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Interfacing RF I/Q Modulators with Popular D/A Converters

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Introduction

Linear Technology's High Frequency Product lineup includes a variety of RF I/Q modulators. The purpose of this application note is to illustrate the circuits required to interface these modulators with several popular D/A converters. Such circuits typically are required to maximize the voltage transfer from the DAC to the baseband inputs of the modulator, as well as provide some reconstruction filtering.

The baseband (I,Q) interface for the modulators falls into one of three categories:

- High impedance, higher common mode DC voltage (LT®5558, LT5518)

  These modulators incorporate a baseband input circuit that presents a high differential impedance (about 2.9k). This circuit generates an internal DC bias voltage of approximately 2.06V; the common mode DC voltage applied to the baseband terminals must match this voltage to within 40mV for proper operation. This corresponds to a source/sink current at each baseband pin of 400µA. Note that this voltage will decrease by about 2.3 mV/°C with temperature.

- Low impedance, lower common mode DC voltage (LT5568, LT5528)

  In this case, the modulator's baseband input circuit presents a low differential impedance (about 100Ω), and generates an internal DC voltage of approximately 0.52V. If the common mode DC voltage applied to the modulator's baseband input terminals deviates from this value by more than about 75mV, the device may not meet the specifications listed in the data sheet, because source voltage affects the current consumed by the mixer core. The common mode voltage is approximately constant over temperature.

- High impedance, lower common mode DC voltage (LT5571, LT5572)

  The baseband input circuit of these modulators presents a very high differential impedance (about 90k). The I, Q inputs do not generate an internal DC voltage, but require an external bias voltage of approximately 0.5V for proper operation. The data sheet for these parts shows changes in performance for applied voltages above and below this level.

  Simplified equivalent input circuits (I, $\overline{I}$, Q or $\overline{Q}$) for these three classes of modulators are shown in Figure 1.

Most D/A converters have differential outputs and fall into one of two categories:

- 0mA to 20mA source current, compliance voltage typically –1V to 1.25V (category 1)

  Examples of these include the following:

Analog Devices	AD9777, AD9779
Texas Instruments	DAC2904, DAC5672, DAC5674
Maxim	MAX5875, MAX5895

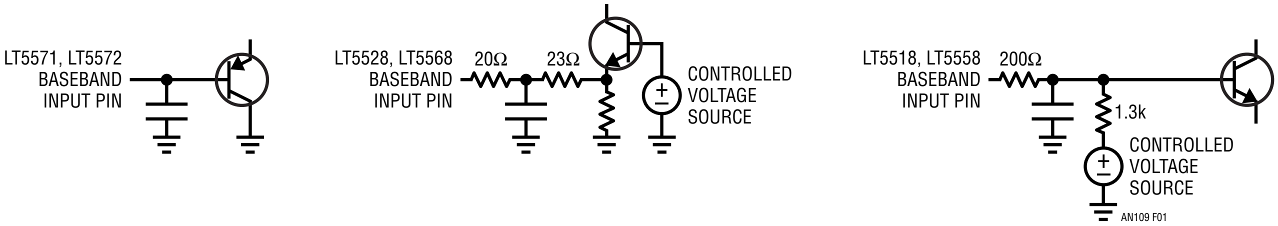

Figure 1. Modulator Baseband Equivalent Circuits (I, $\overline{I}$, Q or $\overline{Q}$)

- 0mA to 20mA source current, compliance voltage 2.8V to 3.8V (category 2)

  Examples of these include the following:

  Texas Instruments DAC5686, DAC5687

There are, in general, three passive networks that are used to couple the output of the D/A converter to the baseband inputs of the I/Q modulator:

- Direct coupling
- Transformer coupling
- Voltage shift network

Coupling networks serve three purposes. First, as all of the D/A converters discussed here are current sources/sinks, the network must provide elements to convert this current to a voltage. Second, the output compliance range of the D/A converter does not always match that of the I/Q modulator. The network addresses this issue, with an eye toward maximizing the gain from DAC output to baseband input. Lastly, these networks usually include reconstruction filters to attenuate the sampling images from the DAC. These filters are typically 3rd or 5th order differential LC filters, designed to match the differential terminating impedances presented by the surrounding network. An example of a passive lowpass filter for a 10MHz baseband bandwidth WCDMA application appears in Figure 2. This filter is a Chebyshev 0.1 dB ripple design. It is designed for a 200Ω differential impedance, with a 10MHz passband frequency and a 40dB cutoff frequency of 21.9MHz.

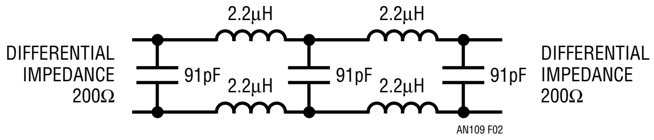

Figure 2. Differential Filter Example

Note that if the modulator is to be used in a power amplifier predistortion loop, the baseband bandwidth must be several times higher than the desired baseband frequency. This is because the predistorted baseband signal contains harmonics that are used to cancel the distortion of the power amplifier.

All of the resistor values shown in the example circuits in this note should be 1% tolerance. Imbalances in these networks can give rise to degraded carrier and sidetone suppression, so the more closely the resistances match each other, the better. Specifically, inequalities in the DC voltages applied to the baseband pins of the modulator will affect the carrier suppression. For example, an otherwise perfect modulator will show a carrier suppression of –40dBc given a 10mV DC offset at any one baseband terminal. Also, if the AC amplitudes of the input signals at the baseband pins are not equal, this can affect the sidetone suppression; see Figure 3 for an example of these effects. If filters are used, unequal phase shifts among the I and Q ports will degrade the sidetone suppression as well. A phase offset of 1°, for example, will degrade an otherwise perfect sidetone suppression to –41.2dBc.

