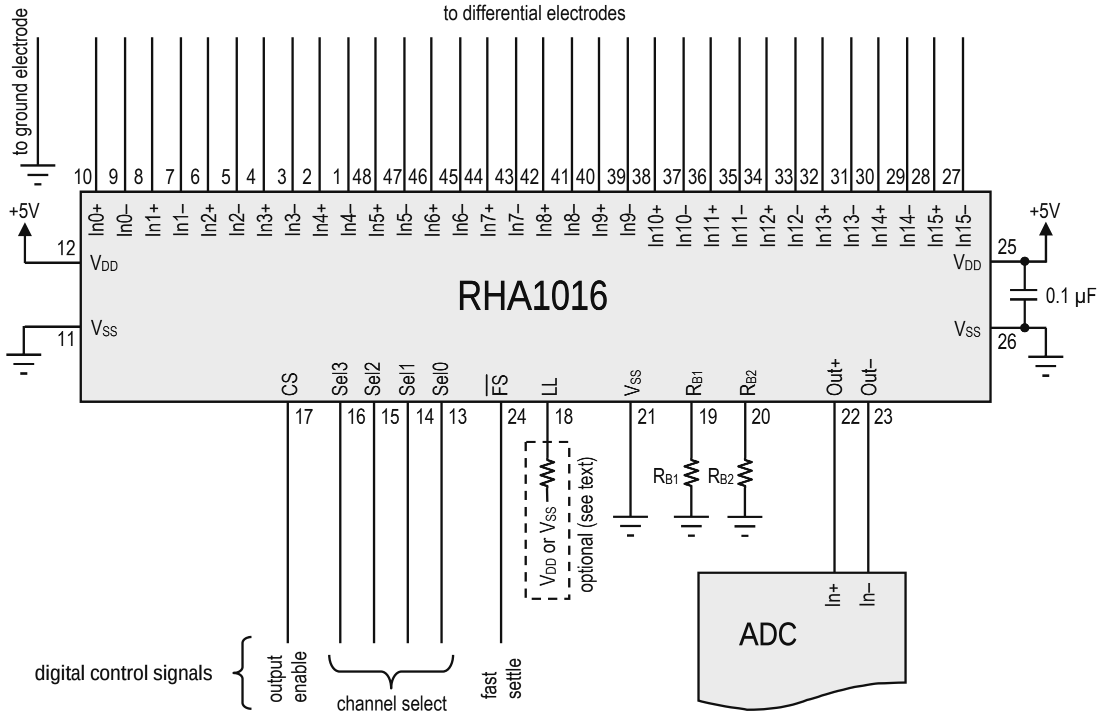
SYMBOL	PARAMETER	CONDITIONS	VALUE	UNITS	COMMENTS
f_{MUX}	Maximum MUX Switching Frequency	$C_L < 200$ pF || $R_L > 100$ kΩ	500	kHz	16 amplifiers can be sampled at >30 kSamples/s each.
t_{settle}	MUX Settling Time	$C_L < 200$ pF || $R_L > 100$ kΩ	< 1.0	μs	
$I_{S\text{-}amp}$	Individual Amplifier Supply Current	$f_H = 10$ kHz $f_H = 1$ kHz $f_H = 100$ Hz $f_H = 10$ Hz	510 350 340 340	μA μA μA μA	Includes MUX
$I_{S\text{-}16}$	16-Amplifier Chip Total Supply Current	$f_H = 10$ kHz $f_H = 1$ kHz $f_H = 100$ Hz $f_H = 10$ Hz	8.2 5.6 5.5 5.5	mA mA mA mA	Includes MUX
$P_{S\text{-}amp}$	Individual Amplifier Power Dissipation	$f_H = 10$ kHz $f_H = 1$ kHz $f_H = 100$ Hz $f_H = 10$ Hz	2.6 1.8 1.7 1.7	mW mW mW mW	Includes MUX
$P_{S\text{-}16}$	16-Amplifier Chip Total Power Dissipation	$f_H = 10$ kHz $f_H = 1$ kHz $f_H = 100$ Hz $f_H = 10$ Hz	41 28 28 28	mW mW mW mW	Includes MUX
	Size of Packaged 16-Amplifier Chip	Including pins Package body only	9.0 × 9.0 7.0 × 7.0	mm^2 mm^2	48-lead plastic LQFP package (1.4 mm thick).
	Die Size of Unpackaged 16-Amplifier Chip		4.3 × 3.1	mm^2	Die is 380 μm thick. Bond pads measure 85 μm × 85 μm.

