ATA Memo No. 42

Performance Tests of Quadrature Downconverters

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Introduction

In this report, I describe tests of two quadrature mixer ICs as candidates for use in the digitizer module, where they would convert the 1—2 GHz IF to in-phase and quadrature baseband signals which would in turn drive two analog-to-digital converters.

Quadrature mixers, or I/Q mixers, are available as integrated circuits from many manufacturers. Most are designed for UHF input signals (300—500 MHz), but there are also several that work up to or slightly beyond 2 GHz. Nearly all of them have per-channel output bandwidths around 30 MHz or less, which is too small for our purposes. The two tested here, the Maxim MAX2108 [1] and the Analog Devices AD8347 [2], are exceptions in that they have output bandwidths of more than 50 MHz while covering the input range 1—2 GHz. The MAX2108 has the largest baseband range of all such ICs that I have found, namely 0—150 MHz (at –3 dB). (Note that in our application the IF bandwidth is twice the maximum baseband frequency.) However, neither device's data sheet contains useful specifications on its accuracy; each claims less than 3 deg phase error and good amplitude match, but only at a very low output frequency, with no information about performance over the whole useful bandwidth. Telephone inquiries to the manufacturers produced disclaimers of any knowledge of the broadband accuracy. Consequently, the tests reported here were undertaken.

Device Properties

Critical parameters from the data sheets, converted to common units, are summarized in Table 1.

Table 1: Selected Specifications From Data Sheets

	MAX2108	**AD8347**
Input (RF and LO) range, MHz	950—2150	800—2700
Input VSWR at 50 ohms, typical	5.0	1.4
Output bandwidth, MHz	150	65
Output amplifier bandwidth, MHz	N/A	50
Gain imbalance (low frequency), dB max	1	0.3
Phase difference error (low freq.), deg max	3	3
Output level, recommended, mV typ	200	500
Output impedance (diff.), ohms	33	not spec.
Gain control range, dB	50	65
Overall gain at max setting, dB	57	70
Noise figure (at max gain), dB	10	11

It can be seen that the AD8347 is more convenient to use. Its inputs (signal and LO) are much better matched to 50 ohms and it provides higher output levels. Both devices have differential outputs, as desired for driving differential-input ADCs, but the AD8347 includes separately-accessible single-ended outputs from the mixers. Nevertheless, the most important parameters for us are the wideband quadrature accuracy and the dynamic range.

Both devices include voltage-controlled gain with a range of about 50 dB. In our system, this may be the only gain adjustment that is separate for each IF channel, so this is a convenient feature, although we need at most a 20 dB range. (The average gain over the 0.5—11.2 GHz RF band will be set at each antenna.)

Test Setup

Figure 1 shows the test setup used. For the AD8347, the device under test (DUT) was an evaluation board provided by Analog Devices (for schematic, see [2]). For the MAX2108, it was a test board was constructed at the RAL; the schematic is shown in Figure 2. Each board includes provisions for installing discrete-component LC lowpass filters in the baseband signal paths. The filter sections were bypassed for these tests so as to supply the full bandwidth of the device to the outputs.

The MAX2108 board includes resistive pads at the signal and LO inputs so as to improve the impedance match to 50 ohms. Each pad has a loss of approximately 18 dB. The AD8347 board does not include padding, but it uses the recommended shunt resistor and blocking capacitor on one signal input, with the other (differential) input terminated; this should achieve the specified impedance match. The LO is transformer coupled, also using the recommended terminating network. For both boards, external SMA pads of 3 to 12 dB were placed at the board connectors to minimize reflections on the input cables.

Most of the test measurements were made with an HP8405A vector voltmeter (VVM). Checks of the phase and gain offsets of this instrument using a BNC tee to apply the same signal to both channels gave errors of less than 0.5 degree and 2%, respectively, over the test frequency range (5 to 160 MHz).

Analysis

Image Rejection

The I and Q outputs of the quadrature mixer may be thought of as representing, respectively, the real and imaginary parts of an analytic signal. Then signals in the lower sideband of the input appear at negative frequencies of the output, and those in the upper sideband appear at positive frequencies. More precisely, a sinusoidal input signal at frequency ω_s will appear at output frequency $\omega = \omega_s - \omega_0$, where ω_0 is the LO frequency. However, if the mixer's gains from the input to the I and Q outputs depart from the ideal where the magnitudes are equal and the phases differ by 90 deg, then a (typically small) additional output will appear at $f_0 - f_s$; this is known as an image.