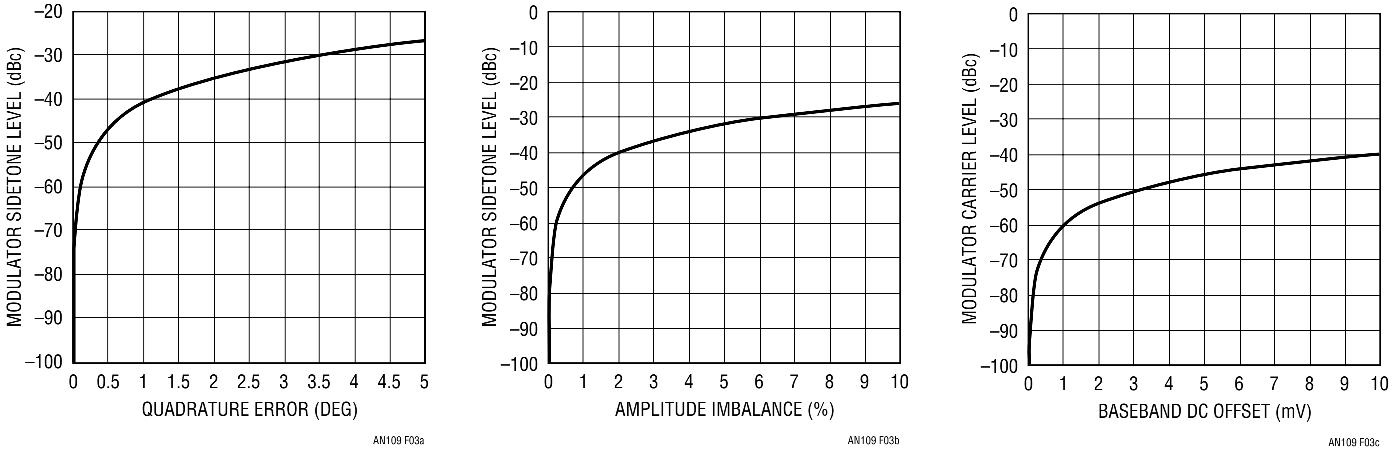

Figure 3. Effects of Modulator Imperfections

The simplest configuration is direct coupling between the output of the DAC and the input of the modulator; see Figure 4. In this case, the network consists of a shunt resistor to ground on each port. This type of network can be used with category 1 DAC's, which have a typical output compliance range of –1V to 1.25V. The DAC is programmed to provide a midrange value of source current, which is typically 10mA. This current flowing into a 52Ω resistor yields a DC voltage of 0.52V. The resulting voltage fits well within the output compliance range of category 1 DAC's, and matches the 0.52V required for proper operation of the LT5528, LT5568, LT5571 and the LT5572.

The maximum output level of the modulator can be increased by increasing the current-to-voltage conversion ratio at the baseband inputs. One way to do this is to change the 52Ω shunt resistor to a higher value, and connect it to a negative voltage rail (instead of ground). This will maintain the DAC within its output compliance voltage range. An example appears in Figure 5. A 1% percent difference between the I^+ and I^- pins of the DAC amounts to a 50mV change in the DC voltage applied to the modulator baseband pins. This has a large effect on carrier suppression, as it will bias the mixer core asymmetrically.