ESD CAUTION

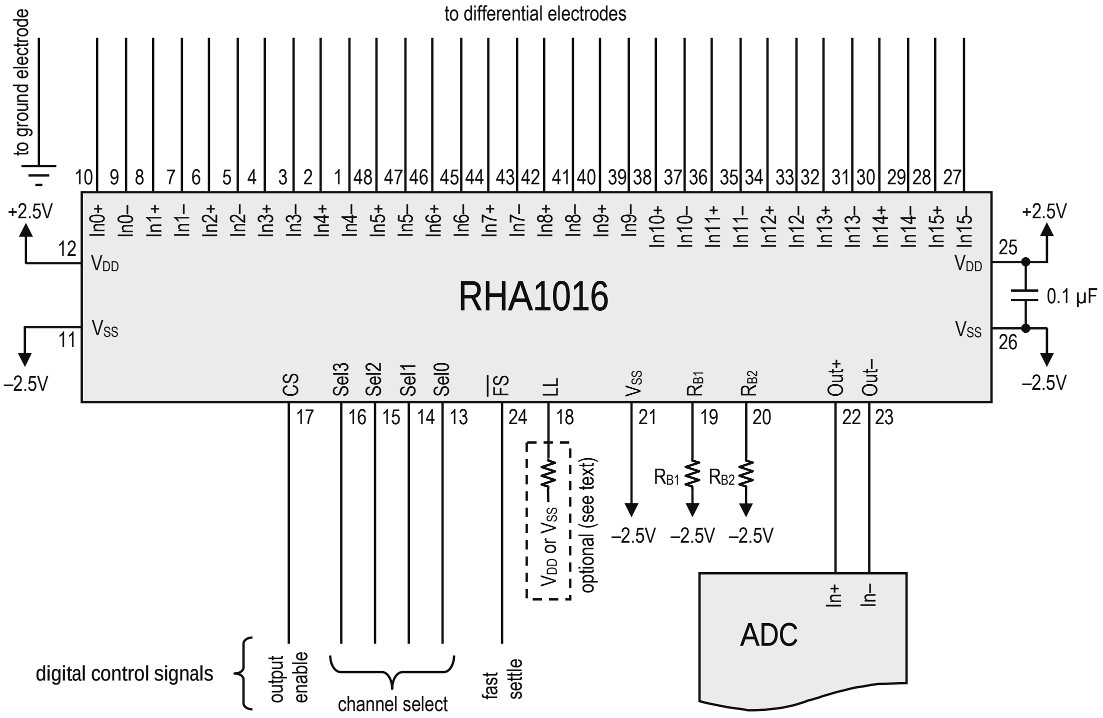
Like all CMOS integrated circuits, the RHA1016 is an ESD (electrostatic discharge) sensitive device. Electrostatic charges of greater than 1000 V can accumulate on the human body and test equipment and can discharge without detection. Although this product features proprietary ESD protection circuitry to protect against mild ESD events, permanent damage may occur on devices subjected to high energy electrostatic discharges. Severe ESD damage can lead to amplifier input bias currents exceeding specified limits. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality. If strong ESD events are possible, external transient voltage suppressors manufactured by a variety of semiconductor companies (e.g., Vishay, Littelfuse, STMicroelectronics) may be used to provide additional protection.

Typical Connection Diagram

SINGLE-POLARITY POWER SUPPLY (GROUND / +5V)



DUAL-POLARITY POWER SUPPLY (-2.5V / GROUND / +2.5V)



Note: If single-ended (non-differential) electrodes are used, tie negative inputs In0– through In15– to ground.

Setting Amplifier Bandwidth

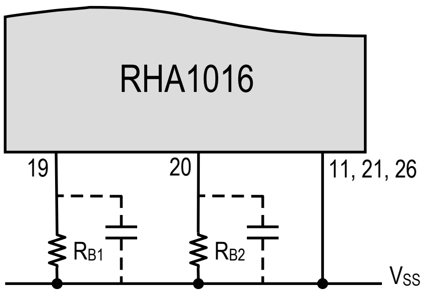
Two off-chip resistors, R_{B1} and R_{B2}, are used to set the bandwidth (f_H) of the amplifiers. The 3rd-order Butterworth low-pass filter characteristic at f_H has a maximally flat pass-band region with -60 dB/decade (-18 dB/octave) of attenuation beyond f_H. The table below lists filter gains for several frequencies above and below f_H.

SIGNAL FREQUENCY	NORMALIZED GAIN V/V	 dB
$0.5 \cdot f_H$	0.99	-0.07 dB
$0.8 \cdot f_H$	0.89	-1.0 dB
f_H	0.707	-3.0 dB
$1.2 \cdot f_H$	0.50	-6.0 dB
$2 \cdot f_H$	0.12	-18 dB
$10 \cdot f_H$	0.001	-60 dB

See the Measured Performance Characteristics section below for a diagram of gain and phase versus signal frequency.

Standard 1% resistor values are given in the table to the right. Resistors with these precise values may be obtained from many electronic component distributors (e.g., Yageo 1/8-W 1% thick film 0805 chip resistors from Digi-Key). Any resistor with a power rating of 10 mW or greater may be used. For bandwidths not listed on this table, interpolate or contact Intan Technologies for recommended resistor values.

Both R_{B1} and R_{B2} should be tied to V_{SS}, as shown below. Care should be taken to minimize parasitic capacitance (such as stray capacitance resulting from long circuit board traces) at the R_{B1} and R_{B2} pins. Capacitance on each of these pins should be kept below 50 pF. (Do *not* add capacitors to these pins; the capacitors in the diagram below represent stray capacitance which should be minimized.) Resistors should be kept close to the RHA1016 on the printed circuit board, particularly when resistor values exceed 1 MΩ.



