DESIGN NOTES

Single-Ended to Differential Amplifier Design Tips – Design Note 454

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Introduction

A fully differential amplifier is often used to convert a single-ended signal to a differential signal, a design which requires three significant considerations: the impedance of the single-ended source must match the single-ended impedance of the differential amplifier, the amplifier's inputs must remain within the common mode voltage limits and the input signal must be level shifted to a signal that is centered at the desired output common mode voltage.
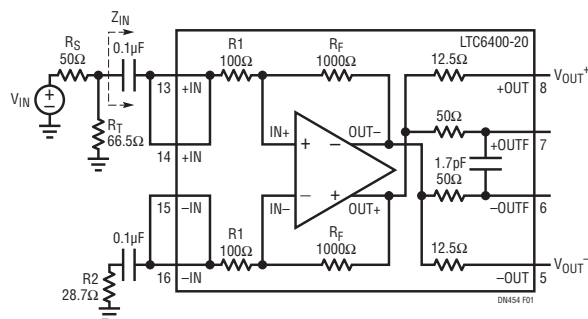
In all cases, input impedance matching to the source impedance is necessary to prevent high frequency reflections. In designs where the single-ended source is DC coupled to a single supply differential amplifier, then level shifting and the common mode limits are also important considerations. The interaction of these three design parameters is non-trivial—component selection requires spreadsheet analysis using the equations described here.

Input Impedance Matching

If input AC coupling is used, then impedance matching is the only design issue. Figure 1 shows an example of a circuit matching a 50Ω single-ended source to an AC-coupled LTC®6400-20 differential amplifier with a gain of 20dB set by internal resistors.

The 66.5Ω resistor, R_T, in parallel with the +IN input impedance, Z_{IN}, matches the circuit input impedance to the 50Ω source. Differential balance is provided with the addition of the 28.7Ω resistor at the –IN input, R2. The balancing resistor assures equivalent feedback factors at the inputs, thus preventing large DC offsets.

To calculate the external resistor values, start by calculating Z_{IN}. Then calculate R_T for impedance matching and the value of the R2 for differential balance. The overall single-ended to differential gain (GAIN) must take into account the input attenuation of the R_S and R_T resistive divider and the effect of adding R2. In this example,

$$Z_{IN} = \frac{\sqrt{\left(R2^2 \bullet \left(4 \bullet R1^2 + R_S^2\right) + 8 \bullet R_F \bullet R1^3 + 4 \bullet R1^4\right)} + R_F \bullet \left(2 \bullet R1 + R_S\right) + 2 \bullet R1 \bullet \left(R1 + R_S\right)}{2 \bullet \left(R_F + 2 \bullet R1 + R_S\right)}$$

$$R_T = \frac{R_S \bullet Z_{IN}}{Z_{IN} - R_S} \qquad R2 = \frac{R_S \bullet R_T}{R_S + R_T}$$

$$GAIN = \frac{V_{OUT}^+ \, V_{OUT}^-}{V_{IN}} \frac{\left(R1 + R2 + R_F\right) \bullet \left(R1 \bullet \left(R_S - R_T\right) + R_S \bullet R_T\right)}{R_S \bullet R_T \bullet \left(R1 + R2\right)}$$

Figure 1. Impedance Matching for a Differential Amplifier with Fixed Gain Integrated Resistors

the overall gain of the amplifier from signal source to differential output is only 4.44 even though the amplifier has a fixed gain of 10.

By AC coupling at the input, the amplifier's input common mode voltage is equal to its output common mode voltage and the single-ended signal is automatically level shifted to an output differential signal centered on the output common mode voltage.

If the input common mode voltage is not 0V, and the source cannot deliver the DC current into 116.5Ω (50Ω + 66.5Ω), then it is also necessary to AC couple the 66.5Ω resistor.

The DC Coupled Differential Amplifier

A general purpose, DC coupled, single-ended-to-differential amplifier circuit with source impedance matching and input level shifting is shown in Figure 2. Level shifting is provided by the reference voltage (V_{REF}). If V_{REF} is set to be equal to the input common mode voltage (V_{INCM}) then the single-ended input signal is

$$R_F = \frac{\sqrt{\left(GN^2 \cdot \left(4 \cdot R1^2 + R_S^2\right) + 2 \cdot GN \cdot R1 \cdot \left(2 \cdot R1 - R_S\right) + R1^2\right)} + GN \cdot \left(2 \cdot R1 + R_S\right) - R1}{2}$$

$$R_T = \frac{R_S \cdot (R1 + R_F)}{R1 + R_F - R_S \cdot (GN + 1)} \qquad R2 = \frac{R_S \cdot R_T}{R_S + R_T}$$