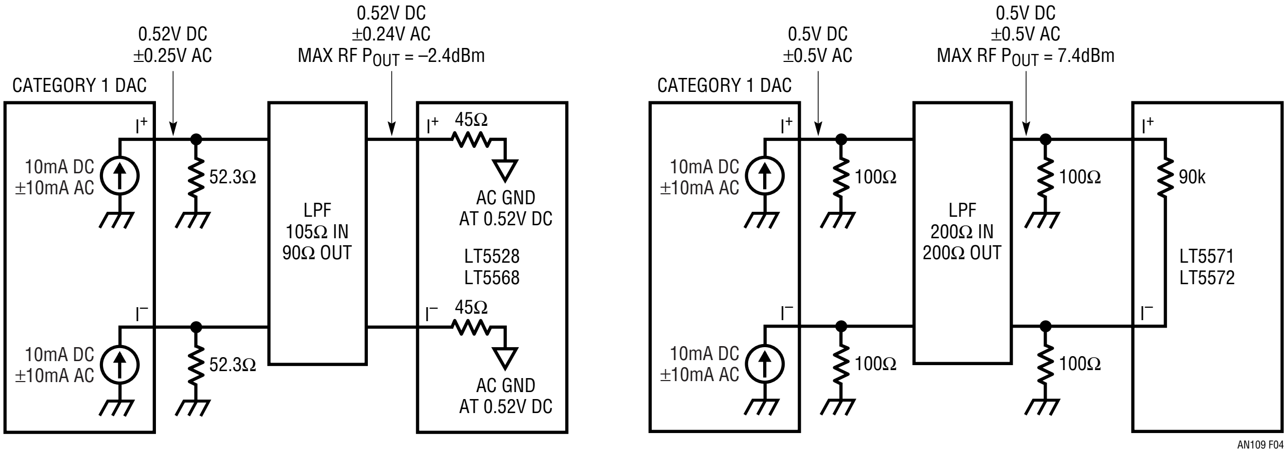

Figure 4. Category 1 DAC Passive DC-Coupled Interfaces

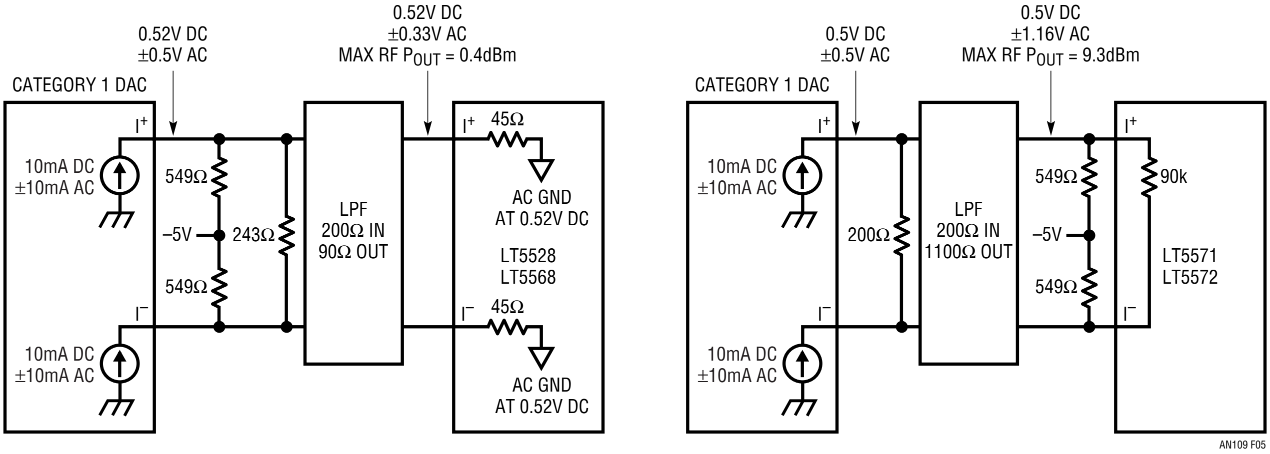

Figure 5. Category 1 DAC Passive DC-Coupled Interfaces with Negative Bias Rail (Only I Channel Shown. Q Channel Interfaces are Identical)

In some cases, the reconstruction filters shown in the example networks are designed with unequal termination impedances. This is done to maximize the voltage gain from the DAC output to the modulator input. In Figure 5 the network used to couple the category 1 DAC to the LT5528/LT5568 includes a lowpass filter with an input impedance of 200Ω and an output impedance of 90Ω. The net differential impedance presented to the DAC output is then 50Ω, while the output impedance of the filter matches the input impedance of the modulator (~90Ω).

In some cases, the compliance range of the DAC will not include the DC input voltage of the modulator. One approach to this problem is transformer coupling. See Figure 6. The transformer effectively provides AC coupling between the DAC and the modulator. The output compliance voltage of the DAC is accommodated by connecting the center tap of the transformer to the appropriate voltage.

One key issue with any network that provides an AC-coupled interface is the low frequency corner. In the case of available transformers, this corner may be as low as 4kHz. Nevertheless, the removal of low frequency baseband signal information may be a problem in some applications. Other cases may require that the carrier suppression of the modulator be optimized by adding small offsets to the DC voltages applied to the modulator inputs. This consideration rules out AC-coupled approaches, unless there is provision for auxiliary trim DAC's at the modulator baseband pins.

