IC Preamplifier Challenges Choppers on Drift

Since the introduction of monolithic IC amplifiers there has been a continual improvement in DC accuracy. Bias currents have been decreased by 5 orders of magnitude over the past 5 years. Low offset voltage drift is also necessary in a high accuracy circuits. This is evidenced by the popularity of low drift amplifier types as well as the requests for selected low-drift op amps. However, until now the chopper stabilized amplifier offered the lowest drift. A new monolithic IC preamplifier designed for use with general purpose op amps improves DC accuracy to where the drift is lower than many chopper stabilized amplifiers.

INTRODUCTION

Chopper amplifiers have long been known to offer the lowest possible DC drift. They are not without problems, however. Most chopper amps can be used only as inverting amplifiers, limiting their applications. Chopping can introduce noise and spikes into the signal. Mechanical choppers need replacement as well as being shock sensitive. Further, chopper amplifiers are designed to operate over a limited power supply, limited temperature range.

Previous low-drift op amps do not provide optimum performance either. Selected devices may only meet their specified voltage drift under restrictive conditions. For example, if a 741 device is selected without offset nulling, the addition of a offset null pot can drastically change the drift. Low drift op amps designed for offset balancing have another problem. The resistor network used in the null circuit is designed to null the drift when the offset voltage is nulled. The mechanism to achieve nulled drift depends on the difference in temperature coefficient between the internal resistors and the external null pot. Since the internal resistors have a non-linear temperature coefficient and may vary device to device as well as between manufacturers, it can only approximately null offset drift. The problem gets worse if the external null pot has a TC other than zero.

A new IC preamplifier is now available which can give drifts as low as 0.2 μV/°C. It is used with conventional op amps and eliminates the problems associated with older devices. As well as improving the DC input characteristics of the op amp, loop-gain is increased when an LM121 is used. This further improves overall accuracy since DC gain error is decreased.

The LM121 preamp is designed to give zero drift when the offset voltage is nulled to zero. The operating current of the LM121 is programmable by the value of the null network resistors. The drift is independent of the value of the nulling network so it can be used over a wide range of operating currents while retaining low drift. The operating current can be chosen to optimize bias current, gain, speed, or noise while still retaining the low drift. Further, since the drift is independent of the match between external and internal resistors when the offset is nulled, lower and more predictable drifts can be expected in actual use. The input is fully differential, overcoming many of the problems with single ended chopper-amps. The device also has enough common mode rejection ratio to allow the low drift to be fully utilized.

CIRCUIT DESCRIPTION

The LM121 is a well matched differential amplifier utilizing super-gain transistors as the input devices. A schematic is shown in *Figure 1*. The input signal is applied to the bases of Q_3 and Q_4 through protection resistors R_1 and R_2. Q_3 and Q_4 have two emitters to allow offset balancing which will be explained later. The operating current for the differential amplifier is supplied by current sources Q_{10} and Q_{11}. The operating current is externally programmed by resistors connected from the emitters of Q_{10} and Q_{11} to the negative supply. Input transistors Q_3 and Q_4 are cascoded by transistors Q_5 and Q_6 to keep the collector base voltage on the input stage equal to zero. This eliminates leakage at high operating temperatures and keeps the common mode input voltage from appearing across the low breakdown super-gain input transistors. Additionally, the cascode improves the common mode rejection of the differential amplifier. Q_1 and Q_2 protect the input against large differential voltages.

