LMV321/LMV358/LMV324 Single/Dual/Quad General Purpose, Low Voltage, Rail-to-Rail Output Operational Amplifiers

General Description
The LMV358/324 are low voltage (2.7–5.5V) versions of the dual and quad commodity op amps, LM358/324, which currently operate at 5–30V. The LMV321 is the single version. The LMV321/358/324 are the most cost effective solutions for the applications where low voltage operation, space saving and low price are needed. They offer specifications that meet or exceed the familiar LM358/324. The LMV321/358/324 have rail-to-rail output swing capability and the input common-mode voltage range includes ground. They all exhibit excellent speed-power ratio, achieving 1MHz of bandwidth and 1V/µs of slew rate with low supply current. The LMV321 is available in space saving SC70-5, which is approximately half the size of SOT23-5. The small package saves space on pc boards, and enables the design of small portable electronic devices. It also allows the designer to place the device closer to the signal source to reduce noise pickup and increase signal integrity.

The chips are built with National’s advanced submicron silicon-gate BICMOS process. The LMV321/358/324 have bipolar input and output stages for improved noise performance and higher output current drive.

Features
(For V+ = 5V and V− = 0V, Typical Unless Otherwise Noted)
- Guaranteed 2.7V and 5V Performance
- No Crossover Distortion
- Space Saving Package SC70-5 2.0x2.1x1.0mm
- Industrial Temp. Range −40˚C to +85˚C
- Gain-Bandwidth Product 1MHz
- Low Supply Current
  - LMV321 130µA
  - LMV358 210µA
  - LMV324 410µA
- Rail-to-Rail Output Swing @ 10kΩ
  - V+ −10mV
  - V− +65mV
- VCM
  - −0.2V to V−−0.8V

Applications
- Active Filters
- General Purpose Low Voltage Applications
- General Purpose Portable Devices

Gain and Phase vs. Capacitive Load

Output Voltage Swing vs. Supply Voltage

Absolute Maximum Ratings (Note 1)
If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

- ESD Tolerance (Note 2)
  - Machine Model: 100V
  - Human Body Model
  - LMV358/324: 2000V
  - LMV321: 900V
- Differential Input Voltage ± Supply Voltage
- Supply Voltage (V⁺ – V⁻): 5.5V
- Output Short Circuit to V⁺ (Note 3)
- Output Short Circuit to V⁻ (Note 4)
- Soldering Information
  - Infrared or Convection (20 sec): 235°C

Storage Temp. Range: −65°C to 150°C
Junction Temperature (Note 5): 150°C

Operating Ratings (Note 1)
- Supply Voltage: 2.7V to 5.5V
- Temperature Range: −40°C to +85°C
- Thermal Resistance (θ JA) (Note 10):
  - 5-pin SC70-5: 478°C/W
  - 5-pin SOT23-5: 265°C/W
  - 8-Pin SOIC: 190°C/W
  - 8-Pin MSOP: 235°C/W
  - 14-Pin SOIC: 145°C/W
  - 14-Pin TSSOP: 155°C/W

2.7V DC Electrical Characteristics
Unless otherwise specified, all limits guaranteed for T J = 25°C, V⁺ = 2.7V, V⁻ = 0V, V CM = 1.0V, V O = V⁺/2 and R L > 1MΩ.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>Typ (Note 6)</th>
<th>Limit (Note 7)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>V OS</td>
<td>Input Offset Voltage</td>
<td></td>
<td>1.7</td>
<td>7</td>
<td>mV max</td>
</tr>
<tr>
<td>TCV OS</td>
<td>Input Offset Voltage Average Drift</td>
<td></td>
<td>5</td>
<td>μV/°C</td>
<td></td>
</tr>
<tr>
<td>I B</td>
<td>Input Bias Current</td>
<td></td>
<td>11</td>
<td>250</td>
<td>nA max</td>
</tr>
<tr>
<td>I OS</td>
<td>Input Offset Current</td>
<td></td>
<td>5</td>
<td>50</td>
<td>nA max</td>
</tr>
<tr>
<td>CMRR</td>
<td>Common Mode Rejection Ratio</td>
<td>0V ≤ V CM ≤ 1.7V</td>
<td>63</td>
<td>50</td>
<td>dB min</td>
</tr>
<tr>
<td>PSRR</td>
<td>Power Supply Rejection Ratio</td>
<td>2.7V ≤ V⁺ ≤ 5V V O = 1V</td>
<td>60</td>
<td>50</td>
<td>dB min</td>
</tr>
<tr>
<td>V CM</td>
<td>Input Common-Mode Voltage Range</td>
<td>For CMRR≥50dB</td>
<td>−0.2</td>
<td>0</td>
<td>V min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.9</td>
<td>1.7</td>
<td>V max</td>
</tr>
<tr>
<td>V O</td>
<td>Output Swing</td>
<td>R L = 10kΩ to 1.35V</td>
<td>V⁺ -10</td>
<td>V⁺ -100</td>
<td>mV min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>180</td>
<td>mV max</td>
</tr>
<tr>
<td>I B</td>
<td>Supply Current</td>
<td>LMV321</td>
<td>80</td>
<td>170</td>
<td>μA max</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LMV358 Both amplifiers</td>
<td>140</td>
<td>340</td>
<td>μA max</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LMV324 All four amplifiers</td>
<td>260</td>
<td>680</td>
<td>μA max</td>
</tr>
</tbody>
</table>