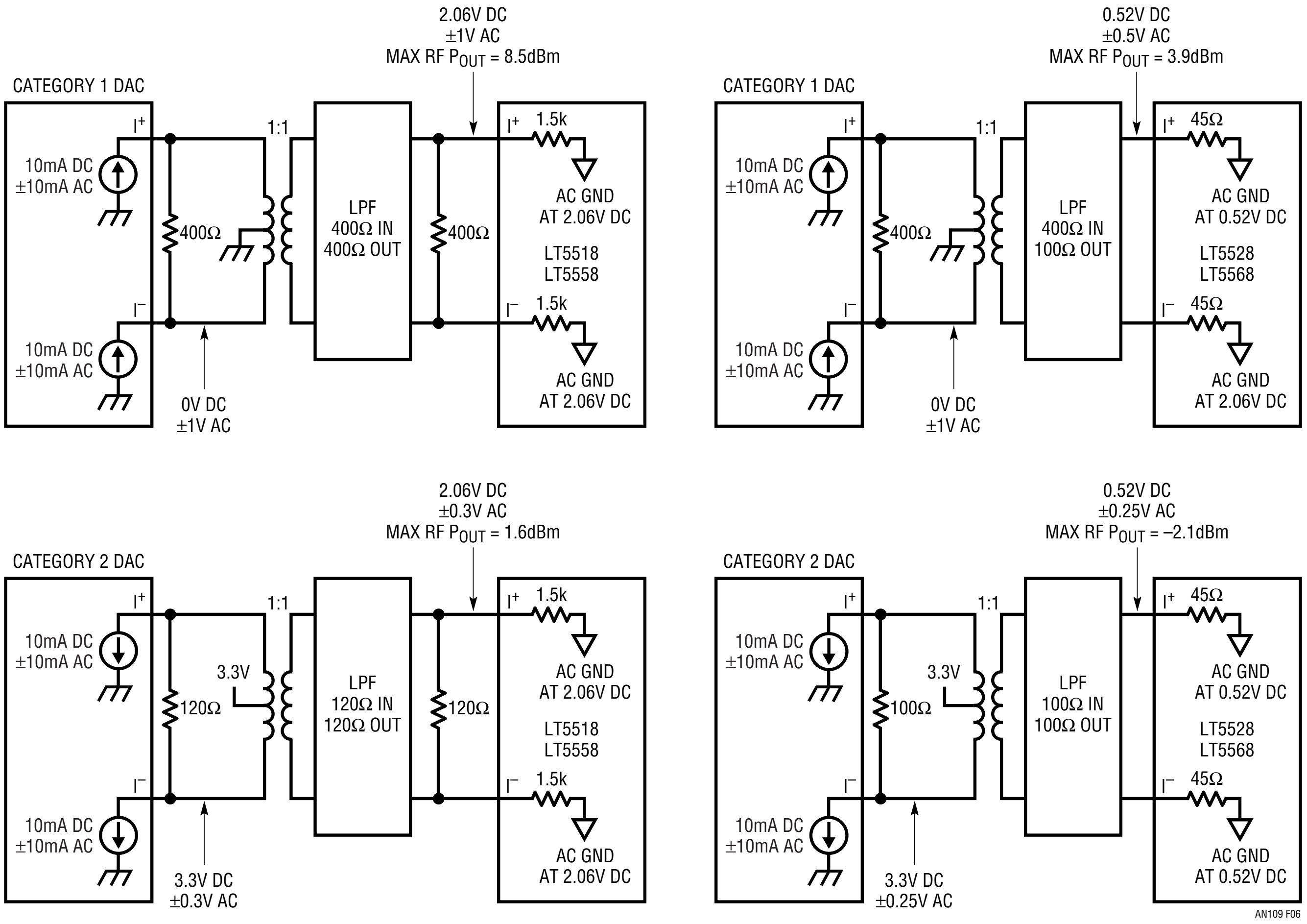

Figure 6. Transformer-Coupled Interfaces

Another approach to the issue of compliance range is AC coupling via series capacitors. See Figure 7. Networks that use capacitors to implement AC coupling present a similar low-frequency issue as those that use transformers; the example shown in Figure 7 yields a corner frequency of 102Hz when a 1µF coupling capacitor is used.

The compliance range of the DAC can also be matched to the DC requirement of the modulator with a resistive level-shifting network. See Figures 8 and 9. In some cases, the network is required to shift the DC voltage at the modulator input upward to accommodate the DAC. In other cases, the voltage shift required is downward.

Resistive level-shifting networks are not frequency-sensitive, but they do come with a penalty. The resistive divider ratio inherent in these circuits attenuates the baseband signal significantly. For example, the network shown in Figure 8 connecting a category 2 DAC to an LT5518/LT5558 will attenuate the baseband signal by 4.2dB, assuming the bypass capacitors are not used. For the category 1 DAC example shown, the attenuation is 11dB. The bypass capacitors shown will eliminate this attenuation for all but the lowest frequencies. The network then becomes a lead-lag network, with pole and zero frequencies depending upon the resistor values required for the voltage transformation.

The coupling network between the DAC and the modulator can also include active elements, such as op amps and active filters. This approach enables a more accurate and balanced reconstruction filtering. If level shifting is required, this can often be incorporated into the active circuit. The LT1565-31, for example, is a 7th order linear phase lowpass filter with a corner frequency of 650kHz. It can be used to provide reconstruction filtering for single channel CDMA or RFID transmitters, and can accommodate the output compliance range of category 1 DACs. The LT1565-31 must be powered from ±5V rails in this