DESIRED BANDWIDTH f_H	R_{B1}	R_{B2}
10 kHz	11.0 kΩ	46.4 kΩ
9.0 kHz	11.0 kΩ	53.6 kΩ
7.5 kHz	12.7 kΩ	61.9 kΩ
5.0 kHz	18.7 kΩ	80.6 kΩ
4.0 kHz	22.6 kΩ	93.1 kΩ
3.0 kHz	29.4 kΩ	118 kΩ
2.5 kHz	34.8 kΩ	137 kΩ
2.0 kHz	42.2 kΩ	165 kΩ
1.5 kHz	56.2 kΩ	210 kΩ
1.0 kHz	82.5 kΩ	309 kΩ
750 Hz	107 kΩ	402 kΩ
500 Hz	165 kΩ	590 kΩ
400 Hz	205 kΩ	732 kΩ
300 Hz	309 kΩ	976 kΩ
250 Hz	383 kΩ	1.15 MΩ
200 Hz	430 kΩ	1.43 MΩ
150 Hz	634 kΩ	1.91 MΩ
100 Hz	887 kΩ	2.87 MΩ
75 Hz	1.33 MΩ	3.74 MΩ
50 Hz	2.05 MΩ	5.62 MΩ
40 Hz	2.61 MΩ	7.15 MΩ
30 Hz	3.32 MΩ	9.09 MΩ
25 Hz	3.92MΩ	10.0 MΩ
20 Hz	5.49 MΩ	14.02 MΩ [1]
15 Hz	6.49 MΩ	18.06 MΩ [2]
10 Hz	11.43 MΩ [3]	29.09 MΩ [4]

[1] Use a series combination of 10.0 MΩ and 4.02 MΩ.
[2] Use a series combination of 10.0 MΩ and 8.06 MΩ.
[3] Use a series combination of 10.0 MΩ and 1.43 MΩ.
[4] Use a series combination of 2 × 10.0 MΩ and 9.09 MΩ.

Values of R_{B1} and R_{B2} below 11.0 kΩ may cause improper chip operation, and should not be used.

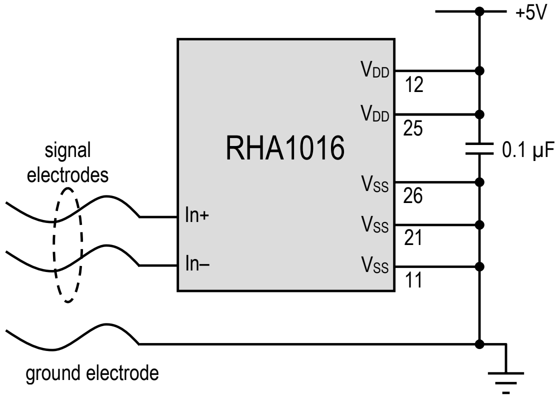
See the Application Notes section below for circuits that can be used to make the amplifier bandwidth digitally programmable.

Supply Voltage Levels

The RHA1016 chip requires a 5V regulated supply for operation. Thus, the positive power supply V_{DD} (pins 12 and 25) should always remain 5V above the negative power supply V_{SS} (pins 11, 21, and 26). A power supply bypass capacitor should be connected between pins 25 and 26, and should be located nearby the chip on the printed circuit board. A ceramic 0.1 μF capacitor is recommended. If the system power supply is particularly noisy, an additional bypass capacitor can be added between pins 11 and 12.

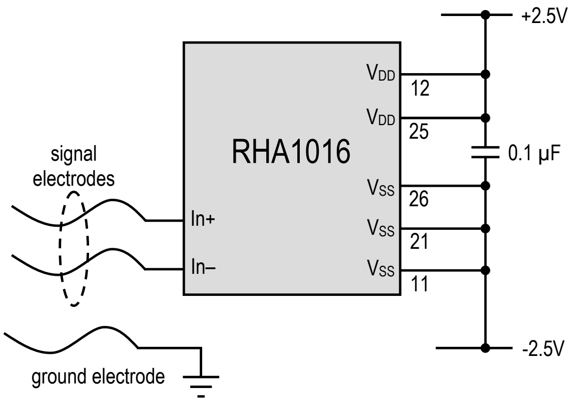
In this discussion, we will define “ground” to be the potential at which the biological tissue is being held. It is assumed that the electrode potentials will be near ground, although positive or negative DC electrode-tissue potentials can be present. The RHA1016 amplifiers have proprietary interface circuitry that allows their input signals to range from as low as 2.5V *below* V_{SS} to as high as V_{DD}. In this input voltage range, currents from the input pins are less than ±200 pA.

This allows the designer to use a single, +5V power supply for the entire system and reference all biopotential signals to V_{SS}, as shown below:



Here, dc offsets on the electrodes can be as high as ±2.5V relative to the ground electrode while maintaining proper amplifier operation. (More precisely, the offsets can range from -2.5V to +5V relative to the ground electrode.)

Alternatively, the chip can be powered from a dual-polarity ±2.5V power supply with ground located halfway between V_{SS} and V_{DD}, as shown below:



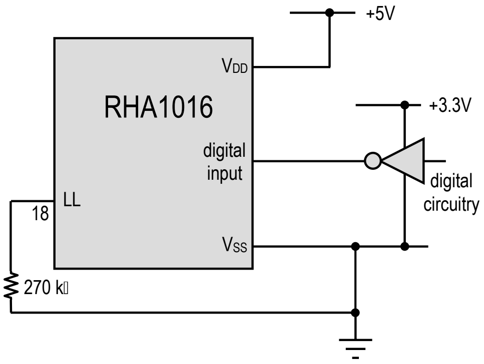
Here, dc offsets on the electrodes can range from -5V to +2.5V relative to ground (i.e., -2.5V to +5V relative to V_{SS}).