The size of the image response can be calculated from measurements of the ratio of the I and Q complex gains, g_I, g_Q, as follows. For a sinusoidal input, the two outputs may be written

$$\begin{aligned} I(t) &= a|g_I|\cos\omega t \\ Q(t) &= a|g_Q|\sin(\omega t + \phi) \end{aligned}$$

where a is the input signal's amplitude and $\phi = \arg g_I - \arg g_Q - \pi/2$ is the phase error. Then the analytic signal interpretation is

$$\begin{aligned} S(t) &= I(t) + jQ(t) \\ &= a[|g_I|\cos\omega t + j|g_Q|(\cos\omega t\cos\phi - \sin\omega t \sin\phi)] \\ &= (a/2)(|g_I| + |g_Q|\cos\phi + j|g_Q|\sin\phi)e^{j\omega t} + (a/2)(|g_I| - |g_Q|\cos\phi + j|g_Q|\sin\phi)e^{-j\omega t} \end{aligned}$$

where I have omitted some of the tedious algebra in the last step. The two major terms in the last expression are at the desired and image frequencies, respectively, and the ratio of their squared magnitudes is the fractional image power:

$$R = \frac{|g_I|^2 + |g_Q|^2 - 2|g_I g_Q|\cos\phi}{|g_I|^2 + |g_Q|^2 + 2|g_I g_Q|\cos\phi}.$$

By adjusting the complex gain in either the I or Q signal path, the image power can be corrected to zero. However, both the magnitude and phase of the correction will generally vary with frequency, and may be different in each sideband, making a broadband correction difficult to implement. Nevertheless, a magnitude and phase adjustment that is fixed with frequency is often worthwhile. If $g_I(\omega)/g_Q(\omega)$ is known, then the correction can be perfect at any one frequency or a compromise can be computed over a range of interesting frequencies. In our system, such a correction can easily be implemented digitally after the ADCs.

Dynamic Range

The specified noise figures and third-order intercept points of the two devices (referred to the input), along with the gain adjustment range, are:

	N	P_3	ΔG
AD8347	11 dB	+10 dBm	65 dB
MAX2108	10	+8	50

The noise figure is specified at maximum gain, but the intercept point is specified at minimum gain. Neither of these necessarily scales with gain, but to make reasonable estimates we assume that the intercept point is inversely proportional to gain; this is essentially an assumption that distortion occurs predominately at the output. We assume that the strongest signals are limited to a level 20 dB below P_3, so that the resulting third order spurious responses are 40 dB below the desired responses. We use the noise figure to calculate the noise in an operating bandwidth of 100 MHz. This results in a dynamic range, when operating at maximum gain, given by

$$P_d = \frac{.01P_3/\Delta G}{(N-1)kT_0B}$$

where k is Plank's constant, $T_0 = 290\text{K}$ is the standard reference temperature, and $B = 100\,\text{MHz}$ is the bandwidth of interest. This gives $P_d = 28.9\,\text{dB}$ for the AD8347 and 40.9 dB for the MAX2108.

When operating at less than maximum gain, these values should improve because much of the variable gain is after the mixers, not in the input amplifier; therefore, the noise figure will degrade much less than the gain, while the intercept point should improve inversely with the gain. In any event, these data sheet values provide a basis for comparison with measurements.

Our application requires at least 45 dB of dynamic range. This permits us to operate with a normal (system noise) level that is 20 dB above the noise added here, while allowing a maximum signal 25 dB stronger without excessive distortion.

MAX2108 Tests

Bandwidth and Quadrature Accuracy

Measurements were made at LO frequencies of 1200 MHz and 1800 MHz, with power levels at the board connectors of 0 dBm for the LO and –5 dBm for the input signal. The gain control voltage was set for approximately 300 mV rms output (–27.4 dBm in 50 ohms) at 10 MHz; this resulted in a control voltage of 2.1 V. More detailed measurements were made at 1800 MHz.

The numerical results are listed in Table 2 and the 1800 MHz results are plotted in Figure 3.

Fig. 3(a) shows that there is an overall slope in gain of about 1 dB from –100 MHz to +100 MHz. No doubt this occurs on the input side of the mixers, from 1700 to 1900 MHz. Neglecting that slope, the gain is flat within 0.5 dB over –100 to +100 MHz, and the –3 dB points are at approximately $\pm 150\,\text{MHz}$, in agreement with the data sheet. Note that the absolute gain includes approximately –18 dB due to the input pad, +20 dB due to the $\times 10$ gain of the buffer amplifiers, and –9.5 dB due to the output voltage divider of the test board (Fig. 2).

Fig. 3(b) shows the measured complex gain ratio of the I and Q channels, and this data is used to calculate the image responses plotted in Fig. 3(c). The latter shows the uncorrected responses along with those corresponding to two different corrections. Each correction makes adjustments to the phase difference and magnitude ratio that are fixed with frequency; the first is calculated from an average of the measured errors over –100 to +100 MHz, and the second from an average over –60 to +60 MHz. The corrections make substantial improvements over most of the target frequency ranges, but each makes the image rejection worse in the range +50 to +100 MHz, where the uncorrected performance was especially good.