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### 2.7V AC Electrical Characteristics
Unless otherwise specified, all limits guaranteed for $T_J = 25^\circ C$, $V^+ = 2.7V$, $V^- = 0V$, $V_{CM} = 1.0V$, $V_O = V^+/2$ and $R_L > 1\, \Omega$.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>Typ (Note 6)</th>
<th>Limit (Note 7)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBWP</td>
<td>Gain-Bandwidth Product</td>
<td>$C_L = 200pF$</td>
<td>1</td>
<td>1 MHz</td>
<td></td>
</tr>
<tr>
<td>$\Phi_m$</td>
<td>Phase Margin</td>
<td></td>
<td>60</td>
<td>Deg</td>
<td></td>
</tr>
<tr>
<td>$G_m$</td>
<td>Gain Margin</td>
<td></td>
<td>10</td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>$e_n$</td>
<td>Input-Referred Voltage Noise</td>
<td>$f = 1kHz$</td>
<td>46</td>
<td>nV/\sqrt{Hz}</td>
<td></td>
</tr>
<tr>
<td>$I_n$</td>
<td>Input-Referred Current Noise</td>
<td>$f = 1kHz$</td>
<td>0.17</td>
<td>pA/\sqrt{Hz}</td>
<td></td>
</tr>
</tbody>
</table>

### 5V DC Electrical Characteristics
Unless otherwise specified, all limits guaranteed for $T_J = 25^\circ C$, $V^+ = 5V$, $V^- = 0V$, $V_{CM} = 2.0V$, $V_O = V^+/2$ and $R_L > 1\, \Omega$. **Boldface** limits apply at the temperature extremes.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>Typ (Note 6)</th>
<th>Limit (Note 7)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{OS}$</td>
<td>Input Offset Voltage</td>
<td></td>
<td>1.7</td>
<td>7</td>
<td>mV max</td>
</tr>
<tr>
<td>TCVOS</td>
<td>Input Offset Voltage Average Drift</td>
<td></td>
<td>5</td>
<td>$\mu$V/°C</td>
<td></td>
</tr>
<tr>
<td>$I_B$</td>
<td>Input Bias Current</td>
<td></td>
<td>15</td>
<td>250</td>
<td>nA max</td>
</tr>
<tr>
<td>$I_{OS}$</td>
<td>Input Offset Current</td>
<td></td>
<td>5</td>
<td>50</td>
<td>nA max</td>
</tr>
<tr>
<td>CMRR</td>
<td>Common Mode Rejection Ratio</td>
<td>$0V \leq V_{CM} \leq 4V$</td>
<td>65</td>
<td>50</td>
<td>dB min</td>
</tr>
<tr>
<td>PSRR</td>
<td>Power Supply Rejection Ratio</td>
<td>$2.7V \leq V^+ \leq 5V$ $V_O = 1V$ $V_{CM} = 1V$</td>
<td>60</td>
<td>50</td>
<td>dB min</td>
</tr>
<tr>
<td>$V_{CM}$</td>
<td>Input Common-Mode Voltage Range</td>
<td>For $CMRR \geq 50dB$</td>
<td>-0.2</td>
<td>0</td>
<td>V min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.2</td>
<td>4</td>
<td>V max</td>
</tr>
<tr>
<td>$A_V$</td>
<td>Large Signal Voltage Gain (Note 8)</td>
<td>$R_L = 2k\Omega$</td>
<td>100</td>
<td>15</td>
<td>V/mV min</td>
</tr>
<tr>
<td>$V_O$</td>
<td>Output Swing</td>
<td>$R_L = 2k\Omega$ to 2.5V</td>
<td>$V^+ -40$</td>
<td>$V^+ -300$</td>
<td>mV min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>120</td>
<td>300</td>
<td>mV max</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$R_L = 10k\Omega$ to 2.5V</td>
<td>$V^+ -10$</td>
<td>$V^+ -100$</td>
<td>mV min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>65</td>
<td>180</td>
<td>mV max</td>
</tr>
<tr>
<td>$I_O$</td>
<td>Output Short Circuit Current</td>
<td>Sourcing, $V_O = 0V$</td>
<td>60</td>
<td>5</td>
<td>m max</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sinking, $V_O = 5V$</td>
<td>160</td>
<td>10</td>
<td>mA min</td>
</tr>
<tr>
<td>$I_S$</td>
<td>Supply Current</td>
<td>LMV321</td>
<td>130</td>
<td>250</td>
<td>µA max</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LMV358</td>
<td>210</td>
<td>440</td>
<td>µA max</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Both amplifiers</td>
<td>210</td>
<td>440</td>
<td>µA max</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LMV324</td>
<td>410</td>
<td>830</td>
<td>µA max</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All four amplifiers</td>
<td>410</td>
<td>830</td>
<td>µA max</td>
</tr>
</tbody>
</table>
### 5V AC Electrical Characteristics