The ouput signal is developed across resistive loads R_3 and R_4. The total collector current of the input is then applied to the base of a fixed gain PNP, Q_7. The collector current of Q_7 sets the operating current of Q_8, Q_{12}, and Q_{13}. These transistors are used to set the operating voltage of the cascode, Q_5 and Q_6. By operating the cascode biasing transistors at the same operating current as the input stage, it is possible to keep collector base voltage at zero; and therefore, collector-base leakage remains low over a wide current range. Further, this minimizes the effects of V_{BE} variations and finite transistor current gain. At high operating currents the collector base voltage of the input stage is increased by about 100 mV due to the drop across R_{15} and R_{16}. This prevents the input transistors from saturating under worst case conditions of high current and high operating temperature.
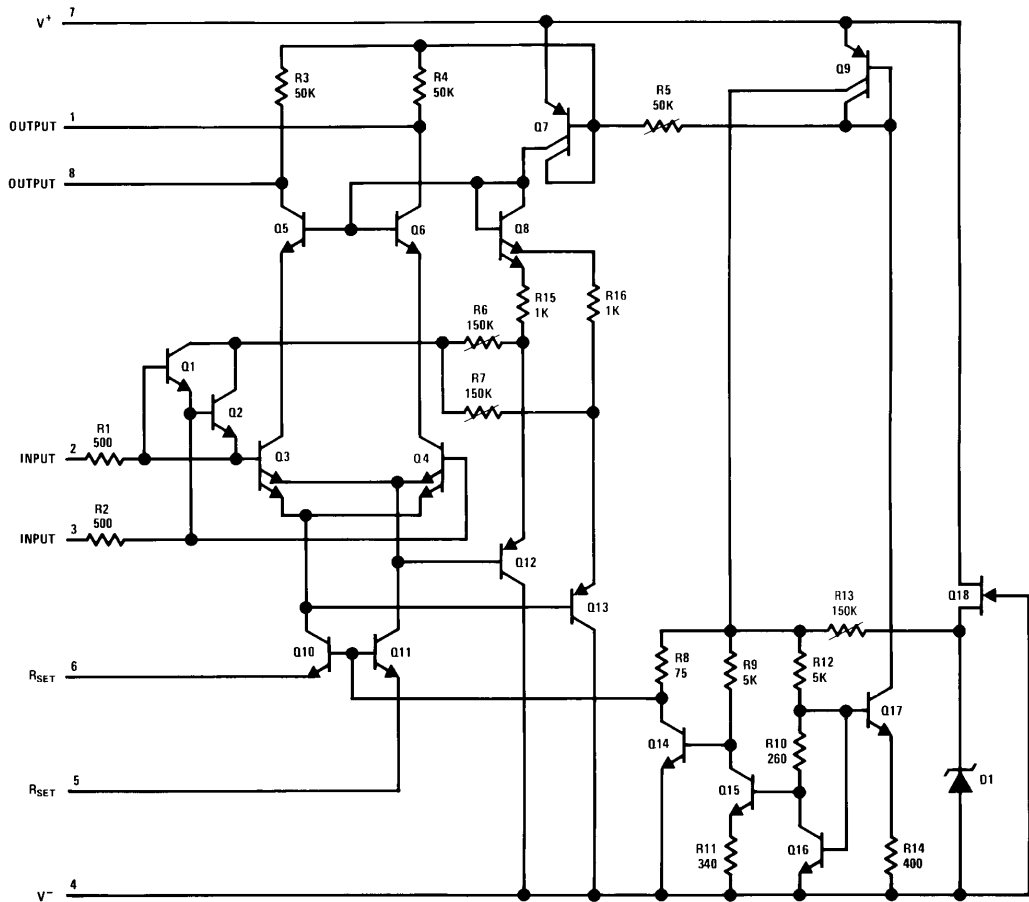
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*Pin connections shown on diagram and typical applications are for TO-5 package.

FIGURE 1. Schematic Diagram of the LM121

The rest of the devices comprise the turn-on and regulator circuitry. Transistors Q_{14}, Q_{15}, and Q_{16} form a 1.2V regulator for the bases of the input stage current source. By fixing the bases of the current sources at 1.2V, their ouput current changes proportional to absolute temperature. This compensates for the temperature sensitivity of the input stage transconductance. Temperature compensating the transconductance makes the preamp more useful in some applications such as an instrumentation amplifier and minimizes bandwidth variations with temperature. The regulator is started by Q_{18} and its operating current is supplied by Q_{17} and Q_9, *Figure 2* shows the LM121 chip.

OFFSET BALANCING

The LM121 was designed to operate with an offset balancing network connected to the current source transistors. The method of balancing the offset also minimizes the drift of the preamp. Unlike earlier devices such as the LM725,

the LM121 depends only upon the highly predictable emitter base voltages of transistors to achieve low drift. Devices like the LM725 depend on the match between internal resistor temperature coefficient and the external null pot as well as the input stage transistors characteristics for drift compensation.