Dynamic Range

Limited measurements of the dynamic range were made. A power meter was connected in place of the I channel termination and VVM probe. A sinusoidal input signal at LO+39 MHz and –10 dBm was applied and the gain was set for an output power of –3 to +1 dBm (low gain). Then the input signal was turned off and the output power (due to noise) was noted. The test was repeated at an input level of –45 dBm, with

Table 3: SNR Measurements

LO freq.	Input Power	Gain Control	Output Sig.	Output Noise	SNR
MHz	dBm	volts	dBm	dBm	dB
1001	-10	2.79	-3.06	-46.4	42.4
1001	-45	3.35	-10.91	-37.3	26.6
2001	-10	3.25	+0.45	-43.0	43.5
2001	-45	4.0	-24.0	-39.85	15.9

the gain near maximum. LO frequencies of 1001 MHz and 2001 MHz were used. The results are summarized in Table 3.

The gain control voltage is logarithmic at .02 to .04 dB/mV.

A few comments are in order. The distortion level was not measured, so the SNRs are not necessarily representative of the available dynamic range. However, at –10 dBm input, the output waveforms were seen to be distorted on an oscilloscope, and at –45 dBm there is insufficient gain to bring the output signals to the same level. It is possible that some distortion is introduced by the AD8129 differential amplifiers; these are not capable of driving 50 ohms directly, so the circuit includes a 100 ohm series resistor. Measurements at an intermediate level are needed. There was no baseband filtering, so the noise was measured over the full device bandwidth of about 300 MHz (see Fig. 3a). Limiting this to about 100 MHz should produce a 5 dB improvement.

Clearly additional tests are needed. The setup should use the final filters and output buffers, and the distortion (second- and third-order intercept points) should be determined.

Output Drive Capability

Although the data sheet gives a differential output impedance of 33 ohms, the MAX2108 seems to be intended to drive only high impedance loads. The test board uses a 2.5k load resistor. Into this load, the differential outputs of the IC can produce 1000 mV peak-peak swings without noticable distortion (although no quantitative measurements were made). To check the ability to drive lower impedances, the 2.5k resistors were temporarily changed to 100 ohms, producing a net load of 166 ohms across the IC outputs. Severe distortion was observed for signal swings greater than 100 mV p-p at the IC pins.

In our application, we want to be able to drive an ADC to full scale at low distortion. Typical fast ADCs have a range of 500 to 1000 mV differential, so with a 100 ohm termination this requires -5 to +1 dBm of available power. Clearly a buffer amplifier is needed to achieve this, but a voltage gain of 1 to 2 is probably sufficient.

Temperature Sensitivity

To get some idea of the temperature sensitivity, the MAX2108 IC was repeatedly cooled with spray-can refrigerant ("FreezeIt") and allowed to warm to room temperature while observing the I and Q outputs on the VVM. This was done at LO frequencies of 1001 and 2001 MHz, input level –10 dBm, output frequency +39 MHz, and gain set for an output level of about 450 mV rms. The cycles were quite repeatable with a warmup time of 2 minutes. At both frequencies, the cooling caused a gain reduction of 5% in each channel; there was no measureable change in the gain ratio. At 1040 MHz, the phase difference (I-Q) changed by –0.8 deg; and at 2040 MHz it changed by –1.3 deg.

AD8347 Tests

Much less extensive tests were conducted on the AD8347.

This device is somewhat different from the MAX2108, in that single-ended outputs are provided from the mixers at low level. They can be connected to the inputs of buffer amplifiers included in the device, avoiding the need for the external amplifiers used on our MAX2108 test board. The low pass filters needed to define the bandwidth can be installed between the mixers and the buffers, so that out-of-band signals need not be amplified to high levels. This should improve the dynamic range. We measured the overall gain from the signal input to the mixer outputs (-25 dB into 50 ohms) and to the buffered outputs (+6 dB into 100 ohms differential) with the gain control at 1.0V. The gain control range is only 1 volt, for a resolution of about .06dB/mV.

Measurements of the gain and quadrature accuracy vs. frequency are listed in Table 4 and plotted in Figure 4. This was done at an LO of 1200 MHz and only for the upper sideband. The buffered outputs were used.

From Fig. 4(a) it is apparent that the –3 dB bandwidth is about 50 MHz, in agreement with the data sheet. Fig. 4(b) shows that the phase error is already 4 deg at 50 MHz and that it increases rapidly for higher frequencies. Consequently, the uncorrected image rejection, upper curve of Fig. 4(c), is poor above 60 MHz. The effect of fixed gain and phase corrections was calculated based on an average of the 10 to 100 MHz and the 10 to 50 MHz data (lower curves). Dramatic improvement is possible over limited frequency ranges; it is possible to obtain better than 30 dB rejection over 0 to 50 MHz.

Conclusions

The larger bandwidth and better quadrature accuracy of the MAX2108 makes it a better choice for our system, in spite of the superior architecture of the AD8347.

There is some uncertaintly about whether the dynamic range of the MAX2108 is adequate, and it is recommended that more detailed tests be done. It is necessary to limit the output voltage swing and to provide a relatively high load impedance, so care must be taken in the selection of buffer amplifiers that will allow it to drive the ADCs.