Unless otherwise specified, all limits guaranteed for $T_J = 25^\circ C$, $V^+ = 5V$, $V^- = 0V$, $V_{CM} = 2.0V$, $V_O = V^+/2$ and $R_L > 1M\Omega$.

**Boldface** limits apply at the temperature extremes.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>Typ (Note 6)</th>
<th>Limit (Note 7)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>Slew Rate</td>
<td>(Note 9)</td>
<td>1</td>
<td></td>
<td>V/µs</td>
</tr>
<tr>
<td>GBWP</td>
<td>Gain-Bandwidth Product</td>
<td>$C_L = 200pF$</td>
<td>1</td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>$\Phi_m$</td>
<td>Phase Margin</td>
<td></td>
<td>60</td>
<td></td>
<td>Deg</td>
</tr>
<tr>
<td>$G_m$</td>
<td>Gain Margin</td>
<td></td>
<td>10</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>$e_{n}$</td>
<td>Input-Reflected Voltage Noise</td>
<td>$f = 1kHz$</td>
<td>39</td>
<td></td>
<td>nV/√Hz</td>
</tr>
<tr>
<td>$i_{n}$</td>
<td>Input-Reflected Current Noise</td>
<td>$f = 1kHz$</td>
<td>0.21</td>
<td></td>
<td>pA/√Hz</td>
</tr>
</tbody>
</table>

**Note 1:** Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is intended to be functional, but specific performance is not guaranteed. For guaranteed specifications and the test conditions, see the Electrical Characteristics.

**Note 2:** Human body model, 1.5kΩ in series with 100pF. Machine model, 0Ω in series with 200pF.

**Note 3:** Shorting output to $V^+$ will adversely affect reliability.

**Note 4:** Shorting output to $V^-$ will adversely affect reliability.

**Note 5:** The maximum power dissipation is a function of $T_{J(MAX)}$, $\theta_{JA}$, and $T_A$. The maximum allowable power dissipation at any ambient temperature is $P_D = (T_{J(MAX)} - T_A)/\theta_{JA}$. All numbers apply for packages soldered directly into a PC board.

**Note 6:** Typical values represent the most likely parametric norm.

**Note 7:** All limits are guaranteed by testing or statistical analysis.

**Note 8:** $R_L$ is connected to $V^+$. The output voltage is $0.5V \leq V_O \leq 4.5V$.

**Note 9:** Connected as voltage follower with 3V step input. Number specified is the slower of the positive and negative slew rates.

**Note 10:** All numbers are typical, and apply for packages soldered directly onto a PC board in still air.
Typical Performance Characteristics

Unless otherwise specified, $V_S = +5V$, single supply, $T_A = 25^\circ C$. 

Supply Current vs. Supply Voltage (LMV321)

Input Current vs. Temperature

Sourcing Current vs. Output Voltage

Sourcing Current vs. Output Voltage

Sinking Current vs. Output Voltage

Sinking Current vs. Output Voltage

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Typical Performance Characteristics

Unless otherwise specified, $V_S = +5V$, single supply, $T_A = 25˚C$. (Continued)
Typical Performance Characteristics  Unless otherwise specified, $V_S = +5V$, single supply, $T_A = 25^\circ C$. (Continued)
Typical Performance Characteristics

Unless otherwise specified, $V_S = +5V$, single supply, $T_A = 25^\circ C$. (Continued)
Typical Performance Characteristics

Unless otherwise specified, $V_S = +5V$, single supply, $T_A = 25^\circ C$. (Continued)
Typical Performance Characteristics

Unless otherwise specified, $V_S = +5V$, single supply, $T_A = 25^\circ C$. (Continued)
Typical Performance Characteristics