The input stage of the LM121 is actually two differential amplifiers connected in parallel, each having a fixed offset. The offset is due to different areas for the transistor emitters. The offset for each pair is given by:

$$\Delta V_{BE} = \frac{kT}{q} \ln \frac{A_1}{A_2}$$

where k is Boltzmann's constant T is absolute temperature,
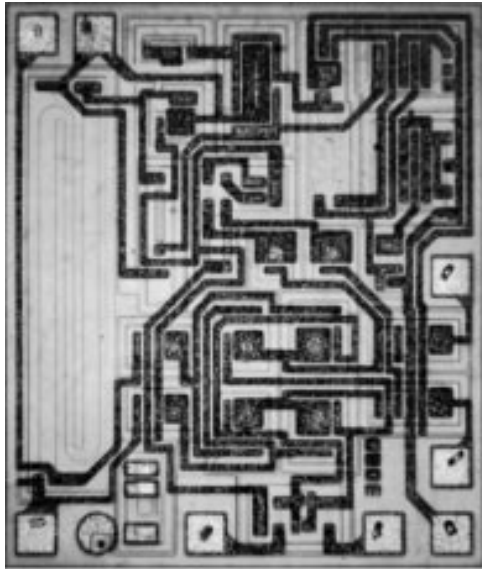
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FIGURE 2. LM121 Chip

q is the charge on an electron, and A_1 and A_2 are emitter areas. Because of the offset, each pair has a fixed drift. When the pairs are connected in parallel, if they match, the offsets and drift cancel. However, since matching is not perfect, the emitters of the pairs are not connected in parallel, but connected to independent current sources to allow offset balancing. The offset and drift effect of each pair is proportional to its operating current, so varying the ratio of the current from current sources will vary both the offset and drift. When the offset is nulled to zero, the drift is nulled to below 1 μV/°C.

The offset balancing method used in the LM121 has several advantages over conventional balancing schemes. Firstly, as mentioned earlier, it theoretically zeros the drift and offset simultaneously. Secondly, since the maximum balancing range is fixed by transistor areas, the effect of null network variations on offset voltage is minimized. Resistor shifts of one percent only cause a 30 μV shift in offset voltage on the LM121, while a one percent shift in collector resistors on a standard diff amp causes a 300 μV offset change. Finally, it allows the value of the null network to set the operating current.

ACHIEVING LOW DRIFT

A very low drift amplifier poses some uncommon application and testing problems. Many sources of error can cause the apparent circuit drift to be much higher than would be predicted. In many cases, the low drift of the op amp is completely swamped by external effects while the amplifier is blamed for the high drift.

Thermocouple effects caused by temperature gradient across dissimilar metals are perhaps the worst offenders. Whenever dissimilar metals are joined, a thermocouple results. The voltage generated by the thermocouple is proportional to the temperature difference between the junction and the measurement end of the metal. This voltage can range between essentially zero and hundred of microvolts per degree, depending on the metals used. In any system using integrated circuits a minimum of three metals are found: copper, solder, and kovar (lead material of the IC).

Nominally, most parts of a circuit are at the same temperature. However, a small temperature gradient can exist across even a few inches — and this is a big problem with low level signals. Only a few degrees gradient can cause hundreds of microvolts of error. The two places this shows up, generally are the package-to printed circuit board interface and temperature gradients across resistors. Keeping package leads short and the two input leads close together help greatly.

For example, a very low drift amplifier was constructed and the output monitored over a 1 minute period. During the 1 minute it appeared to have input referred offset variations of ± 5 μV. Shielding the circuit from air currents reduced this to ± 0.5 μV. The 10 μV error was due to thermal gradients across the circuit from air currents.

Resistor choice as well as physical placement is important for minimizing thermocouple effects. Carbon, oxide film and some metal film resistors can cause large thermocouple errors. Wirewound resistors of evenohm or managanin are best since they only generate about 2 μV/°C referenced to copper. Of course, keeping the resistor ends at the same temperature is important. Generally, shielding a low drift stage electrically and thermally will yield good results.

