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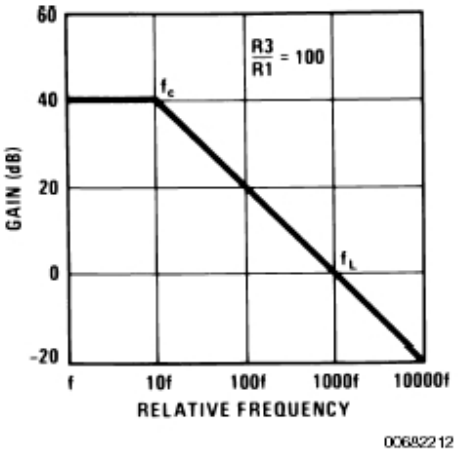


FIGURE 12. Low Pass Filter Response

简单低通滤波器的电路如***图11***。本电路在闭环3dB转折点为fc，对高于fc的信号有6dB/2倍频程的衰减。低于fc频率的信号的增益由R3/R1决定，在输入信号频率远大于fc的情况下，电路可以看成是对交流信号的积分器；可以认为，在此时，从时域响应上看，比起积分来说，RC（的时间延迟特性）更明显。R2的阻值应选为R1和R3的并联阻值，以减小输入偏置电流带来的误差。在这里可以选择带内部频率补偿的OP或者在外部对单位增益的频率特性进行补偿。电路的增益波特图见***图12***，本图说明了LPF和真正的积分器之间在频率特性上的区别。

10. The Current-to-Voltage Converter

电流—电压转换电路：

Current may be measured in two ways with an operational amplifier. The current may be converted into a voltage with a resistor and then amplified or the current may be injected directly into a summing node. Converting into voltage is undesirable for two reasons: first, an impedance is inserted into the measuring line causing an error; second, amplifier offset voltage is also amplified with a subsequent loss of accuracy. The use of a current-to-voltage transducer avoids both of these problems. The current-to-voltage transducer is shown in Figure 13. The input current is fed directly into the summing node and the amplifier output voltage changes to extract the same current from the summing node through R1. The scale factor of this circuit is R1 volts per amp. The only conversion error in this circuit is I_{bias} which is summed algebraically with I_{IN}. This basic circuit is useful for many applications other than current measurement. It is shown as a photocell amplifier in the following section. The only design constraints are that scale factors must be chosen to minimize errors due to bias current and since voltage gain and source impedance are often indeterminate (as with photocells) the amplifier must be compensated for unity-gain operation. Valuable techniques for bias current compensation are contained in Reference 5.

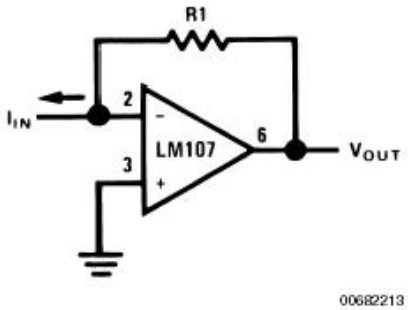


FIGURE 13. Current to Voltage Converter

利用OP进行电流测量，有两种方法。利用电流在电阻上的压降，再进行电压放大，或者直接将电流注入OP的求和点。这样的电路，转换得到的电压信号可以直接加在OP放大的输入端上。这种转换方式有两个不妥的地方：首先电阻的加入将会破坏电路原来的状态，带来测量上的误差。其次OP的失调电压也会被OP自己放大，并加到测量的输出结果中去。使用电流——电压转换电路可以避免上面两点不足。电路结构如***图13***。输入电流直接接入OP的求和点（反相输入端），由KCL定理可知，OP输出端将通过R1向这个点（求和点）提供同样大小的电流以达到平衡，电路的增益（这里叫跨导似乎更好——译者）由R1决定。本电路唯一的误差来源于输入偏置电流I_{bias}，该电流作为误差，和输入电流I_{IN}做了代数叠加。

电流——电压转换电路的用途不限于电流的测量上，还可以用在例如后面的光电池放大电路中。在设计中唯一需要注意的是电路的增益的选择，增益的选择要做到使得偏置电流所带来的误差达到最小。由于信号源的电压和内阻通常是不恒定的，OP必须对单位增益做补偿。偏置电流的补偿方法可以参考***文献5***。

11. Photocell Amplifiers

光电放大器：

Amplifiers for photoconductive, photodiode and photovoltaic cells are shown in Figures 14, 15, 16 respectively. All photogenerators display some voltage dependence of both speed and linearity. It is obvious that the current through a photoconductive cell will not display strict proportionality to incident light if the cell terminal voltage is allowed to vary with cell conductance. Somewhat less obvious is the fact that photodiode leakage and photovoltaic cell internal losses are also functions of terminal voltage.

The current-to-voltage converter neatly sidesteps gross linearity problems by fixing a constant terminal voltage, zero in the case of photovoltaic cells and a fixed bias voltage in the case of photoconductors or photodiodes.