REFERENCES

[1] Maxim Integrated Products, Inc., "Direct conversion tuner IC." MAX2108 data sheet, rev. 0, dated 4/99, 12 pages.
http://www.maxim-ic.com

[2] Analog Devices, Inc., "Direct-conversion quadrature demodulator." AD8347 preliminary data sheet, rev. 0, dated 10/01, 20 pages.
http://www.analog.com

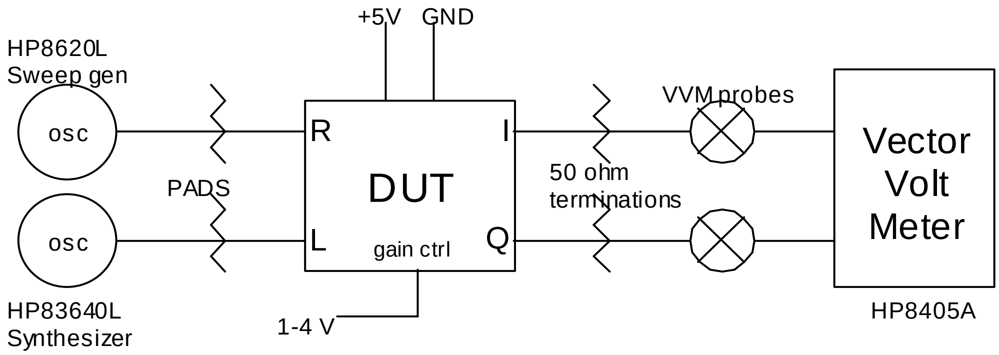
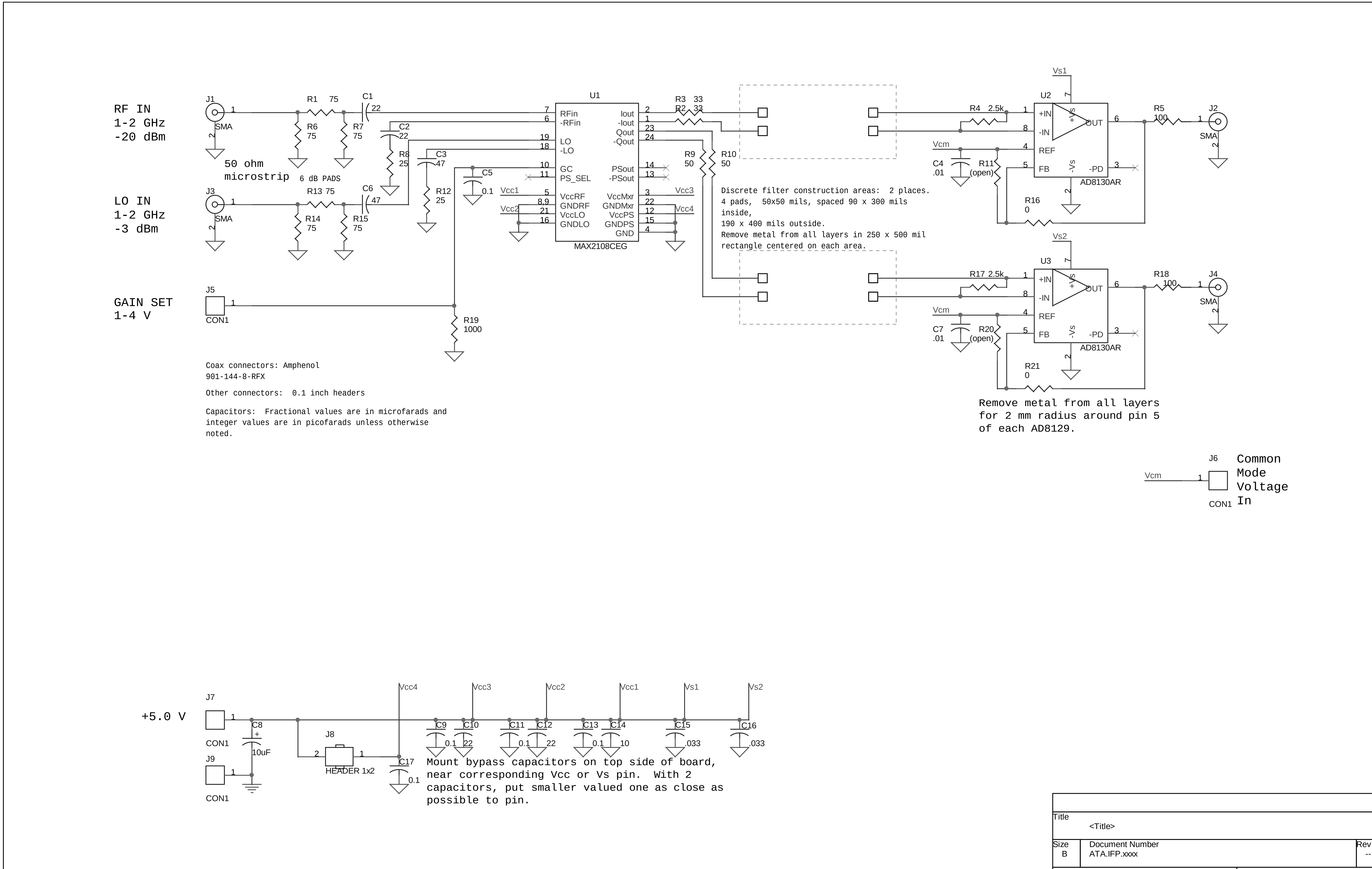


Figure 1: Test setup block diagram.