Resistors can cause other errors besides gradient generated voltages. If the gain setting resistors do not track with temperature a gain error will result. For example a gain of 1000 amplifier with a constant 10 mV input will have a 10V output. If the resistors mistrack by 0.5% over the operating temperature range, the error at the output is 50 mV. Referred to input, this is a 50 μV error. Most precision resistors use different material for different ranges of resistor values. It is not unexpected that resistors differing by a factor of 1000, do not track perfectly with temperature. For best results insure that the gain fixing resistors are of the same material or have tracking temperature coefficients.

Testing low drift amplifiers is also difficult. Standard drift testing techniques such as heating the device in an oven and having the leads available through a connector, thermoprobe, or the soldering iron method — do not work. Thermal gradients cause much greater errors than the amplifier drift. Coupling microvolt signals through connectors is especially bad since the temperature difference across the connector can be 50°C or more. The device under test along with the gain setting resistor should be isothermal. The circuit in *Figure 3* will yield good results if well constructed.
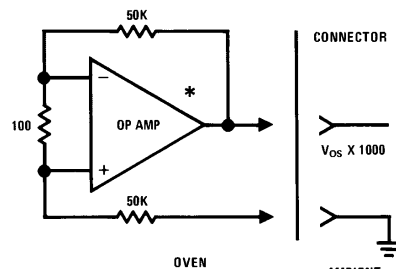
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*Op amp shown in *Figure 9*.

FIGURE 3. Drift Measurement Circuit

PERFORMANCE

It is somewhat difficult to specify the performance of the LM121 since it is programmable over a wide range of operating currents. Changing the operating current varies gain, bias current, and offset current — three critical parameters in a high accuracy system. However, offset voltage and drift are virtually independent of the operating current.

Typical performance at an operating current of 20 μA is shown in Table I. *Figures 4* and *5* show how the bias current, offset current, and gain change as a function of programming current. Drift is guaranteed at 1 μV/°C independent of the operating current.

TABLE I. Typical Performance at an Operating Current of 10 μA Per Side

Offset Voltage	Nulled
Bias Current	7 nA
Offset Current	0.5 nA
Offset Voltage Drift	0.3 μV/°C
Common Mode Rejection Ratio	125 dB
Supply Voltage Rejection Ratio	125 dB
Common Mode Range	±13V
Gain	20 V/V
Supply Current	0.5 mA
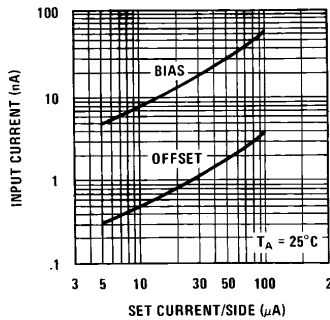
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FIGURE 4. Bias and Offset Current vs Set Current
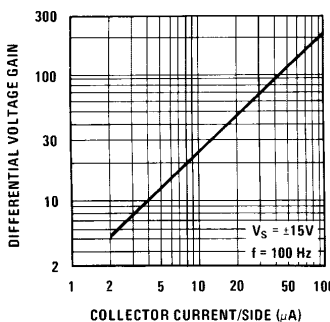
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FIGURE 5. Gain vs Set Current

Over a temperature range of −55°C to +125°C the LM121 has less than 1 μV/°C offset voltage drift when nulled. It is important that the offset voltage is accurately nulled to achieve this low drift. The drift is directly related to the offset voltage with 3.8 μV/°C drift resulting from every millivolt of

offset. For example, if the offset is nulled to 100 μV, about 0.4 μV/°C will result — or twice the typically expected drift. This drift is quite predictable and could even be used to cancel the drift elsewhere in a system. *Figure 6* shows drift as a function of offset voltage. For critical applications selected devices can achieve 0.2 μV/°C.