Unless otherwise specified, $V_S = +5V$, single supply, $T_A = 25^\circ C$. (Continued)
Typical Performance Characteristics

Unless otherwise specified, \( V_S = +5V \), single supply, \( T_A = 25^\circ C \). (Continued)

Open Loop Output Impedance vs. Frequency

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Output Impedance (( \Omega ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1k</td>
<td>1000</td>
</tr>
<tr>
<td>10k</td>
<td>900</td>
</tr>
<tr>
<td>100k</td>
<td>800</td>
</tr>
<tr>
<td>1M</td>
<td>700</td>
</tr>
</tbody>
</table>

\( V_S = 2.7V \)

\( V_S = 5V \)

Short Circuit Current vs. Temperature (Sinking)

<table>
<thead>
<tr>
<th>Temperature (( ^\circ C ))</th>
<th>Short Circuit Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>0</td>
</tr>
<tr>
<td>-30</td>
<td>10</td>
</tr>
<tr>
<td>-20</td>
<td>20</td>
</tr>
<tr>
<td>-10</td>
<td>30</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>70</td>
<td>110</td>
</tr>
<tr>
<td>80</td>
<td>120</td>
</tr>
<tr>
<td>90</td>
<td>130</td>
</tr>
</tbody>
</table>

\( V_S = 2.7V \)

\( V_S = 5V \)

Short Circuit Current vs. Temperature (Sourcing)

<table>
<thead>
<tr>
<th>Temperature (( ^\circ C ))</th>
<th>Short Circuit Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>0</td>
</tr>
<tr>
<td>-30</td>
<td>10</td>
</tr>
<tr>
<td>-20</td>
<td>20</td>
</tr>
<tr>
<td>-10</td>
<td>30</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>60</td>
<td>100</td>
</tr>
</tbody>
</table>

\( V_S = 2.7V \)

\( V_S = 5V \)
Application Notes

1.0 BENEFITS OF THE LMV321/358/324

Size: The small footprints of the LMV321/358/324 packages save space on printed circuit boards, and enable the design of smaller electronic products, such as cellular phones, pagers, or other portable systems. The low profile of the LMV321/358/324 make them possible to use in PCMCIA type III cards.

Signal Integrity
Signals can pick up noise between the signal source and the amplifier. By using a physically smaller amplifier package, the LMV321/358/324 can be placed closer to the signal source, reducing noise pickup and increasing signal integrity.

Simplified Board Layout
These products help you to avoid using long pc traces in your pc board layout. This means that no additional components, such as capacitors and resistors, are needed to filter out the unwanted signals due to the interference between the long pc traces.

Low Supply Current
These devices will help you to maximize battery life. They are ideal for battery powered systems.

Low Supply Voltage
National provides guaranteed performance at 2.7V and 5V. These guarantees ensure operation throughout the battery lifetime.

Rail-to-Rail Output
Rail-to-rail output swing provides maximum possible dynamic range at the output. This is particularly important when operating on low supply voltages.

Input Includes Ground
Allows direct sensing near GND in single supply operation. The differential input voltage may be larger than $V^+$ without damaging the device. Protection should be provided to prevent the input voltages from going negative more than $-0.3V$ (at 25°C). An input clamp diode with a resistor to the IC input terminal can be used.

Ease Of Use & Crossover Distortion
The LMV321/358/324 offer specifications similar to the familiar LM324. In addition, the new LMV321/358/324 effectively eliminate the output crossover distortion. The scope photos in Figure 1 and Figure 2 compare the output swing of the LMV324 and the LM324 in a voltage follower configuration, with $V_{IN} = \pm 2.5V$ and $R_L (= 2k\Omega)$ connected to GND. It is apparent that the crossover distortion has been eliminated in the new LMV324.

2.0 CAPACITIVE LOAD TOLERANCE
The LMV321/358/324 can directly drive 200pF in unity-gain without oscillation. The unity-gain follower is the most sensitive configuration to capacitive loading. Direct capacitive loading reduces the phase margin of amplifiers. The combination of the amplifier’s output impedance and the capacitive load induces phase lag. This results in either an under-damped pulse response or oscillation. To drive a heavier capacitive load, circuit in Figure 3 can be used.

![Figure 1. Output Swing of LMV324](image1)

![Figure 2. Output Swing of LM324](image2)

![Figure 3. Indirectly Driving A Capacitive Load Using Resistive Isolation](image3)
Application Notes (Continued)

In Figure 3, the isolation resistor $R_{ISO}$ and the load capacitor $C_L$ form a pole to increase stability by adding more phase margin to the overall system. The desired performance depends on the value of $R_{ISO}$. The bigger the $R_{ISO}$ resistor value, the more stable $V_{OUT}$ will be. Figure 4 is an output waveform of Figure 3 using 620Ω for $R_{ISO}$ and 510pF for $C_L$.