RF IN
1-2 GHz
-20 dBm
LO IN
1-2 GHz
-3 dBm
GAIN SET
1-4 V
+5.0 V
50 ohm
microstrip
6 dB PADS
MAX2108CEG
AD8130AR
Discrete filter construction areas: 2 places.
4 pads, 50x50 mils, spaced 90 x 300 mils inside,
190 x 400 mils outside.
Remove metal from all layers in 250 x 500 mil rectangle centered on each area.
Coax connectors: Amphenol
901-144-8-RFX
Other connectors: 0.1 inch headers
Capacitors: Fractional values are in microfarads and integer values are in picofarads unless otherwise noted.
Remove metal from all layers
for 2 mm radius around pin 5
of each AD8129.
Common
Mode
Voltage
In
Mount bypass capacitors on top side of board,
near corresponding Vcc or Vs pin. With 2
capacitors, put smaller valued one as close as
possible to pin.
Title
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Date: Thursday, August 09, 2001
Sheet 1 of 1

Table 2: Tests of MAX2108 I/Q mixer on RAL test board **7-Aug-01**

RF: -5.0 dBm at board.
Gain control signal: 2.5 V

LO freq	I/Q freq	I	Q	dphi	Dphi	Gratio,dB
1200	10	355	340	-89.0	1.0	0.375
1200	40	351	341	-88.5	1.5	0.251
1200	60	350	345	-88.8	1.2	0.125
1200	80	339	339	-90.0	0.0	0.000
1200	100	320	320	-88.7	1.3	0.000
1200	120	293	295	-86.8	3.2	-0.059
1200	140	254	250	-85.4	4.6	0.138
1200	160	211	202	-85.8	4.2	0.379

LO freq	I/Q freq	I	Q	dphi	Dphi	Gratio,dB
1800	-160	233	223	82.5	-7.5	0.381
1800	-140	270	265	83.0	-7.0	0.162
1800	-120	302	300	84.7	-5.3	0.058
1800	-100	319	317	86.0	-4.0	0.055
1800	-80	330	326	87.6	-2.4	0.106
1800	-60	333	325	88.6	-1.4	0.211
1800	-40	328	313	89.0	-1.0	0.407
1800	-20	323	308	88.5	-1.5	0.413
1800	-10	322	304	88.7	-1.3	0.500
1800	10	315	299	-90.0	0.0	0.453
1800	20	315	298	-89.4	0.6	0.482
1800	40	312	300	-89.1	0.9	0.341
1800	60	309	303	-89.1	0.9	0.170
1800	80	298	298	-89.4	0.6	0.000
1800	100	277	281	-91.9	-1.9	-0.125
1800	120	247	248	-93.7	-3.7	-0.035
1800	140	208	205	-94.8	-4.8	0.126
1800	160	176	169	-95.7	-5.7	0.353