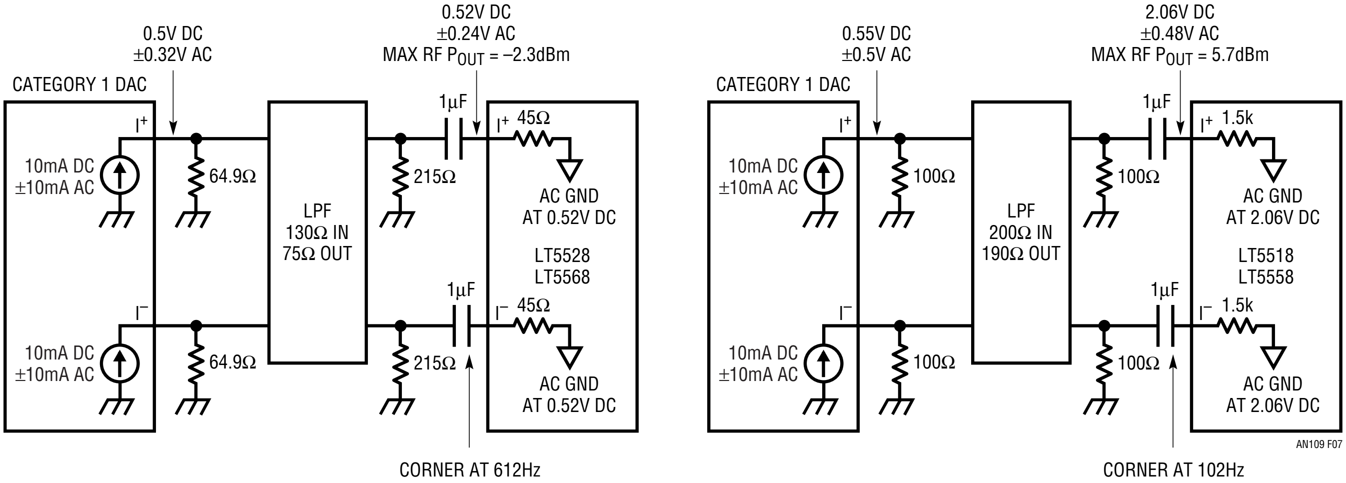

Figure 7. AC-Coupled Interfaces

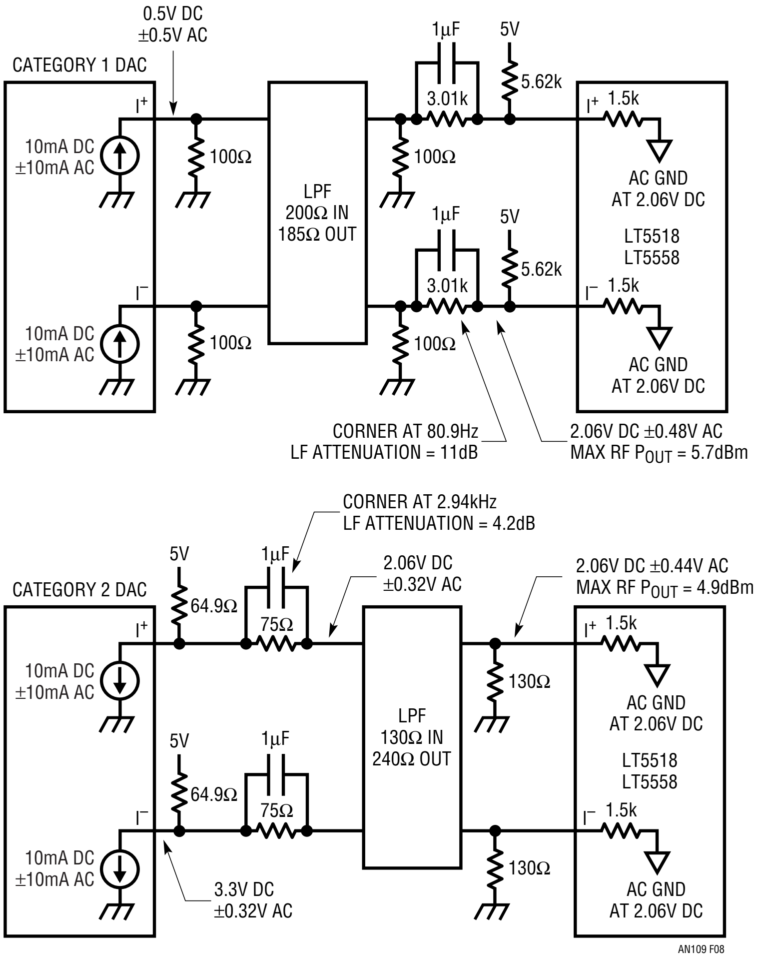

Figure 8. Lead-Lag Coupling Interfaces to 2.1V Baseband Modulators

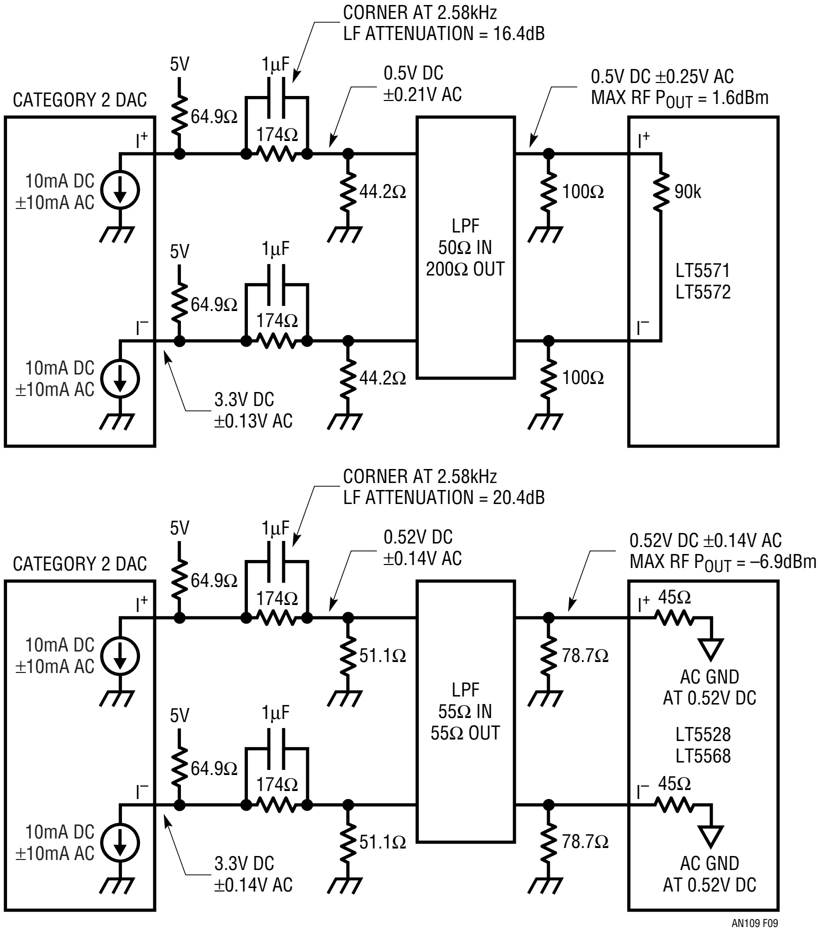

Figure 9. Lead-Lag Coupling Interfaces to 0.5V Baseband Modulators

case. It will drive the LT5518/LT5558 and LT5571/LT5572 modulators, and the output common mode voltage of the LT1565-31 is set by applying a DC voltage at Pin 3. See Figure 10 for details.

Noise may also be an issue with the use of active devices in the baseband circuit. Any active device will have an output noise level that is higher than that of a passive circuit. Take Figure 10 showing the circuit coupling the category 1 DAC to the LT5518/LT5558 as an example. The noise output specification for the LT1565-31 is $118\mu V_{RMS}$ over the bandwidth of the filter. Given a cutoff frequency of 650kHz, the effective noise bandwidth is approximately 780kHz. Assuming the noise level in band is flat, the equivalent output noise level of this device is $133.6nV/\sqrt{Hz}$. The voltage gain of the LT5518 at 2GHz is –4dB, or a factor of 0.63. The output noise level of the modulator at this frequency, due to the noise of the LT1565-31, is then $84.2nV/\sqrt{Hz}$. Given an RF system impedance of 50Ω, this is 45.5dB above kTB, or –128.5dBm/Hz. Note, however, that this elevation of noise level occurs only within the passband of the active filter. So the broadband output noise level of the modulator is not affected by the use of the active device. To assess the effect of the in-band noise, consider a 64QAM signal applied to the modulator. Assume, for example, the level of the modulated signal at the modulator output is 0dBm. The symbol-to-noise ratio is then 69.6dB, which will give rise to an EVM (error vector magnitude) of only 0.035%. This is a very small degradation in comparison to most system EVM specifications, which are on the order of 5% or more.