Control Voltage Levels

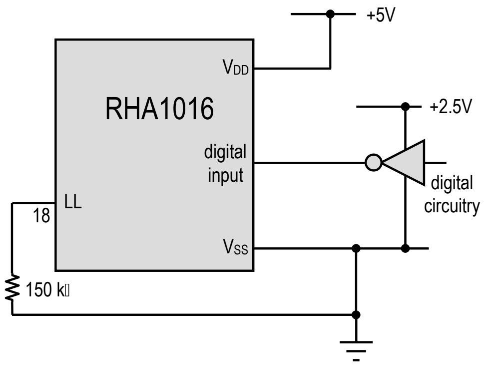
The RHA1016 has six digital input pins: Select0–Select3 control which amplifier signal appears at the output pins, CS can set the output pins to a high impedance state, and FS performs a fast settle on the amplifiers. These five pins can be interfaced to digital circuitry operating with voltage levels other than 5V. The LL pin (pin 18) can be used to set the threshold voltage that the RHA1016 uses to discriminate a logic high from a logic low.

If LL is left unconnected, the internal logic threshold is 2.5V above V_{SS}. This is the proper level for 5V logic signals that vary between V_{DD} (logic high) and V_{SS} (logic low).

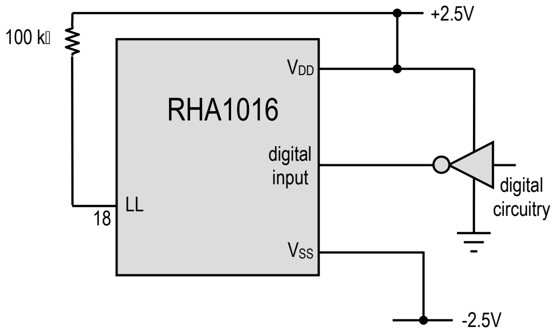
If 3.3V logic signals are used to control the RHA1016, the LL pin should be tied to V_{SS} with a 270 kΩ resistor, as shown below. This sets the internal logic threshold to 1.65V above V_{SS}.



There are two ways in which 2.5V logic signals can be connected to the RHA1016. First, the 2.5V logic signals could swing from V_{SS} (logic low) to V_{SS}+2.5V (logic high), as shown below. In this case, the LL pin should be tied to V_{SS} with a 150 kΩ resistor. This sets the internal logic threshold to 1.25V above V_{SS}.



Alternatively, the 2.5V logic signals could swing from V_{DD} (logic high) to V_{DD}-2.5V (logic low), as shown below. In this case, the LL pin should be tied to V_{DD} with a 100 kΩ resistor. This sets the internal logic threshold to 1.25V below V_{DD}.



The internal logic threshold can be measured on the LL pin with a standard voltmeter.

The digital inputs of RHA1016 should always be driven either high or low. An input pin left unconnected can drift or oscillate unpredictably.

Fast Settle Function

Due to the long time constant associated with the low cutoff frequency f_L, it may be useful to reset the amplifiers if a large input causes the output signals to saturate. The fast settle pin (FS) is an active-low digital input that should be held high in normal operation. To settle the amplifiers, FS should be pulled low for one second. It is recommended (though not required) to hold FS low for one second after powering up the chip as well.

Output Signals

The voltages on output pins Out+ and Out– (pins 22 and 23) maintain DC levels approximately halfway between V_{SS} and V_{DD} (i.e., approximately 2.5V above V_{SS}). To take advantage of the fully-differential design of the RHA1016 amplifiers, the output should be taken as the voltage difference between Out+ and Out–. (For quick testing, a single-ended output can be observed, but this reduces the effective gain from 200 V/V to 100 V/V.)

In most applications, Out+ and Out– will be connected to an analog-to-digital converter (ADC) with a fully-differential input. (See for example the Analog Devices AD7679 18-bit, 570 kSamples/s SAR ADC and other devices in the AD76XX series.) The designer must ensure that the total capacitive loading C_L on each output pin does not exceed 200 pF and that any load resistance R_L is no smaller than 100 kΩ. Larger capacitive loads will impair the ability of the analog MUX to switch at the fastest specified speed.

When testing the RHA1016, it is important to remember that standard coaxial cable has a capacitance of approximately 100 pF/meter, so care must be taken to minimize the length of high-capacitance shielded cables connected to the output.

In some applications, it may be desirable to convey the analog output signal of the RHA1016 some distance over ribbon cable or a twisted pair of wires. Ribbon cable typically has an inter-wire capacitance of 30 – 50 pF/meter; twisted pair capacitance can range from 60 – 80 pF/meter. This differential capacitance has twice the effect of capacitance to ground (or other fixed potentials) and thus should be limited to 100 pF if the analog MUX is to be used at the fastest allowable rates.

When the MUX select inputs Select0–Select3 change, the output voltage will change to reflect the signal from the newly selected amplifier. The output voltage takes a maximum of 1.0 µs to settle to a new value. Thus, if an ADC is used to sample the RHA1016 output signal, a conversion should not be engaged until at least 1.0 µs *after* Select0–Select3 are updated.