Figure 4 is an output waveform of Figure 3 using 620Ω for $R_{ISO}$ and 510pF for $C_L$.

The circuit in Figure 5 is an improvement to the one in Figure 3 because it provides DC accuracy as well as AC stability. If there were a load resistor in Figure 3, the output would be voltage divided by $R_{ISO}$ and the load resistor. Instead, in Figure 5, $R_F$ provides the DC accuracy by using feed-forward techniques to connect $V_{IN}$ to $R_L$. Caution is needed in choosing the value of $R_F$ due to the input bias current of the LMV321/358/324. $C_F$ and $R_{ISO}$ serve to counteract the loss of phase margin by feeding the high frequency component of the output signal back to the amplifier’s inverting input, thereby preserving phase margin in the overall feedback loop. Increased capacitive drive is possible by increasing the value of $C_F$. This in turn will slow down the pulse response.

![FIGURE 4. Pulse Response of the LMV324 Circuit in Figure 3](image)

The circuit in Figure 5 is an improvement to the one in Figure 3 because it provides DC accuracy as well as AC stability. If there were a load resistor in Figure 3, the output would be voltage divided by $R_{ISO}$ and the load resistor. Instead, in Figure 5, $R_F$ provides the DC accuracy by using feed-forward techniques to connect $V_{IN}$ to $R_L$. Caution is needed in choosing the value of $R_F$ due to the input bias current of the LMV321/358/324. $C_F$ and $R_{ISO}$ serve to counteract the loss of phase margin by feeding the high frequency component of the output signal back to the amplifier’s inverting input, thereby preserving phase margin in the overall feedback loop. Increased capacitive drive is possible by increasing the value of $C_F$. This in turn will slow down the pulse response.

![FIGURE 5. Indirectly Driving A Capacitive Load with DC Accuracy](image)

3.0 INPUT BIAS CURRENT CANCELLATION

The LMV321/358/324 family has a bipolar input stage. The typical input bias current of LMV321/358/324 is 15nA with 5V supply. Thus a 100kΩ input resistor will cause 1.5mV of error voltage. By balancing the resistor values at both inverting and non-inverting inputs, the error caused by the amplifier’s input bias current will be reduced. The circuit in Figure 6 shows how to cancel the error caused by input bias current.

![FIGURE 6. Cancelling the Error Caused by Input Bias Current](image)

4.0 TYPICAL SINGLE-SUPPLY APPLICATION CIRCUITS

4.1 Difference Amplifier

The difference amplifier allows the subtraction of two voltages or, as a special case, the cancellation of a signal common to two inputs. It is useful as a computational amplifier, in making a differential to single-ended conversion or in rejecting a common mode signal.

![FIGURE 7. Difference Amplifier](image)

4.2 Instrumentation Circuits

The input impedance of the previous difference amplifier is set by the resistors $R_1$, $R_2$, $R_3$, and $R_4$. To eliminate the problems of low input impedance, one way is to use a voltage follower ahead of each input as shown in the following two instrumentation amplifiers.
4.2.1 Three-Op-Amp Instrumentation Amplifier
The quad LMV324 can be used to build a three-op-amp instrumentation amplifier as shown in Figure 8.

The first stage of this instrumentation amplifier is a differential-input, differential-output amplifier, with two voltage followers. These two voltage followers assure that the input impedance is over 100 MΩ. The gain of this instrumentation amplifier is set by the ratio of R2/R1. R3 should equal R1, and R4 equal R2. Matching of R3 to R1 and R4 to R2 affects the CMRR. For good CMRR over temperature, low drift resistors should be used. Making R4 slightly smaller than R2 and adding a trim pot equal to twice the difference between R2 and R4 will allow the CMRR to be adjusted for optimum.

4.2.2 Two-op-amp Instrumentation Amplifier
A two-op-amp instrumentation amplifier can also be used to make a high-input-impedance dc differential amplifier (Figure 9). As in the three-op-amp circuit, this instrumentation amplifier requires precise resistor matching for good CMRR. R4 should equal R1, and R3 should equal R2.

4.3 Single-Supply Inverting Amplifier
There may be cases where the input signal going into the amplifier is negative. Because the amplifier is operating in single supply voltage, a voltage divider using R3 and R4 is implemented to bias the amplifier so the input signal is within the input common-mode voltage range of the amplifier. The capacitor C1 is placed between the inverting input and resistor R1 to block the DC signal going into the AC signal source, V_in. The values of R1 and C1 affect the cutoff frequency, \( fc = \frac{1}{2\pi R_1 C_1} \).