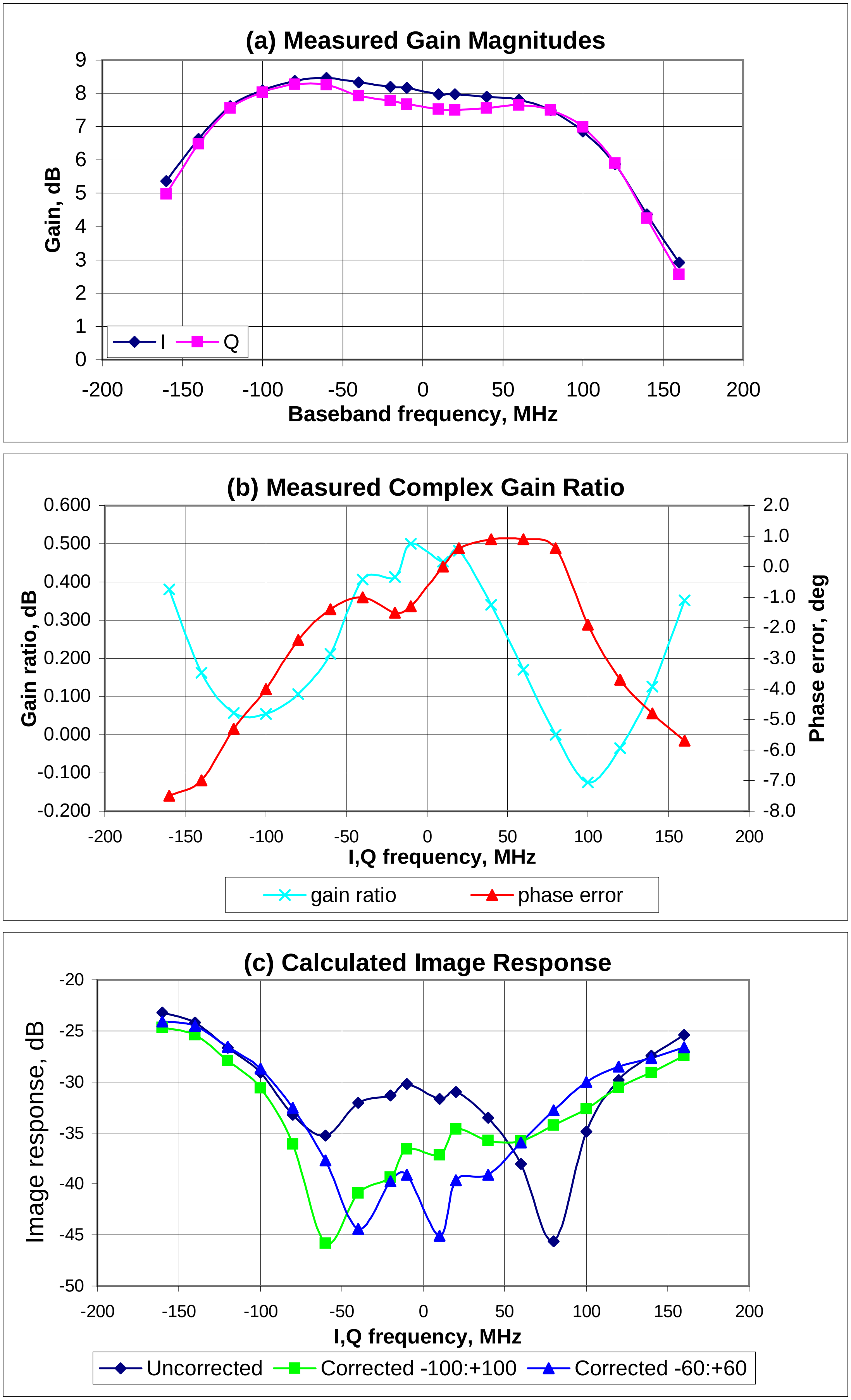


Figure 3: MAX2108 gain and image rejection tests

LO = 1800 MHz, input = -5 dBm, gain control 2.1V, testboard1.

Table 4: Tests of AD8347 IQ mixer on Analog Devices Evaluation Board

8/6/01

LO port of board: 1.2 GHz -6 dBm from Racal-Dana 9867 synthesizer
RF port: 1.1--1.3 GHz at -10 dBm thru SMA pads from HP8620C/86222B sweeper
IOPP,QOPP ports: to HP8405A vector voltmeter, thru blocking capacitors and 50ohm loads
Vref out connected to gain control in (+1.0V)
At 10-20 MHz out:

RF=-10dBm => IOPP=220mV p-p
RF=-3.5dBm => IOPP=500mV p-p

LO freq MHz	I/Q freq MHz	I mV	Q mV	dphi deg	Dphi dB	Gratio,dB	Image Rej
	30	136	125	90.9	0.9	0.733	-27.4
	40	124	112	92.2	2.2	0.884	-25.3
	50	110	100	93.6	3.6	0.828	-24.9
	60	99	90	94.7	4.7	0.828	-24.0
	80	75.5	58	99	9	2.290	-16.3
	100	54	51.5	102.3	12.3	0.412	-19.1