If we budget 1.0 µs for the MUX to settle and another 1.0 µs to wait while the ADC samples the RHA1016 output voltage and initiates a conversion, then we can sample at the rate of 500 kSamples/s. This would allow us to sample each of the 16 amplifiers on the RHA1016 chip at a rate of over 30 kSamples/s.

Under normal operation, the CS (chip select) pin should be held high. If CS is held low, the output pins assume a high-impedance state. This allows multiple RHA1016 chips to share a single ADC. See the Application Notes section for an example of this technique.

Measured Performance Characteristics

Figure 1. Normalized gain vs. frequency for f_H = 1 kHz.

Figure 2. Phase lag vs. frequency for f_H = 1 kHz.

Figure 3. Typical input-referred noise for f_H = 10 kHz.

Figure 4. Typical input-referred noise for f_H = 1 kHz.

Figure 5. Typical input-referred noise for f_H = 100 Hz.

Figure 6. Typical input-referred noise for f_H = 10 Hz.

Measured Performance Characteristics

Figure 7. Input-referred noise spectra for f_H = 10 Hz (dot), f_H = 100 Hz (dash-dot), f_H = 1 kHz (dash), and f_H = 10 kHz (solid).

Figure 8. Output MUX switching with load of 100 pF || 10 MΩ on each output pin. Select0 toggles at t = 0 and t = 2 µs.

Figure 9. ECG signal recorded with Ag/AgCl electrodes on chest (f_H = 100 Hz).

Figure 10. EMG signal recorded with Ag/AgCl electrodes over bicep during two brief muscle contractions (f_H = 1 kHz).

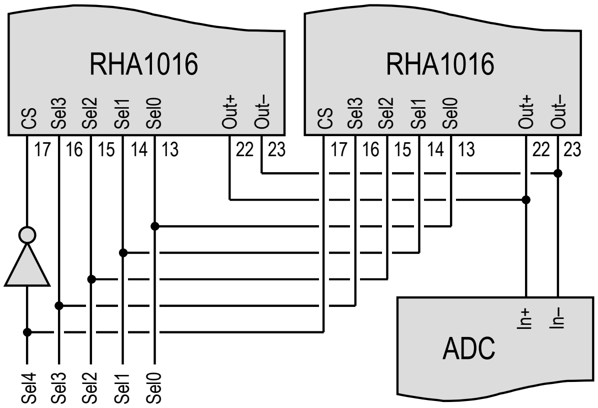
Figure 11. EEG signal recorded from occipital region O_1-O_2 (f_H = 50 Hz). Subject's eyes were closed initially, then opened at t = 0, suppressing the 10-Hz alpha waves.

Figure 12. EEG signal recorded from frontal region F_{p1}-F_3 on the forehead (f_H = 50 Hz). Two eye-blink artifacts (commonly observed in this region of the head) are visible.

Application Notes

MULTIPLE AMPLIFIER CHIPS SHARING ONE ADC

Multiple RHA1016 chips can be connected in parallel to create recording systems with 32 or more channels that use only one analog-to-digital converter (ADC). The output pins of multiple chips can be connected in parallel (as shown below) as long as only one of the chips has its Chip Select (CS) signal asserted. The other chips should have CS driven low to keep their outputs in a high-impedance state so that only one chip drives the shared output pins at a time.



In the example shown above, an inverter is added to create a 5-bit address bus to select between one of 32 amplifiers across two RHA1016 chips. Slightly more complex logic could be used to create a 4-chip, 64-channel recording system with a 6-bit address bus used to select amplifiers.

Ultimately, the finite MUX settling time will limit the number of amplifier chips that can be tied in parallel and sampled with a shared ADC. Note that the resistors tied to R_{B1} and R_{B2} (and possibly LL) *cannot* be shared between multiple RHA1016 chips, and must be replicated for each chip.

WIRELESS RECORDING SYSTEMS

The RHA1016 makes an ideal front-end amplifier for wireless recording systems where size, weight, and power must be minimized. Modern wireless chipsets like Texas Instruments' Chipcon series achieve high data transmission rates at low levels of power dissipation. For example, The CC1150 transmitter chip is capable of sending digital data at 500 kbps and draws only 13.7 mA at -10 dBm transmit power. This chip can be configured to transmit on one of three different frequency bands: 315 MHz, 433 MHz, or 868/915 MHz. The CC2550 transmitter chip draws 12.8 mA at -12 dBm transmit power while transmitting 500 kbps using a 2.4 GHz carrier frequency. The CC2400 achieves data rates of 1 Mbps while drawing 11 mA at -25 dBm transmit power at 2.4 GHz.

These chips come in packages no larger than the RHA1016 and require only a few off-chip surface-mount components for operation.

ADDING A DIGITAL HIGH-PASS FILTER

The RHA1016 has a very low frequency high-pass filter (below 0.05 Hz) which blocks DC offsets but may pass undesirable signals in some recording applications. For example, in extracellular neural recording, it may be desirable to filter out all signals below 300 Hz to isolate action potentials ("spikes") and block local-field potential (LFP) waveforms. In ECG applications, respiration may generate unwanted very-low-frequency signals.