Photodetector speed is optimized by operating into a fixed low load impedance. Currently available photovoltaic detectors show response times in the microsecond range at zero load impedance and photoconductors, even though slow, are materially faster at low load resistances. The feedback resistance, R1, is dependent on cell sensitivity and should be chosen for either maximum dynamic range or for a desired scale factor. R2 is elective: in the case of photovoltaic cells or of photodiodes, it is not required in the case of photoconductive cells, it should be chosen to minimize bias current error over the operating range.

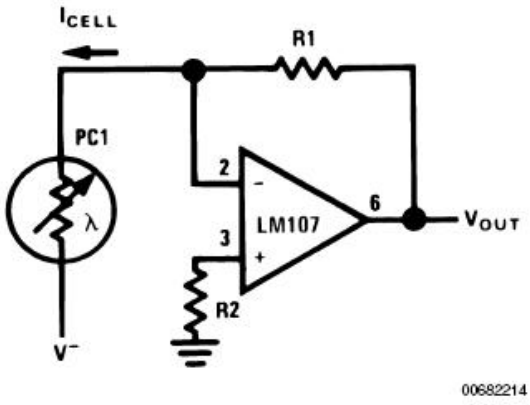
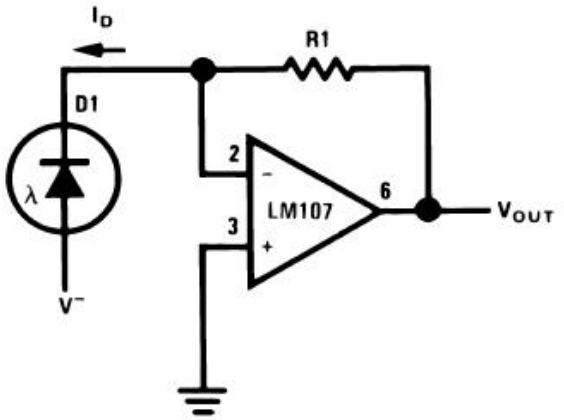
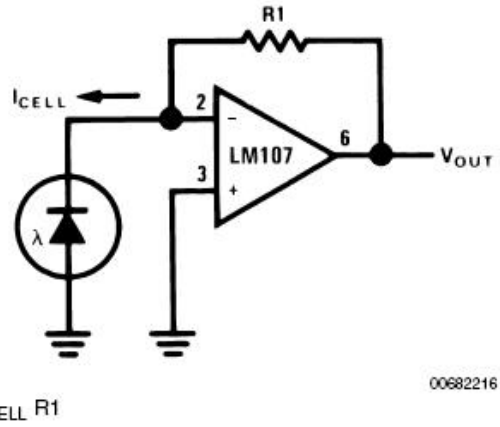


FIGURE 14. Amplifier for Photoconductive Cell



$V_{OUT} = R1\ I_D$

FIGURE 15. Photodiode Amplifier



$V_{OUT} = I_{CELL}\ R1$

FIGURE 16. Photovoltaic Cell Amplifier

光电放大器用于放大由光电导、光电二极管和光电池所得到的光强度信号，如***图 14***、***15***、***16***。这些光电传感器的输出电压与线性度和（响应）速度有关。显然，如果任由光电导电池的端电压随其电导变化而变化，那么其输出电流与入射光强度之间就不会遵循严格的比例关系。此外，光电二极管的漏电流和光电池的内部损耗也是其端电压的函数。

电流——电压转换电路利用在光电检测器的输出端加上一个恒定的电压来巧妙地解决了整体上的线性度问题。对于光电池来说，这个电压为 0V；对于光电导或光电二极管来说，是一个偏置电压。

光电检测器件，在负载为适当的低阻抗时，其信号转换速度将得到优化。现行的光电检测器在 0 负载的情况下，响应速度可以达到毫秒数量级，半导体光电器件稍慢，但是在低阻抗负载的情况下，其速度也会得到质的提高。反馈电阻 R1 的取值由电池的灵敏度和要求的最大动态范围，或者需要的电流——电压转换比例决定。R2 分情况选取：在光电池和光电二极管时不需要这个电阻，在光电导的时候，电阻的阻值应该能使在工作范围内，由 OP 输入偏置电流所带来的误差最小。