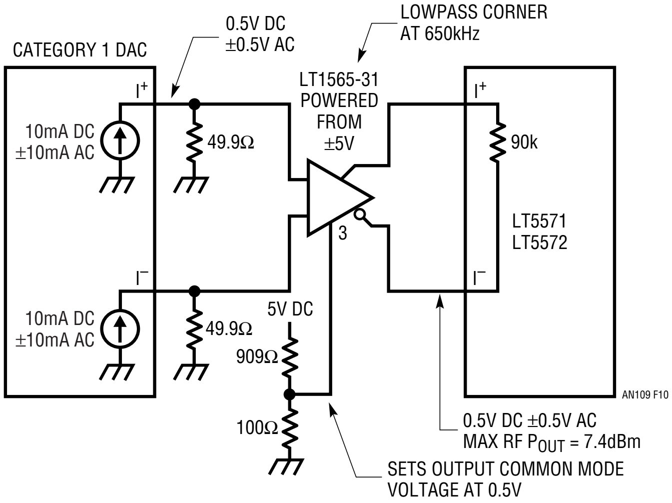

Figure 10. Active Filter Interface with 650kHz Bandwidth

The active device can also provide baseband gain in those cases where the DAC cannot drive the modulator to maximum signal swing. The LT6600-XX, for example, is an active lowpass filter available with bandwidths of 2.5MHz, 10MHz and 20 MHz. It includes a 4th-order linear phase lowpass filter, and the gain can be configured with external resistors. The output common mode voltage is set by applying a DC voltage at Pin 3. See Figures 11 and 12 for details.

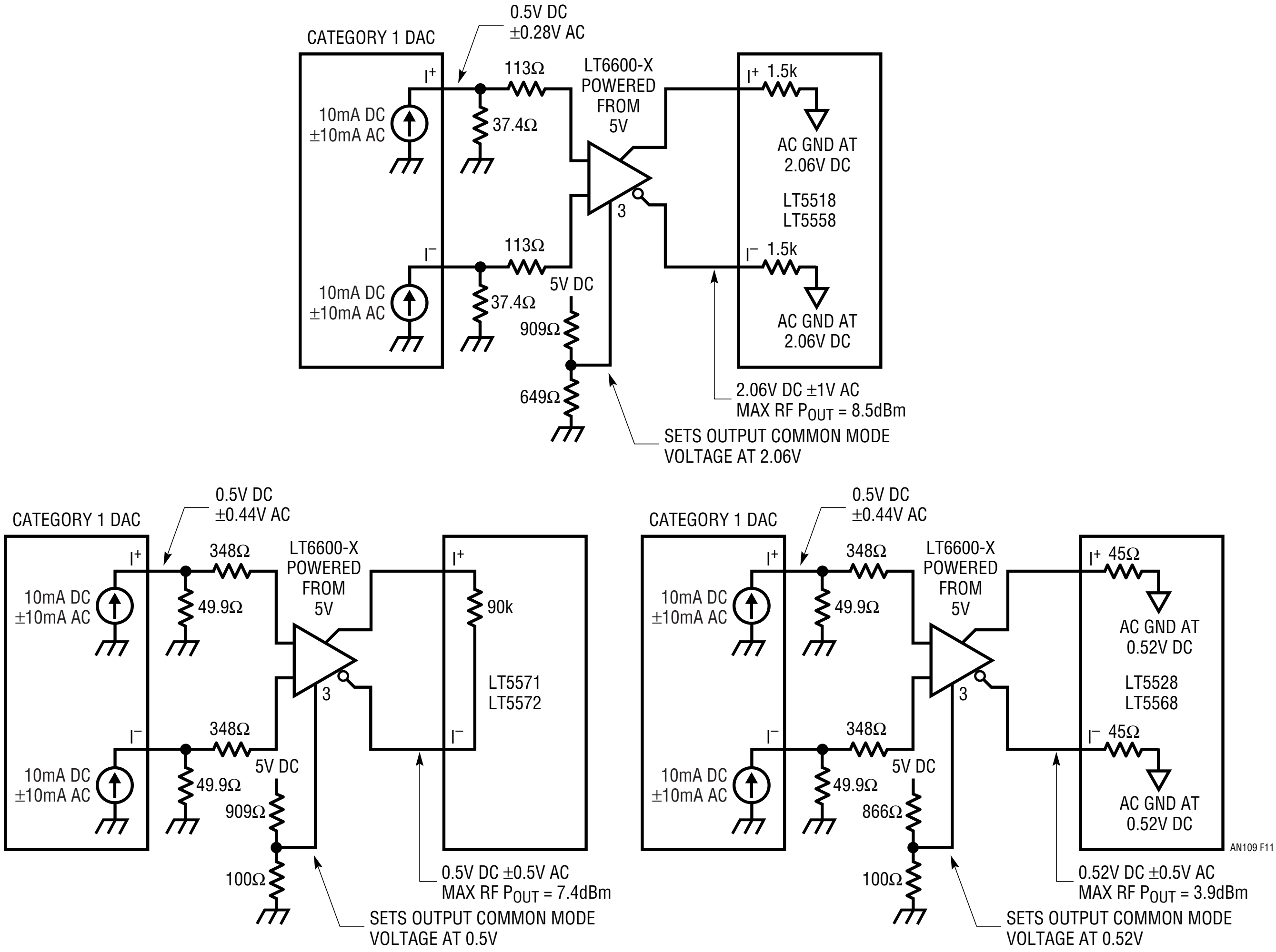

Figure 11. Category 1 DAC Active Filter Interfaces with 2.5MHz, 10MHz or 20MHz Bandwidth