Figures 7 and *8* show the bias current, offset current, and gain variation over a −55°C to +125°C temperature range. These performance characteristics do not tell the whole story. Since the LM121 is used with an operational amplifier, the op amp characteristics must be considered for over-all amplifier performance.
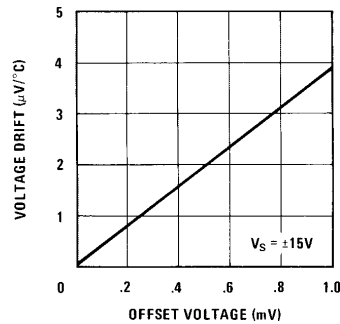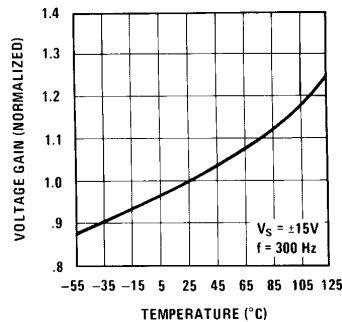
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FIGURE 6. Drift vs Offset Voltage
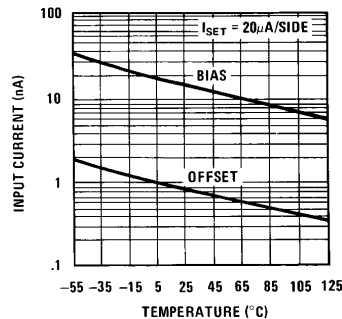
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FIGURE 7. Bias and Offset Current vs Temperature

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FIGURE 8. Gain vs Temperature for the LM121

OP AMP EFFECTS

The LM121 is nominally used with a standard type of operational amplifier. The op amp functions as the second and ensuing stages of the amplifying system. When the LM121 is connected to an op amp, the two devices may be treated (and used) just as a single op amp. The inputs of the combination are the inputs of the LM121 and the output is from the op amp. Feedback, as with any op amp, is applied back to the inputs. *Figure 9* shows the general configuration of an amplifier using the LM121.

The offset voltage and drift of the op amp used have an effect on overall performance and must be considered. (The bias and offset currents of today's op amp are low enough to be ignored.) Although the exact effects of the op amp stage are difficult and tedious to calculate, a few approximations will show the sources of drift.

Op amp drift is perhaps the most important source of error. Drift of the op amp is directly reduced by the gain of the LM121. The drift referred to the input is given by:

$$\text{input drift} = \frac{\text{op amp drift}}{\text{LM121 gain}} + \text{LM121 drift}.$$

If the op amp has a drift of 10 μV/°C and the LM121 is operated at a gain of $A_V = 50$, there will be a 0.2 μV/°C component of the total drift due to the op amp. It is therefore important that the LM121 be operated at relatively high gain to minimize the effects of op amp drift. Lower gains for the LM121 will give proportionately less reduction in op amp drift. Of course, a moderately low drift op amp such as the LM108A eases the problem.

Op amp offset voltage also has an effect on total drift. For purpose of analysis assume the LM121 to be perfect with no offset or drift of its own. Then any offset seen when the LM121 is connected to an op amp is due to the op amp alone. The offset is equal to:

$$\text{offset voltage} = \frac{\text{op amp offset}}{\text{LM121 gain}}$$

or the offset is reduced by the gain of the LM121. For example, with a gain of 50 for the LM121, 2 mV of offset on the op amp appears as 40 μV of offset at the LM121 input. Unlike offset due to a mismatch in the LM121, this 40 μV of offset does not cause any drift. However, when the system is nulled so the offset at the input of the LM121 is zero, 40 μV of imbalance has been inserted into the LM121. The imbalance caused by nulling the offset induced by the op amp will cause a drift of about 0.14 μV/°C. With the system nulled the drift due to op amp will cause a drift of about 0.15 μV/°C. With the system nulled the drift due to op amp offset can be expressed as:

$$\text{drift } (\mu V/°C) = \frac{\text{op amp offset (mV)}}{\text{LM121 gain}} (3.6 \ \mu V/°C).$$

In actual operation, drift due to op amp offsets will usually be better than predicted. This is because offset voltage and drift are not independent. With the LM121 there is a strong, predictable, correlation between offset and drift. Also, there is a correlation with op amps, but it is not as strong. The drift of the op amp tends to cancel the drift induced in the LM121 when the system is nulled.

In the previous example the drift due to the op amp offset was 0.15 μV/°C. If the op amp has a drift of 3.6 μV/°C per millivolt of offset (like the LM121) it will have a drift of 7.2 μV/°C. This drift is reduced by the gain of the LM121 ($A_V = 50$) to 0.14 μV/°C. This 0.14 μV/°C will cancel the 0.14 μV/°C drift due to balancing the LM121. Since op amps do not always have a strong correlation between offset and drift, the cancellation of drifts is not total. Once again, high gain for the LM121 and a low offset op amp helps achieve low drifts.