$$V_A = \frac{R_F \cdot V_{INCM} + \left(V_{OCM} \pm \frac{GN}{2} \cdot V_{INP-P}\right) \cdot (R1 + R2)}{R1 + R2 + R_F}$$

$$V_T = \frac{\left((R1 + R_F) \cdot (R_S + R_T)\right) \cdot V_{INCM} + R_S \cdot R_T \cdot V_{OCM}}{R1 \cdot (R_S + R_T) + R_F \cdot (R_S + R_T) + R_S \cdot R_T} \pm \frac{V_{INP-P}}{4}$$
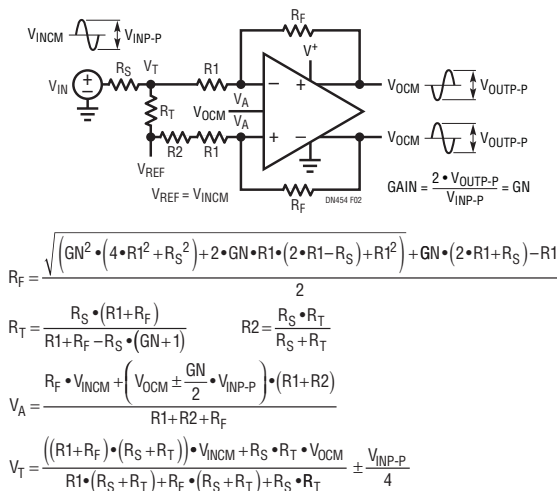
Figure 2. Impedance Matching and Level Shifting for a Differential Amplifer with Gain Set By External Resistors

shifted to a differential signal centered on the output common mode voltage (V_{OCM}).

The design of a single-ended to differential amplifier with external resistors provides an additional design option: specifying the amplifier gain. Figure 2 shows the design equations when the R_F and R1 resistors are selectable, not fixed.

The design of this circuit begins with the value of R1. This resistor must be larger than the input source resistance but not so large as to increase circuit noise. Next, calculate the value of the feedback resistor R_F using the desired gain (GN). Then calculate the value of resistors R_T and R2.

Figure 3 shows an example of a single-ended-to-differential amplifier matching a 75Ω source and level shifting from a 2.5V input common mode to a 1.25V output common mode voltage (typical level shifting required from a 5V single-ended circuit to a 3V differential circuit to drive a high speed ADC). The single-ended-to-differential gain of the Figure 3 amplifier is 2 (the 1V$_{P-P}$ input signal is amplified into a 2V$_{P-P}$ differential output signal, a typical input voltage range of a high speed ADC).

For linear operation, the amplifier's input common mode limits must not be exceeded. Figure 2 shows the calculations for the bias voltage (V_T) of the input T-network (R_S, R_T and R1) and the common mode voltage at the differential amplifier's inputs. For example, in Figure 3, the 1.99V to 2.44V at the amplifier's inputs (as calculated by the V_A equation) is well within the rail-to-rail input common mode range of the LTC6406 (0V to V$^+$).

Table 1. Sample of LTC High Speed Differential Amplifiers

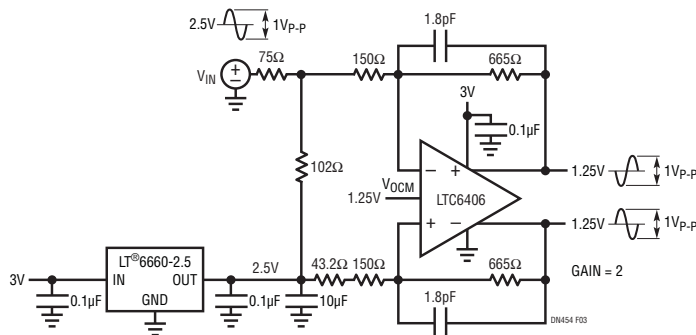| AMPLIFIER	GBW GHz	SLEW RATE V/μs	VOLTAGE NOISE nV/√Hz	GAIN V/V
LTC6400-26	1.9	6670	1.5	20
LTC6400-20	1.8	4500	2.1	10
LTC6400-14	1.9	4800	2.5	5
LTC6400-8	2.2	3810	3.7	2.5
LTC6401-20	1.3	4500	2.1	10
LTC6401-14	2	3600	2.5	5
LTC6404-1	0.5	450	1.5	R SET
LTC6404-2	0.9	700	1.5	R SET
LTC6405	2.7	690	1.6	R SET
LTC6406	3	630	1.6	R SET

Figure 3. Putting it All Together: A 133MHz Differential Amplifier with External Gain Setting Resistors, Impedance Matching to a 75Ω Source and Shifting from 2.5V to 1.25V