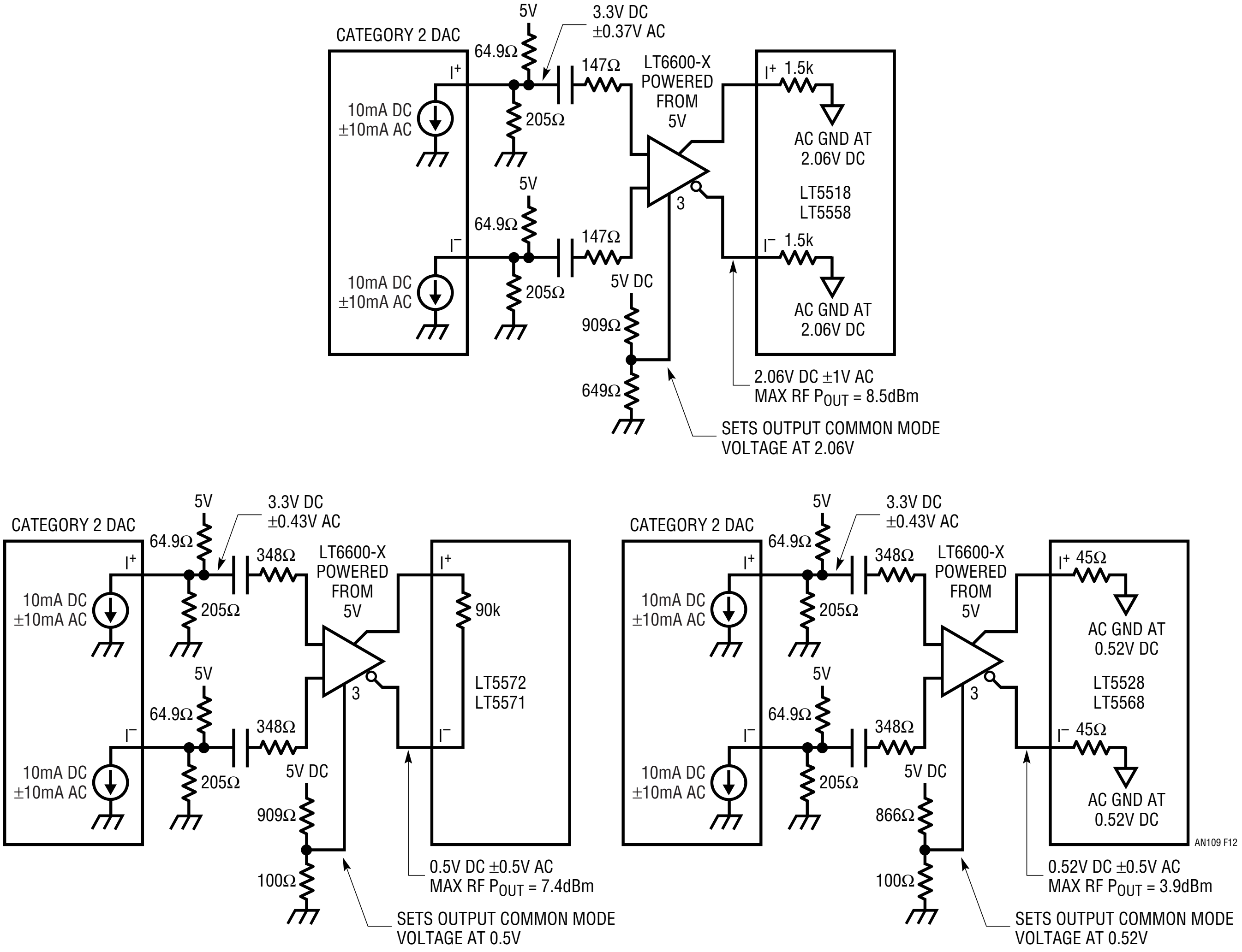

Figure 12. Category 2 DAC Active Filter Interfaces with 2.5MHz, 10MHz or 20MHz Bandwidth

In the case of the LT5518/LT5558, the simple resistive divider used to set the output common mode level of the LT6600-XX does not allow this voltage to track the variation of the modulator baseband voltage over temperature. At temperature extremes, the common mode voltage applied to the baseband pins will be outside the optimum range for the LT5518/LT5558, and some performance degradation will occur. For best performance over temperature, the common mode voltage from the baseband drive circuit should closely match that at the modulator baseband terminals. An example of such a circuit appears in Figure 16 of the LT5558 data sheet.

Op amps with differential outputs can also be used to level shift and amplify the baseband signals. The LT1994 is ideal for this purpose, as it can operate from a single 5V rail. See Figures 13 and 14 for details.