FREQUENCY COMPENSATION

The additional gain of the LM121 preamplifier when used with an operational amplifier usually necessitates additional frequency compensation. This is because the additional gain introduced by the LM121 must be rolled-off before the phase shift through the LM121 and op amp reaches 180°. The additional compensation depends on the gain of the LM121 as well as the closed loop gain of the system. Two frequency compensation techniques are shown here that will operate with any op amp that is unity gain stable.

When the closed loop gain of the op amp with the LM121 is less than the gain of the LM121 alone, more compensation is needed. The worst case situation is when there is 100% feedback — such as a voltage follower or integrator — and the gain of the LM121 is high. When high closed loop gains are used — for example $A_V = 1000$ — and only an additional gain of 100 is inserted by the LM121, the frequency compensation of the op amp will usually suffice.

The basic circuit of the LM121 in *Figure 9* shows two compensation capacitors connected to the op amp (disregarding the 30 pF frequency compensation for the op
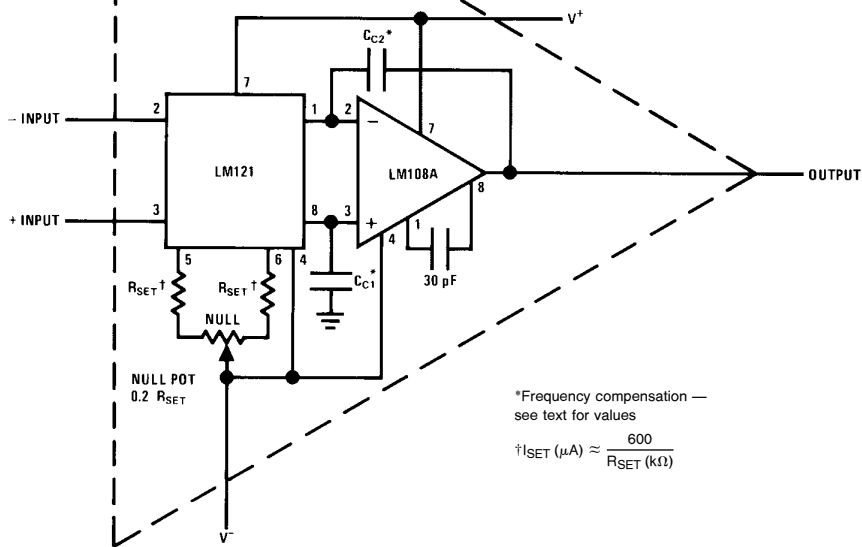
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FIGURE 9. General Purpose Amplifier Using the LM121

amp alone). The capacitor from pin 6 to pin 2 around the op amp acts as an integrating capacitor to roll off the gain. Since the output of the LM121 is differential, a second capacitor is needed to roll off pin 3 of the op amp. These capacitors are C_{C1} and C_{C2} in *Figure 9*.

With capacitors equal, the circuit retains good AC power supply rejection. The approximate value of the compensation capacitors is given by:

$$C_C = \frac{8}{10^6 \, A_{CL} \, R_{SET}} \text{ farads}$$

where R_{SET} is the current set resistor from each current source and where A_{CL} is closed loop gain. Table II shows typical capacitor values.

An alternate compensation scheme was developed for applications requiring more predictable and smoother roll off. This is useful where the amplifier's gain is changed over a wide range. In this case C_{C1} is made large and connected to V^+ rather than ground. The output of the LM121 is rendered single ended by a 0.01 μF bypass capacitor to V^+. Overall frequency compensation then is achieved by an integrating capacitor around the op amp:

$$\text{Bandwidth at unity gain} \cong \frac{12}{2\pi \, R_{SET} \, C}$$

$$\text{for 0.5 MHz bandwidth } C = \frac{4}{10^6 \, R_{SET}}$$

TABLE II. Typical compensation capacitors for various operating currents and closed loop gains. Values given apply to LM101A, LM108, and LM741 type amplifiers.