In these cases it is necessary to apply a digital high-pass filter to the digitized waveform recorded from each amplifier. A single-pole high-pass filter is easy to implement in software and requires little computational power.

The pseudo-code to implement a single-pole high-pass filter is shown below:

```
float sample, state, waveform;

state = 0.0;
do {
  sample = read_voltage_from_ADC();
  state = B*sample + A*state;
  waveform = sample – state;
}
```

Here, the variable `sample` is used to store the current ADC conversion, and `state` is the state variable of the filter. The output of the filter is `waveform`, which is updated to a new value with each pass through the infinite loop.

To design this high-pass filter for a particular cutoff frequency f_L', the constants `A` and `B` must be set using the following equations:

$$A = \exp(-2\pi f_L' / f_{sample})$$

$$B = 1 - A$$

where f_{sample} is the ADC sampling rate for each channel and exp(x) is the exponential function e^x. For example, if we are sampling each amplifier channel at 7.5 kSamples/s and we wish to implement a 300-Hz high-pass filter, we should use $A = \exp(-2\pi \times 300 / 7500) = 0.7778$ and $B = 0.2222$.

To illustrate this simple but effective algorithm, we apply it to the following EEG signals recorded from the occipital region (O_1-O_2) with the RHA1016 (with f_H set to 50 Hz):

This signal represents the variable `sample` in the high-pass filter algorithm. Here we see prominent 10-Hz alpha wave activity until the subject opens his eyes at t = 2.3 s. However, there is also a large, undesired low-frequency signal present. To isolate the alpha wave activity, we apply the digital single-pole high-pass filter at $f_L' = 4$ Hz. Plotting the variable `waveform`, we get:

Now the alpha wave activity (and suppression after the subject opens his eyes) are much easier to see.

If the information *below* f_L' is of interest, it is easily extracted from the algorithm with no extra computation. The variable `state` represents the input signal passed through a single-pole *low-pass* filter at the same cutoff frequency. Plotting the variable `state` from the previous EEG example, we see the components of the signals that are *below* 4 Hz:

This allows the amplifier signal to be separated easily into two frequency bands: one above f_L', and one below f_L'. For example, in neural recording applications one could isolate spikes above 300 Hz and local field potentials (LFPs) below 300 Hz.

Technical side note for programmers

Note that if we select our lower cutoff frequency such that $f_L' = f_{sample} / 21.84$ (e.g., f_{sample} = 7.5 kSamples/s and f_L' = 343 Hz) then we get A = 0.75 = 3/4 and B = 0.25 = 1/4. Using these values of A and B, the high-pass filter can be implemented without using floating point arithmetic, and instead using bit shifts to multiply by 0.5 (one right shift) and 0.25 (two right shifts). In this way, the multiplications in the middle line of the loop presented above can be simplified to:

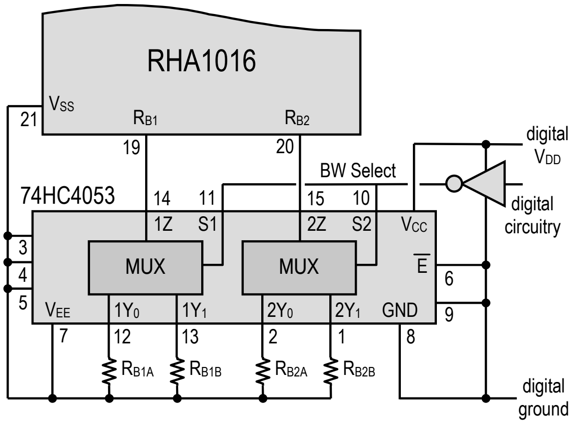
```
state =
     sample>>2 + (state>>1 + state>>2);
```

where `>>n` indicates a bit shift to the right by `n` bits. Thus, the digital high-pass filter can be implemented on a simple microcontroller using only integer operations. It is recommended that extra bits be used to preserve the right-shifted bits and prevent errors due to “rounding.” For example, if a 12-bit ADC is used to sample the signal, the variables should maintain at least 14 bits of internal precision.

Other potentially useful values of f_L' are $f_L' = f_{sample} / 9.06$ (which gives A = B = 0.5 = 1/2), and $f_L' = f_{sample} / 47.05$ (which gives A = 0.875 = 7/8 and B = 0.125 = 1/8).

PROGRAMMABLE AMPLIFIER BANDWIDTH

The bandwidth of the RHA1016 amplifiers may be made digitally controllable by using standard, inexpensive analog multiplexer (MUX) integrated circuits such as the 74HC4051 (an 8-to-1 analog MUX), the 74HC4052 (a dual 4-to-1 analog MUX), or the 74HC4053 (a triple 2-to-1 analog MUX). These ICs are compatible with 2.5V, 3.3V, or 5V power and logic levels. An example using a 74HC4053 to select between two different amplifier bandwidths is shown below.



Two of the three 2-to-1 multiplexers in the 74HC4053 are used to select either resistors R_{B1A} and R_{B2A} (when the digital signal BW Select is low) or resistors R_{B1B} and R_{B2B} (when BW Select is high) to set the bandwidth of the RAH1016 amplifiers.

If more than two bandwidth settings are desired, a 74HC4052 can be used to select between four different resistor pairs, or two 74HC4051 chips can be used to select between eight different resistor pairs.