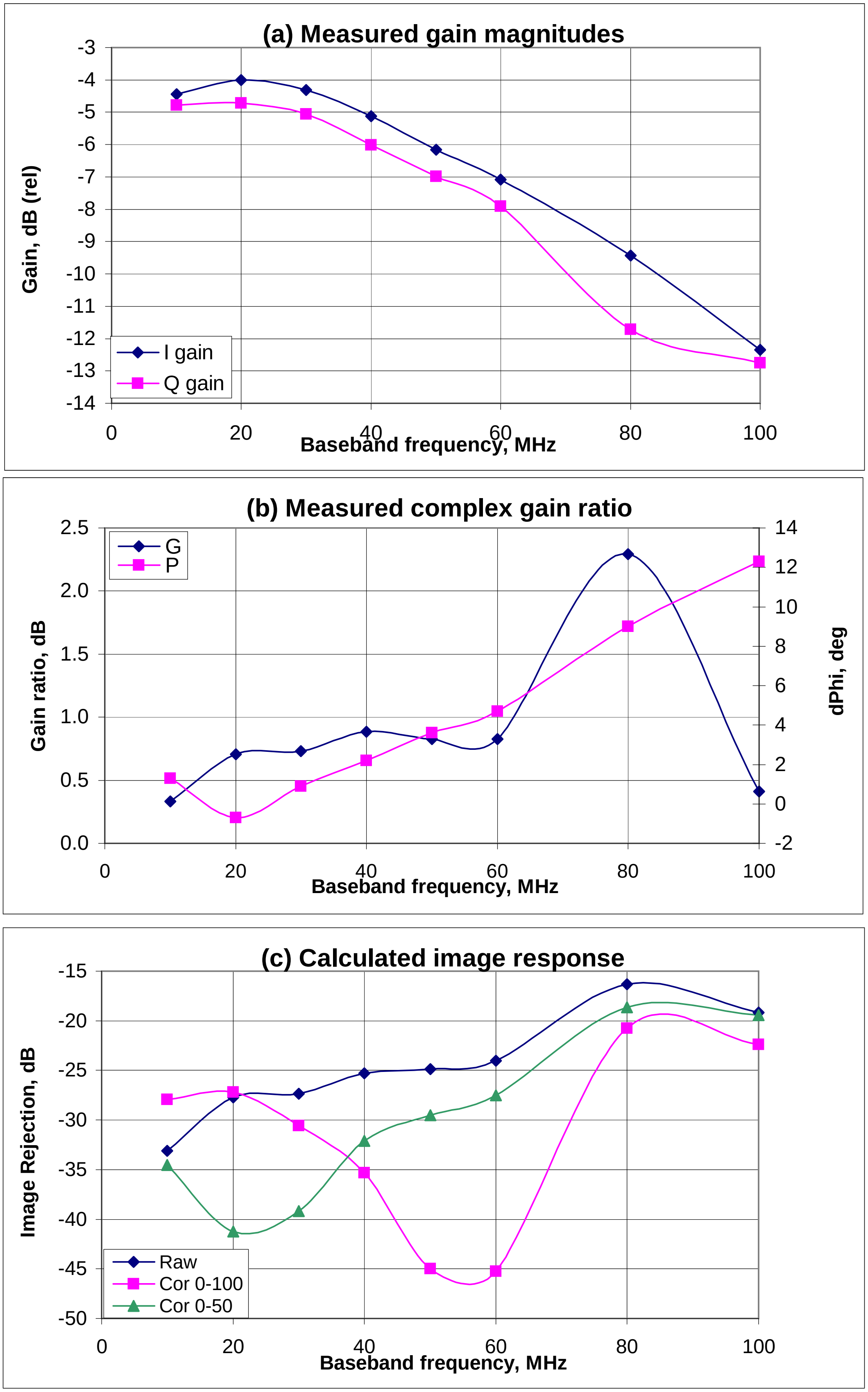


Figure 4: AD8347 gain and quadrature accuracy tests.
LO=1200 MHz, input=-10 dBm, gain control = 1.0V; AnalogDevices evaluation board.

Addendum: Additional Dynamic Range Tests

2002 February 15

After the main body of this report was written, additional measurements of the dynamic range of the MAX2108 were made. Those results are reported here.

The test setup used the analog board of the Digitizer Breadboard set [A1], which is different from the test board of Fig. 2 used earlier. The schematic is given in Figure A1. Here the IF input path includes an attenuator of approximately 20 dB, and the outputs are buffered by AD8131 differential drivers. The latter can drive 50 ohms from each of their dirrerential outputs, and they have a fixed differential voltage gain of 2. The 100 ohm differential drive was then converted to 50 ohms single-ended via a transformer.

The tests were all done at an LO frequency of 2.000 GHz and an IF input frequency of 1.990 GHz. The input level and gain control voltage were varied while observing the Q channel output on a spectrum analyzer. An attempt was made to determine the overall gain, noise figure, 1 dB compression point (P1), second-order intercept point (IP2), and third-order intercept point (IP3) at various gain settings. The results are summarized in Table A1.

If was first noted that the compression point, referred to the input, is largely independent of gain setting (about –4 dBm at 1 dB compression). This is consistent with saturation of the input amplifier. The data sheet shows two stages of input amplification, where the second is the variable gain stage. There is apparently no variable gain in the output section (after the mixers), contrary to an assumption made earlier under "Analysis" (unlike the AD8347, which has variable gain in both sections).

The input compression made it difficult to determine IP2 and IP3 at the output except at high gain. The input distortion produces only out-of-band harmonics, so the IP2 and IP3 of interest are those caused by the output stages.

Table A1: MAX2108 Dynamic Range Measurement Results

V_g mV	Net Gain dB	P1(in) dBm	IP2(out) dBm	IP2(in) dBm	IP3(out) dBm	IP3(in) dBm	Noise(out) dBm/50MHz	SNR dB
4000	+6	—	+30	+24	+18.5	+12.5	–57.5	46.5
3900	+2	–5	+31	+29	+19	+17	[–59.8]	48.8
3800	–3	–3	+32.5	+35.5	+19	+22	[–55.2]	50
3700	–5	–4	—	—	—	—	–58.5	
3600	–10							

The "SNR" column in Table A1 is the power at which the worst harmonic (2nd) is at –40 dBc divided by the noise in 50 MHz.