12. Precision Current Source

精密电流源：

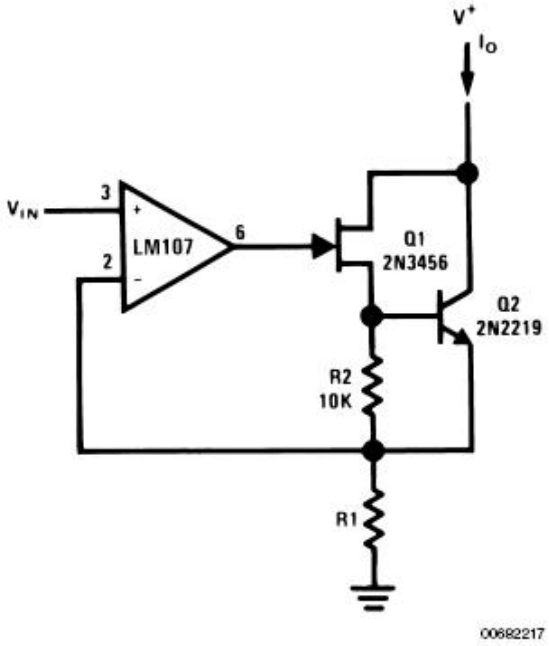
The precision current source is shown in Figures 17, 18. The configurations shown will sink or source conventional current respectively.

Caution must be exercised in applying these circuits. The voltage compliance of the source extends from BV_{CER} of the external transistor to approximately 1 volt more negative than V_{IN}. The compliance of the current sink is the same in the positive direction.

The impedance of these current generators is essentially infinite for small currents and they are accurate so long as V_{IN} is much greater than V_{OS} and I_O is much greater than I_{bias}.

The source and sink illustrated in Figures 17, 18 use an FET to drive a bipolar output transistor. It is possible to use a Darlington connection in place of the FET-bipolar combination in cases where the output current is high and the base current of the Darlington input would not cause a significant error.

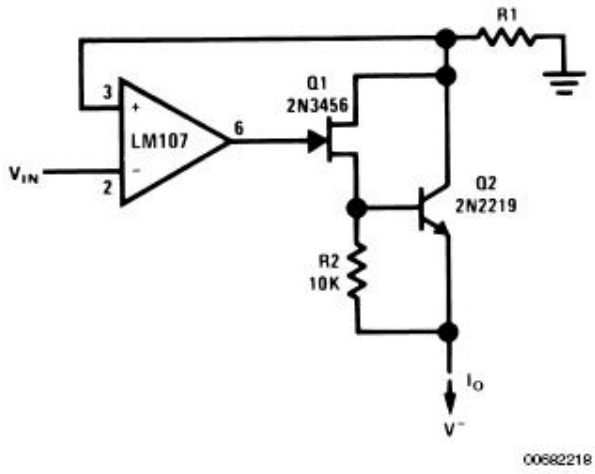
The amplifiers used must be compensated for unity-gain and additional compensation may be required depending on load reactance and external transistor parameters.



$$I_O = \frac{V_{IN}}{R1}$$

$V_{IN} \geq 0V$

FIGURE 17. Precision Current Sink



$$I_O = \frac{V_{IN}}{R1}$$

$V_{IN} \leq 0V$

FIGURE 18. Precision Current Source

图17、18 分别给出了精密电流源电路在吸入和输出电流两种情况下的电路结构。

在实际应用本电路的时候必须注意，（OP 输出端的）电压范围为外部晶体管的 BV_{CER} 到比输入电压 V_{IN} 低约 1V（多）。

从原则上说，电流源电路在小电流状态下内阻是无穷大的。在 V_{IN} 大于 V_{OS}，并且 I_O 比 OP 的偏置电流大得多的情况下，可以认为输出电流是精确的。

图17、18 中使用了一个 FET 来驱动输出级的 BJT。当需要大的输出电流的时候，可以选用达林顿来取代这个输出电路。并且其（栅极）输入电流不会对电路带来显著的误差。

本电路使用的 OP 必须对单位增益进行补偿。并且根据负载特性和输出级电路的特性可能需要额外的补偿。

13. Adjustable Voltage References

可调参考电压源：

Adjustable voltage reference circuits are shown in Figures 19, 20, 21, 22. The two circuits shown have different areas of applicability. The basic difference between the two is that Figures 19, 20 illustrate a voltage source which provides a voltage greater than the reference diode while Figures 21, 22 illustrates a voltage source which provides a voltage lower than the reference diode. The figures show both positive and negative voltage sources.

High precision extended temperature applications of the circuit of Figures 19, 20 require that the range of adjustment of V_{OUT} be restricted. When this is done, R1 may be chosen to provide optimum zener current for minimum zener T.C. Since Iz is not a function of V+, reference T.C. will be independent of V+.

The circuit of Figures 21, 22 are suited for high precision extended temperature service if V+ is reasonably constant since Iz is dependent on V+. R1, R2, R3, and R4 are chosen to provide the proper Iz for minimum T.C. and to minimize errors due to I_{bias}.

The circuits shown should both be compensated for unity-gain operation or, if large capacitive loads are expected, should be overcompensated. Output noise may be reduced in both circuits by bypassing the amplifier input.

The circuits shown employ a single power supply, this requires that common mode range be considered in choosing an amplifier for these applications. If the common mode range requirements are in excess of the capability of the amplifier, two power supplies may be used. The LH101 may be used with a single power supply since the common mode range is from V+ to within approximately 2 volts of V-.