For finer bandwidth control, “digital potentiometer” ICs could be used for R_{B1} and R_{B2}. However, care should be taken to ensure that the parasitic capacitance on pins 19 and 20 does not exceed 50 pF, or amplifier oscillations may occur. Consult the datasheets of potential digital potentiometer ICs for capacitance specifications.

The voltage on pins 19 and 20 never exceeds V_{SS} + 0.3V, so it would also be possible to use two MOSFETs or JFETs as variable resistors in place of R_{B1} and R_{B2}. The drain should be tied to pin 19 or 20, the source to V_{SS}, and the gate voltage used to vary the effective resistance. The exact resistance would depend on the threshold voltage and other device parameters of the FET, which may not be well controlled.

DESIGN PHILOSOPHY

The design philosophy embodied in the RHA1016 can be summarized as follows:

- DC offsets on electrodes convey no information and can saturate high-gain amplifiers, so they should be completely blocked.
- Signals above the desired amplifier bandwidth f_H cause aliasing during sampling, so they should be blocked effectively (e.g., with a 3rd-order Butterworth low-pass filter).
- Signals below the desired low-frequency cutoff f_L can be eliminated after sampling using a simple digital filter. Modern ADCs permit rapid sampling at high resolution (16 bits or more), so high frequency information is not lost. Indeed, in many applications this low-frequency information may be useful (e.g., LFPs in neural recording).
- In worst-case situations where large ac signals saturate the amplifier, a “fast settle” option should be provided since the time constant of the amplifier may be long.

Recommended Test Equipment

It can be challenging to characterize low-noise amplifiers accurately. For example, the input-referred noise of the RHA1016 is 2 μV_{rms}. After being amplified by a gain of 200, the differential output signal will have a noise level of 400 μV_{rms} if no other noise sources are present (i.e., the inputs to the amplifiers are tied to ground through a low-resistance connection). However, even high-quality oscilloscopes have baseline RMS noise levels in the hundreds of microvolts, and using a low-capacitance 10x probe can raise this noise level to 3 mV_{rms} or more. Therefore, when quantifying low noise levels it is necessary to use additional amplification on the test bench.

Below, we show a configuration of equipment used at Intan Technologies to test integrated amplifiers. A good low-noise preamplifier is essential for boosting the noise on the amplifier output to levels well above the inherent input noise levels of the oscilloscope and spectrum analyzer. The Stanford Research Systems SR560 is an excellent preamplifier for this task, and it conveniently has a differential input. If no commercial amplifier is available, an instrumentation amplifier may be constructed out of low-noise JFET operational amplifiers such as the TL084.

For careful characterization of the amplifier noise and transfer function, there is no substitute for a good spectrum analyzer. RF spectrum analyzers are often not useable at low frequencies, so we use a Stanford Research Systems SR770 FFT Network Analyzer, which works from the μHz range up to 100 kHz. The SR780 Dual Channel Dynamic Signal Analyzer also works well for this task, and there are many PC-based spectrum analyzers available that cover this frequency range. Spectrum analyzers can be used to measure the noise spectrum; integrating under this curve and dividing by the total gain is the most accurate way to measure input-referred RMS noise.

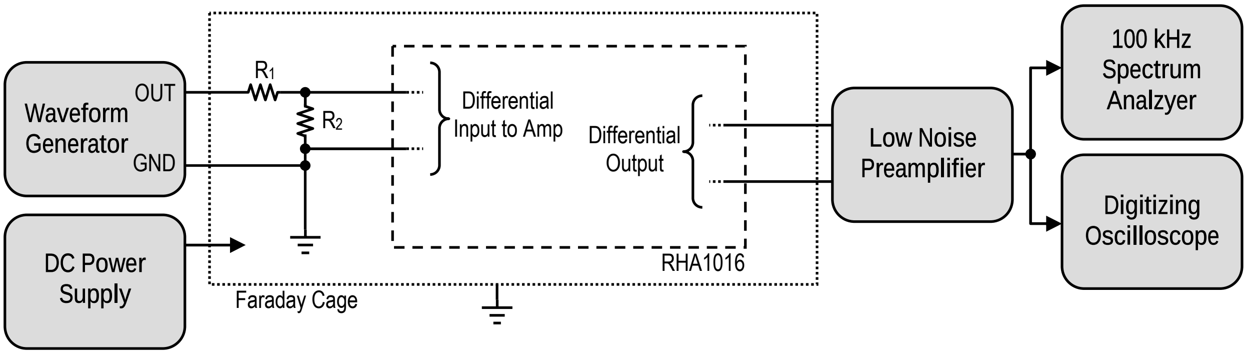
A modern digitizing oscilloscope such as the Tektronix TDS3014B can calculate the RMS value of a waveform, although this is a less accurate measurement of noise since the value is only calculated at one timescale. Troublesome low-frequency (1/f) noise only shows up at relatively slow timescales (e.g., 20 ms/division). Also, many scopes do not subtract the mean level of the waveform before calculating the RMS value, leading to erroneously high noise estimates. Small offsets from the preamplifier can throw off the RMS measurement unless care is taken to null them out. The easiest way to accomplish this is to use a modern oscilloscope with an "advanced math" option that allows for the real-time calculation of a waveform with its mean value subtracted [e.g., CH1 – MEAN(CH1)].