As a result, the output signal is centered around mid-supply (if the voltage divider provides \( V^+/2 \) at the non-inverting input). The output can swing to both rails, maximizing the signal-to-noise ratio in a low voltage system.

4.4 ACTIVE FILTER

4.4.1 Simple Low-Pass Active Filter
The simple low-pass filter is shown in Figure 11. Its low-frequency gain (\( \omega \rightarrow 0 \)) is defined by \(-R_3/R_1\). This allows low-frequency gains other than unity to be obtained. The filter has a -20dB/decade roll-off after its corner frequency fc. R2 should be chosen equal to the parallel combination of R1 and R3 to minimize errors due to bias current. The frequency response of the filter is shown in Figure 12.

\[
V_o = \left(1 + \frac{R_4}{R_3}\right) \left(V_2 - V_i\right), \text{ where } R_1 = R_4 \text{ and } R_2 = R_3
\]

As shown: \( V_o = \frac{R_2}{R_1} V_i \)

FIGURE 8. Three-op-amp Instrumentation Amplifier

FIGURE 9. Two-Op-amp Instrumentation Amplifier

FIGURE 10. Single-Supply Inverting Amplifier

FIGURE 11. Simple Low-Pass Active Filter

FIGURE 12. Frequency Response of the Filter
Application Notes (Continued)

Note that the single-op-amp active filters are used in to the applications that require low quality factor, \( Q \leq 10 \), low frequency (\( \leq 5 \) kHz), and low gain (\( \leq 10 \)), or a small value for the product of gain times \( Q \) (\( \leq 100 \)). The op amp should have an open loop voltage gain at the highest frequency of interest at least 50 times larger than the gain of the filter at this frequency. In addition, the selected op amp should have a slew rate that meets the following requirement:

\[
\text{Slew Rate} \geq 0.5 \times (\omega_n V_{\text{OPP}}) \times 10^{-6} \text{ V/µsec}
\]

where \( \omega_n \) is the highest frequency of interest, and \( V_{\text{OPP}} \) is the output peak-to-peak voltage.

4.4.2 Sallen-Key 2nd-Order Active Low-Pass Filter

The Sallen-Key 2nd-order active low-pass filter is illustrated in Figure 13. The dc gain of the filter is expressed as

\[
A_L = -\frac{R_3}{R_1}
\]

\[
f_c = \frac{1}{2\pi R_3 C_1}
\]

\[
R_2 = R_1 \parallel R_3
\]

FIGURE 13. Sallen-Key 2nd-Order Active Low-Pass Filter

The following paragraphs explain how to select values for \( R_1, R_2, R_3, R_4, C_1, \) and \( C_2 \) for given filter requirements, such as \( A_{LP}, Q, \) and \( f_c \).

The standard form for a 2nd-order low pass filter is

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} (s) = \frac{A_{LP} \omega_c}{s^2 + \frac{(\omega_c)}{Q} s + \omega_c^2}
\]

where

- \( Q \): Pole Quality Factor
- \( \omega_c \): Corner Frequency

Comparison between the Equation (2) and Equation (3) yields

\[
\omega_c^2 = \frac{1}{C_1 C_2 R_1 R_2}
\]

(4)

\[
\frac{\omega_c}{Q} = \frac{1}{C_1 R_1} + \frac{1}{C_1 R_2} + \frac{1}{C_2 R_2} - \frac{A_{LP}}{C_2 R_2}
\]

(5)

To reduce the required calculations in filter design, it is convenient to introduce normalization into the components and design parameters. To normalize, let \( \omega_n = 1\text{rad/s}, \) and \( C_1 = C_2 = C_n = 1F, \) and substitute these values into Equation (4) and Equation (5). From Equation (4), we obtain

\[
R_1 = \frac{1}{R_2}
\]

(6)

From Equation (5), we obtain

\[
R_2 = \frac{1 \pm \sqrt{1 - 4Q^2 (2 - A_{LP})}}{2Q}
\]

(7)
For minimum dc offset, $V^+ = V^-$, the resistor values at both inverting and non-inverting inputs should be equal, which means

$$R_1 + R_2 = \frac{R_3 R_4}{R_3 + R_4}$$  \hspace{1cm} (8)$$

From Equation (1) and Equation (8), we obtain

$$R_3 = (R_1 + R_2) A_{LP}$$  \hspace{1cm} (9)$$

$$R_4 = \left(\frac{A_{LP}}{A_{LP} - 1}\right) (R_1 + R_2)$$  \hspace{1cm} (10)$$