Closed Loop Gain	Current Set Resistor				
	120 kΩ	60 kΩ	30 kΩ	12 kΩ	6 kΩ
$A_V = 1$	68 pF	130 pF	270 pF	680 pF	1300 pF
$A_V = 5$	15 pF	27 pF	50 pF	130 pF	270 pF
$A_V = 10$	10 pF	15 pF	27 pF	68 pF	130 pF
$A_V = 50$	1 pF	3 pF	5 pF	15 pF	27 pF
$A_V = 100$		1 pF	3 pF	5 pF	10 pF
$A_V = 500$			1 pF	1 pF	3 pF
$A_V = 1000$					

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For use with higher frequency op amps such as the LM118 the bandwidth may be increased to about 2 MHz. If closed loop gain is greater than unity "C" may be decreased to:

$$C = \frac{4}{10^6 \, A_{CL} \, R_{SET}}$$

APPLICATIONS

No attempt will be made to include precision op amp applications as they are well covered in other literature. The previous sections detail frequency compensation and drift problems encountered in using very low drift op amps. The circuit shown in *Figure 9* will yield good results in almost any op amp application. However, it is important to choose the operating current properly. From the curves given it is relatively easy to see the effects of current changes. High currents increase gain and reduce op amp effects on drift. Bias and offset current also increase at high current. When the operating source resistance is relatively high, errors due to high bias and offset current can swamp offset voltage drift errors. Therefore, with high source impedances it may be advantageous to operate at lower currents.

Another important consideration is output common mode voltage. This is the voltage between the outputs of the LM121 and the positive power supply. Firstly, the output common mode voltage must be within the operating common mode range of the output op amp. At currents above 10 μA there is no problems with the LM108, LM101, and LM741 type devices. Higher currents are needed for devices with more limited common mode range, such as the LM118. As the operating current is increased, the positive common mode limit for the LM121 is decreased. This is because there is more voltage drop across the internal 50k load resistors. The output common mode voltage and positive common mode limits are about equal and given by:

Output common mode voltage positive common mode limit $\approx V^+ - \left(0.6V + \dfrac{0.65 \times 50\,k\Omega}{R_{SET}} \right)$

If it is necessary to increase the common mode output voltage (or limit), external resistors can be connected in parallel with the internal 50 kΩ resistors. This should only be done at high operating currents (80 μA) since it reduces gain and diverts part of the input stage current from the internal bias-ing circuitry. A reasonable value for external resistors is 50 kΩ.

The external resistors should be of high quality and low drift, such as wirewound resistors, since they will affect drift if they do not track well with temperature. A 20 ppm/°C difference in external resistor temperature coefficient will introduce an additional 0.3 μV/°C drift.

An unusually simple gain of 1000 instrumentation amplifier can be made using the LM121. The amplifier has a floating, full differential, high impedance input. Linearity is better than 1%, depending upon input signal level with maximum error at maximum input. Gain stability, as shown in *Figure 10*, is about ±2% over a −55°C to +125°C temperature range. Finally, the amplifier has very low drift and high CMRR.
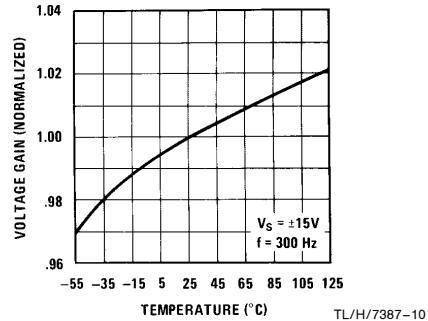

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**FIGURE 10. Instrumentation Amplifier
Gain vs Temperature**

Figure 11 shows a schematic of the instrumentation amplifier. The LM121 is used as the input stage and operated open-loop. It converts an input voltage to a differential output current at pins 1 and 8 to drive an op amp. The op amp acts as a current to voltage converter and has a single-ended output.

Resistors R_1 and R_2 with null pot R_3 set the operating current of the LM121 and provide offset adjustment. R_4 is a fine trim to set the gain at 1000. There is very little interaction between the gain and null pots.