Applying test signals to the chip also presents challenges. Although the RHA1016 amplifiers completely reject DC offset voltages, the AC amplitude of any input signals should be kept below 5 mV. Larger input signals will not damage the chip; however, the output signals will begin clipping, as the differential output is only capable of swinging ±1V. Since most waveform generators cannot be dialed this low, it is usually necessary to build a resistor voltage divider to attenuate the input signal. A simple input circuit is shown below. Remember to ground the other differential input to prevent it from picking up interference.

When using resistor voltage dividers, it is a good idea to keep $R_2 < 200\ \Omega$ to ensure that the resistor network does not contribute significant levels of Johnson noise to the amplifier input. Using $R_1 = 47\ k\Omega$ and $R_2 = 47\ \Omega$ will give approximately 1000x attenuation from the signal generator to the amplifier. (The high value of R_1 does not contribute significant noise to the amplifier input as the equivalent resistance for Johnson noise calculations is $R_1||R_2$.)

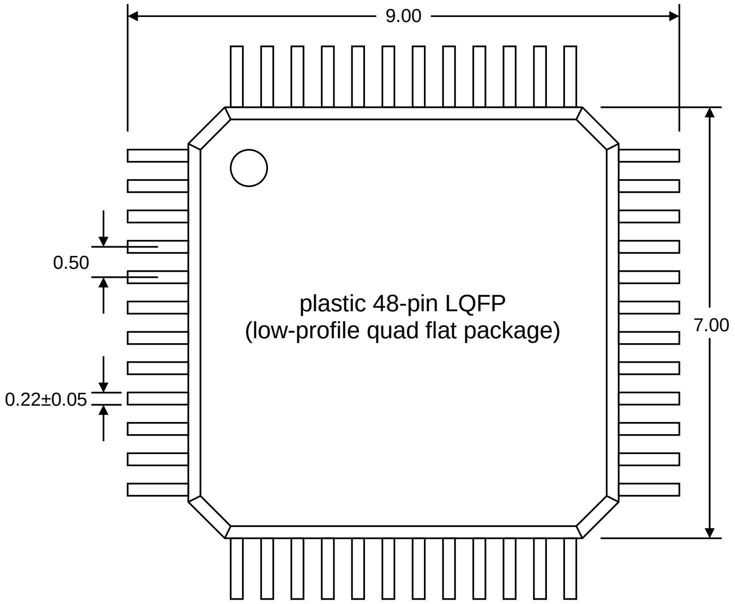
While batteries contribute less noise than active power supplies, we have not noticed any increase in amplifier noise levels when moving from batteries to a benchtop DC supply. "Switching" power supplies are notoriously noisy and should be avoided for all instrumentation applications.

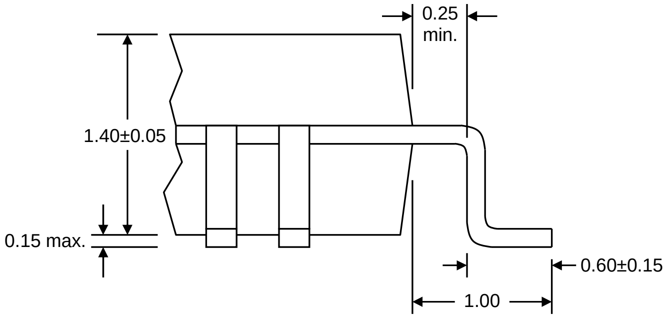
For ultra-low current measurements (such the amplifier input bias current), the Keithley 6485 Picoammeter is a useful tool.



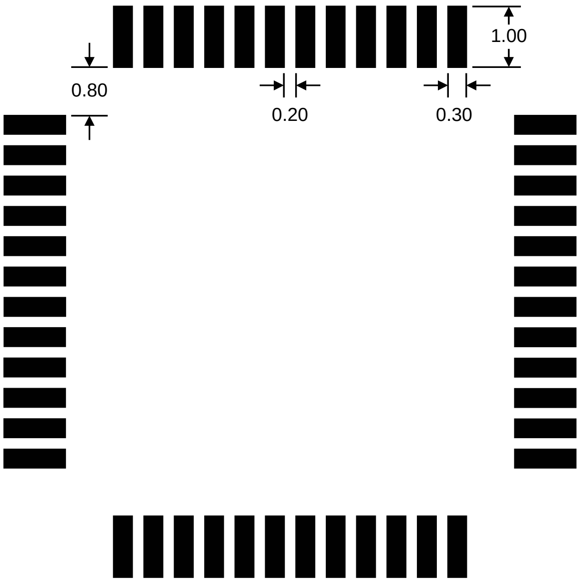
Package Dimensions

All dimensions are in millimeters.





PRINTED CIRCUIT BOARD LAYOUT



Pricing Information

See www.intantech.com for current pricing. All price information is subject to change without notice. Quantities may be limited. All orders are subject to current pricing at time of acceptance by Intan Technologies. Additional charges may apply for international purchases and shipping.

Contact Information

This datasheet is meant to acquaint engineers and scientists with the general characteristics of the RHA1016 integrated bioinstrumentation amplifier array developed at Intan Technologies. We value feedback from potential end users. We can discuss your specific needs and suggest a custom integrated solution tailored to your applications.

For more information, contact Intan Technologies at:

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