The values of $C_1$ and $C_2$ are normally close to or equal to

$$C = \frac{10}{f_c} \mu F$$

As a design example:

Require: $A_{LP} = 2$, $Q = 1$, $f_c = 1 KHz$

Start by selecting $C_1$ and $C_2$. Choose a standard value that is close to

$$C = \frac{10}{f_c} \mu F$$

$$C_1 = C_2 = \frac{10}{1 \times 10^3} \mu F = 0.01 \mu F$$

From Equations (6), (7), (9), (10),

$$R_1 = 1 \Omega$$

$$R_2 = 1 \Omega$$

$$R_3 = 4 \Omega$$

$$R_4 = 4 \Omega$$

The above resistor values are normalized values with $\omega_n = 1 \text{rad/s}$ and $C_1 = C_2 = C_n = 1F$. To scale the normalized cut-off frequency and resistances to the real values, two scaling factors are introduced; frequency scaling factor ($k_f$) and impedance scaling factor ($k_m$).

$$k_f = \frac{\omega_c}{\omega_n} = \frac{2 \pi \times 1 \times 10^3}{1} = 2 \pi \times 10^3$$

$$k_m k_f = \frac{C_n}{C_1}$$

$$k_m = 1.59 \times 10^4$$

Scaled values:

$$R_3 = R_4 = 15.9 \text{ k}\Omega$$

$$R_3 = R_4 = 63.6 \text{ k}\Omega$$

$$C_1 = C_2 = 0.01 \mu F$$

An adjustment to the scaling may be made in order to have realistic values for resistors and capacitors. The actual value used for each component is shown in the circuit.

### 4.4.3 2nd-order High Pass Filter

A 2nd-order high pass filter can be built by simply inter-changing those frequency selective components ($R_1$, $R_2$, $C_1$, $C_2$) in the Sallen-Key 2nd-order active low pass filter. As shown in Figure 14, resistors become capacitors, and capacitors become resistors. The resulted high pass filter has the same corner frequency and the same maximum gain as the previous 2nd-order low pass filter if the same components are chosen.

![Sallen-Key 2nd-Order Active High-Pass Filter](image)

$$\frac{V_{OUT}}{V_{IN}}(S) = \frac{S^{-2} A_{HP}}{S^2 + S \left(\frac{1}{C_1 R_2} + \frac{1}{C_2 R_2} + \frac{1 - A_{HP}}{C_1 R_1}\right) + \frac{1}{C_1 C_2 R_1 R_2}}$$

Where $A_{HP} = \frac{R_3}{R_4}$

### FIGURE 14. Sallen-Key 2nd-Order Active High-Pass Filter

### 4.4.4 State Variable Filter

A state variable filter requires three op amps. One convenient way to build state variable filters is with a quad op amp, such as the LMV324 (Figure 15).

This circuit can simultaneously represent a low-pass filter, high-pass filter, and bandpass filter at three different outputs. The equations for these functions are listed below. It is also called "Bi-Quad" active filter as it can produce a transfer function which is quadratic in both numerator and denominator.
A design example for a bandpass filter is shown below:
Assume the system design requires a bandpass filter with \( f_0 = 1\text{kHz} \) and \( Q = 50 \). What needs to be calculated are capacitor and resistor values.
First choose convenient values for \( C_1, R_1 \), and \( R_2 \):

\[
C_1 = 1200 \text{pF} \\
2R_2 = R_1 = 30\text{k}\Omega
\]

Then from Equation (11),

\[
R_3 = R_2 (2Q - 1) \\
R_3 = 15 \text{k}\Omega \times (2 \times 50 - 1) \\
= 1.5 \text{M}\Omega
\]

From Equation (12),

\[
R = \frac{1}{\omega_0 C_1} \\
R = \frac{1}{(2\pi \times 10^3)(1.2 \times 10^{-9})} \\
= 132.7 \text{k}\Omega
\]

From the above calculated values, the midband gain is \( H_0 = R_3/R_2 = 100 \text{(40\,dB)} \). The nearest 5% standard values have been added to Figure 15.