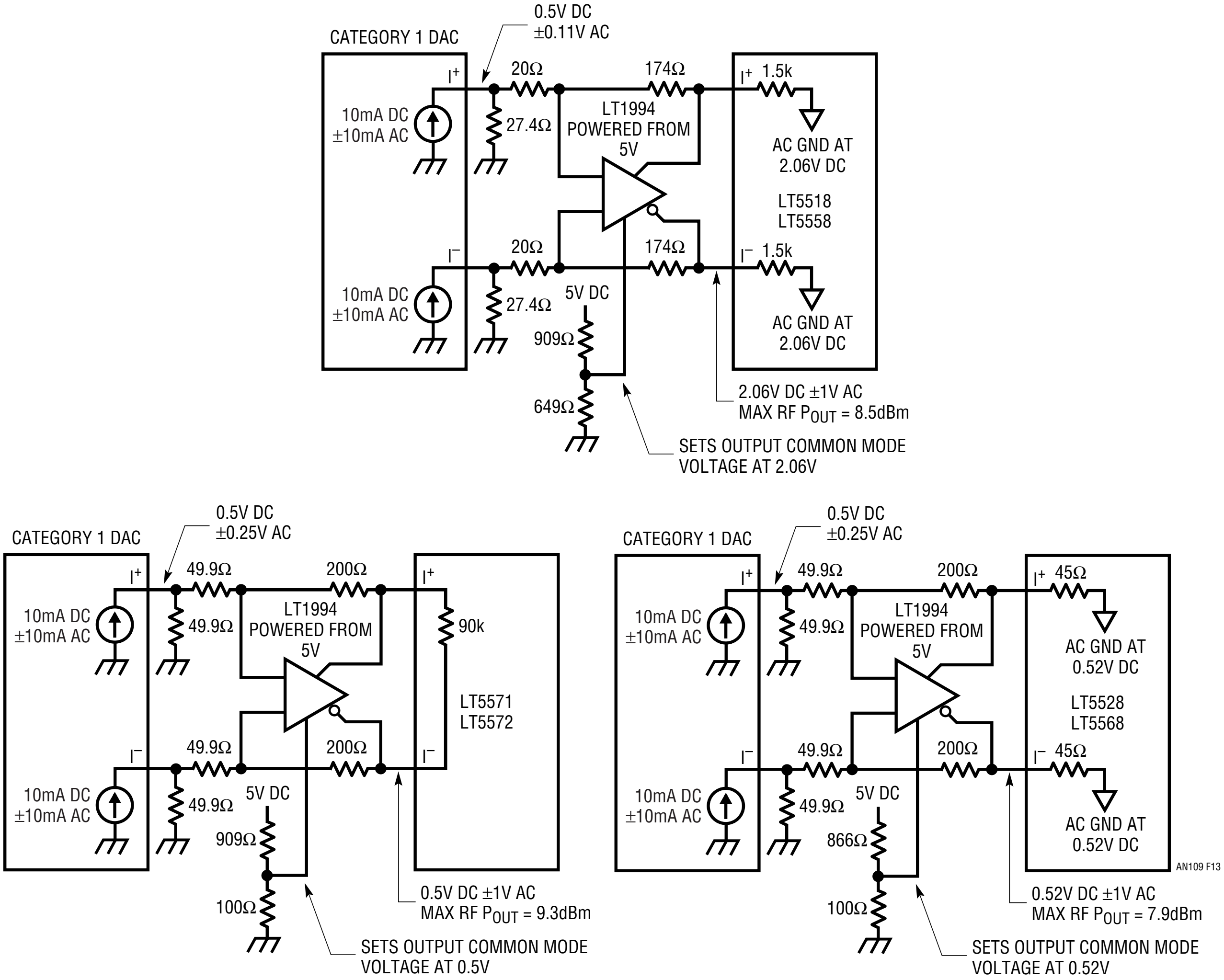

Figure 13. Category 1 DAC Active Interfaces

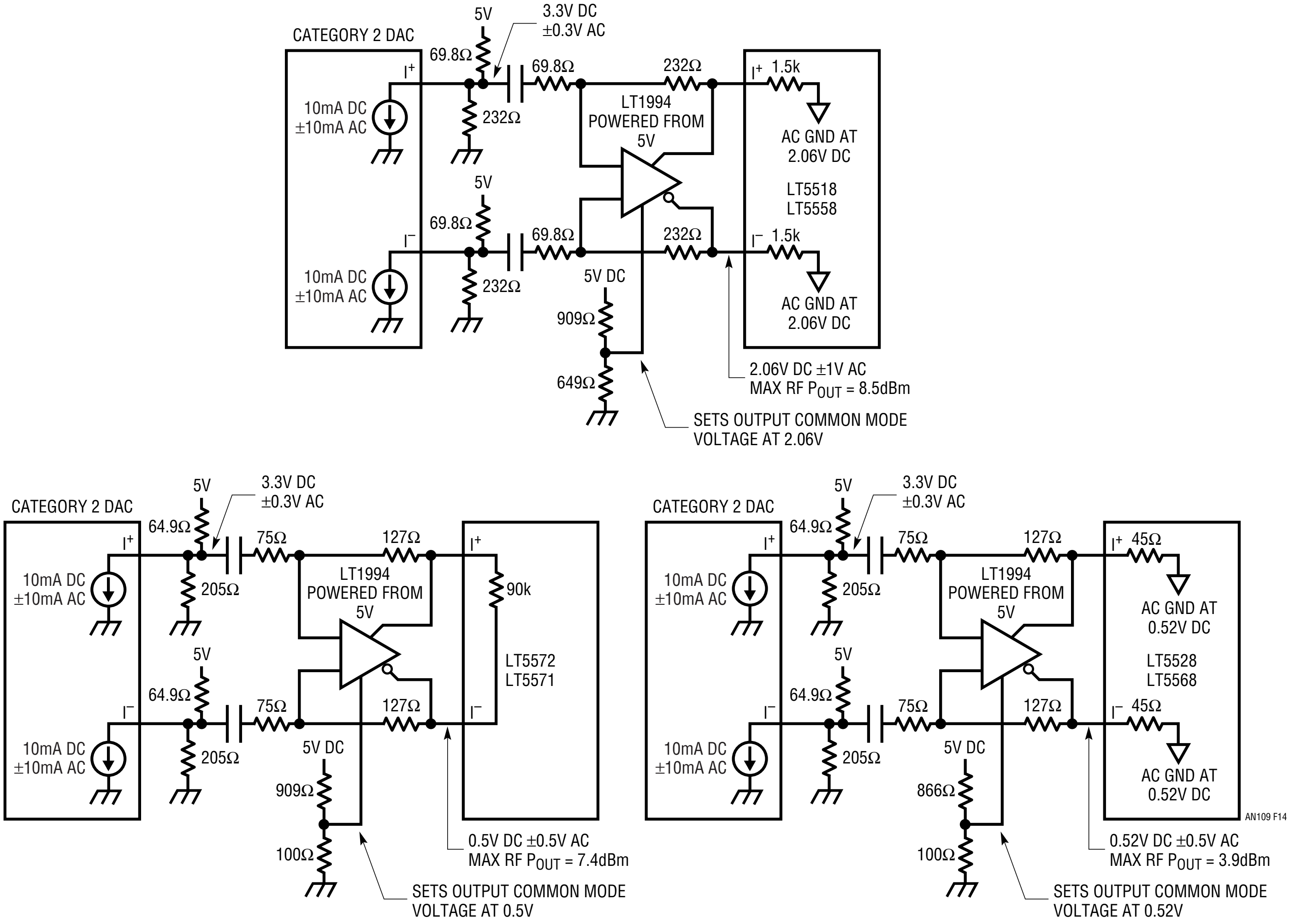

Figure 14. Category 2 DAC Active Interfaces

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