*Offset adjust

†Gain trim

‡Better than 1% linearity for input signals up to ±10 mV gain stability typical ±2% from −55°C to +125°C CMRR 110 dB.
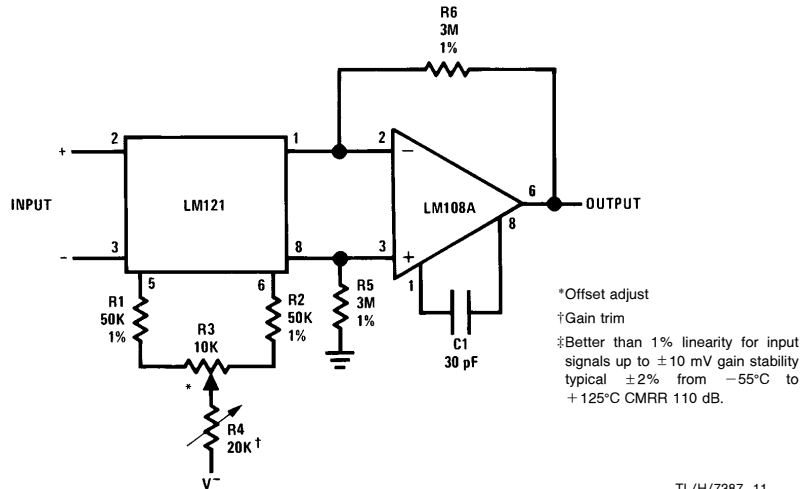
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FIGURE 11. Gain of 1000 Instrumentation Amplifier

This instrumentation amplifier is limited to a maximum input signal of ±10 mV for good linearity. At high signal levels the transfer characteristic of the LM121 becomes rapidly non-linear, as with any differential amplifier. Therefore, it is most useful as a high gain amplifier.

Since feedback is not applied around the LM121, CMRR is not dependent on resistor matching. This eliminates the need for precisely matched resistor as with conventional instrumentation amplifiers. Although the linearity and gain stability are not as good as conventional schemes, this amplifier will find wide application where low drift and high CMRR are necessary.

A precision reference using a standard cell is shown in *Figure 12*. The low drift and low input current of the LM121A allow the reference amplifier to buffer the standard cell with high accuracy. Typical long term drift for the LM121 operat-

ing at constant temperature is less than 2 μV per 1000 hours.

To minimize temperature gradient errors, this circuit should be shielded from air currents. Good single-point wiring should also be used. When power is not applied, it is necessary to disconnect the standard cell from the input of the LM121 or it will discharge through the internal protection diodes.

CONCLUSIONS

A new preamplifier for operational amplifiers has been described. It can achieve voltage drifts as low as many chopper amplifiers without the problems associated with chopping. Operating current is programmable over a wide range so the input characteristics can be optimized for the particular application. Further, using a preamp and a conventional op amp allows more flexibility than a single low-drift op amp.
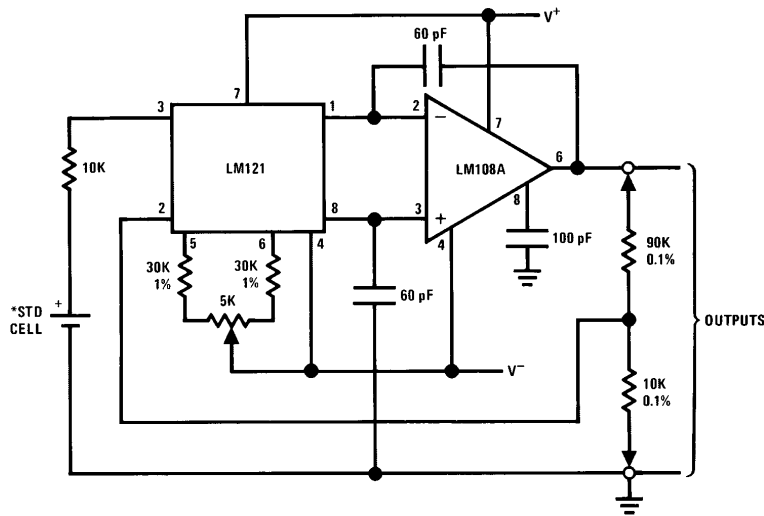

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FIGURE 12. 10V Reference