4.5 PULSE GENERATORS AND OSCILLATORS

A pulse generator is shown in Figure 16. Two diodes have been used to separate the charge and discharge paths to capacitor C.
When the output voltage $V_O$ is first at its high, $V_{OH}$, the capacitor $C$ is charged toward $V_{OH}$ through $R_2$. The voltage across $C$ rises exponentially with a time constant $\tau = R_2C$, and this voltage is applied to the inverting input of the op amp. Meanwhile, the voltage at the non-inverting input is set at the positive threshold voltage ($V_{TH+}$) of the generator. The capacitor voltage continually increases until it reaches $V_{TH+}$, at which point the output of the generator will switch to its low, $V_{OL} (= 0V$ in this case). The voltage at the non-inverting input is switched to the negative threshold voltage ($V_{TH-}$) of the generator. The capacitor then starts to discharge toward $V_{OL}$ exponentially through $R_1$, with a time constant $\tau = R_1C$. When the capacitor voltage reaches $V_{TH-}$, the output of the pulse generator switches to $V_{OH}$. The capacitor starts to charge, and the cycle repeats itself.

As shown in the waveforms in Figure 17, the pulse width ($T_1$) is set by $R_2$, $C$ and $V_{OH}$, and the time between pulses ($T_2$) is set by $R_1$, $C$ and $V_{OL}$. This pulse generator can be made to have different frequencies and pulse width by selecting different capacitor value and resistor values.

Figure 18 shows another pulse generator, with separate charge and discharge paths. The capacitor is charged through $R_4$ and is discharged through $R_2$.

Figure 19 is a squarewave generator with the same path for charging and discharging the capacitor.
4.6 CURRENT SOURCE AND SINK
The LMV321/358/324 can be used in feedback loops which regulate the current in external PNP transistors to provide current sources or in external NPN transistors to provide current sinks.

4.6.1 Fixed Current Source
A multiple fixed current source is shown in Figure 20. A voltage \( V_{\text{REF}} = 2V \) is established across resistor \( R_3 \) by the voltage divider \( (R_3 \text{ and } R_4) \). Negative feedback is used to cause the voltage drop across \( R_1 \) to be equal to \( V_{\text{REF}} \). This controls the emitter current of transistor \( Q_1 \) and if we neglect the base current of \( Q_1 \) and \( Q_2 \), essentially this same current is available out of the collector of \( Q_1 \).

Large input resistors can be used to reduce current loss and a Darlington connection can be used to reduce errors due to the \( \beta \) of \( Q_1 \).

The resistor, \( R_2 \), can be used to scale the collector current of \( Q_2 \) either above or below the 1mA reference value.

4.6.2 High Compliance Current Sink
A current sink circuit is shown in Figure 21. The circuit requires only one resistor \( (R_E) \) and supplies an output current which is directly proportional to this resistor value.

4.7 POWER AMPLIFIER
A power amplifier is illustrated in Figure 22. This circuit can provide a higher output current because a transistor follower is added to the output of the op amp.

4.8 LED DRIVER
The LMV321/358/324 can be used to drive an LED as shown in Figure 23.
4.9 COMPARATOR WITH HYSTERESIS

The LMV321/358/324 can be used as a low power comparator. Figure 24 shows a comparator with hysteresis. The hysteresis is determined by the ratio of the two resistors.

\[ V_{TH+} = \frac{V_{REF}}{1+\frac{R_1}{R_2}} + V_{OH} \left(1 + \frac{R_2}{R_1}\right) \]

\[ V_{TH-} = \frac{V_{REF}}{1+\frac{R_1}{R_2}} + V_{OL} \left(1 + \frac{R_2}{R_1}\right) \]

\[ V_H = \frac{(V_{OH} - V_{OL})}{1+\frac{R_2}{R_1}} \]

where

- \( V_{TH+} \): Positive Threshold Voltage
- \( V_{TH-} \): Negative Threshold Voltage
- \( V_{OH} \): Output Voltage at High
- \( V_{OL} \): Output Voltage at Low
- \( V_H \): Hysteresis Voltage

Since LMV321/358/324 have rail-to-rail output, the \((V_{OH} - V_{OL})\) equals to \(V_S\), which is the supply voltage.

\[ V_H = \frac{V_S}{1+\frac{R_2}{R_1}} \]

The differential voltage at the input of the op amp should not exceed the specified absolute maximum ratings. For real comparators that are much faster, we recommend you to use National’s LMV331/393/339, which are single, dual and quad general purpose comparators for low voltage operation.

Connection Diagrams

Ordering Information

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<th>Transport Media</th>
<th>NSC Drawing</th>
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SC70-5 Tape and Reel Specification

SOT-23-5 Tape and Reel Specification

TAPE FORMAT

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TAPE DIMENSIONS

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#### REEL DIMENSIONS

![Diagram of Reel Dimensions]

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Physical Dimensions

inches (millimeters) unless otherwise noted

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NS Package Number MAA05A

5-Pin SOT23-5
NS Package Number MA05B
Physical Dimensions inches (millimeters) unless otherwise noted (Continued)

14-Pin SOIC NS Package Number M14A

14-Pin TSSOPNS Package Number MTC14
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