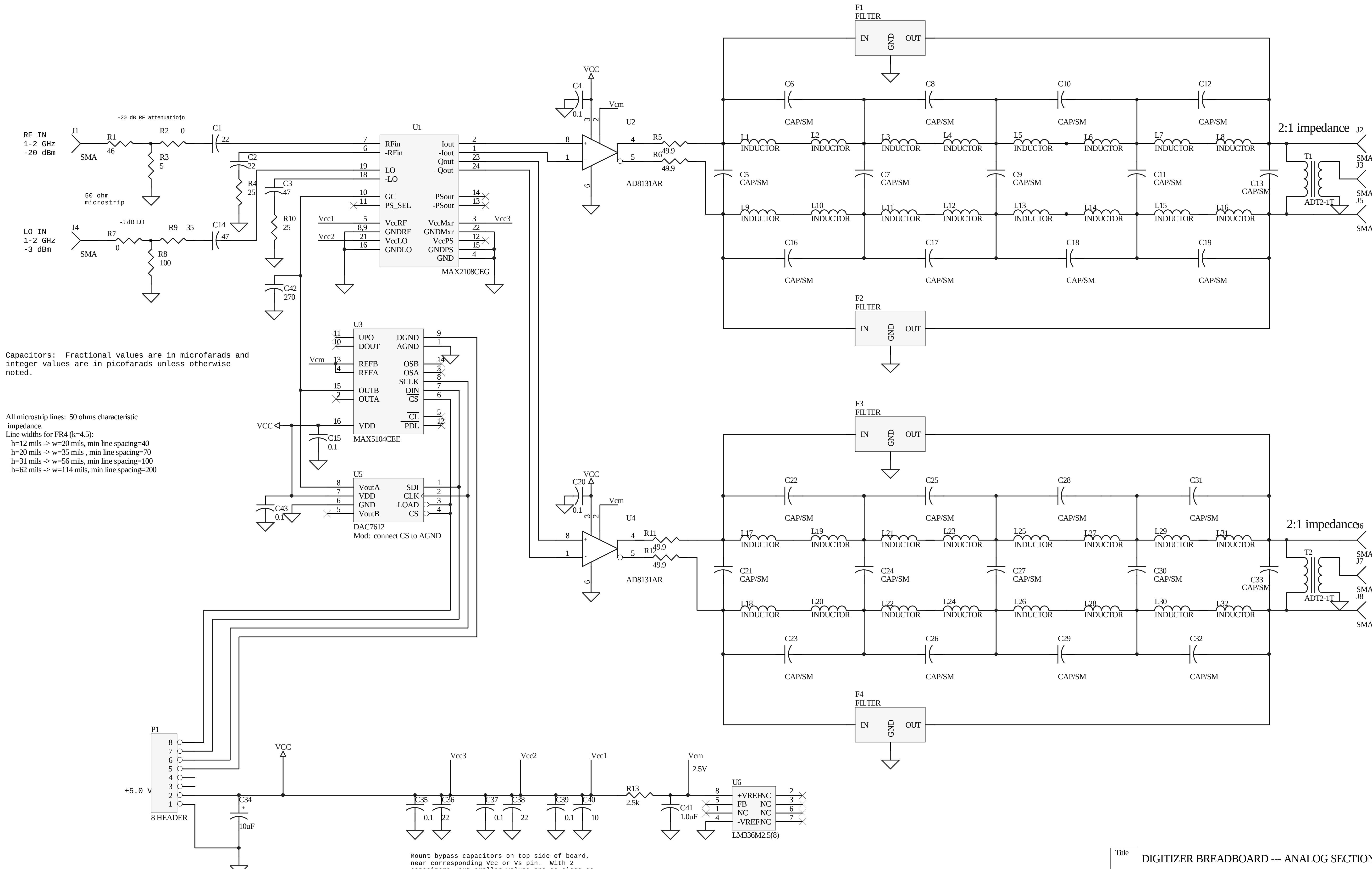
We conclude that the maximum input (IF) level should be less than –8 dBm in order to be below the 1 dB compression point. Maximum SNR is obtained at the lowest gain settings (as expected), but this conflicts with the need to drive the ADCs to full scale without substantial additional gain. All available gains, including maximum (4000 mV) produce SNRs exceeding our requirement of 45 dB. At an input level of –8 dBm, a gain setting of 3870 mV (net gain approximately +0.5 dB) gives a worst harmonic level of –40 dBc. Thus, –8 dBm in and 3870 mV gain control are recommended as the nomonal values. The latter allows 5 dB of gain range from nominal to maximum. The nominal output level is then 0.37V p-p (differential, referred to the MAX2108 output pins). To drive an ADC to 1.0V p-p (full scale for the SPT7722, and typical of others) then requires an additional voltage gain of 2.7.

It should be mentioned that we have received a report [A2] that another device in the same family (MAX2105) exhibits anomalous compression when the input includes narrow but weak pulses. This would be a problem if it occurs in our device, so that possibility should be investigated.

REFERENCES

[A1] L. D'Addario, "ATA Digital Subsystem: Breadboard Circuits." ATA Memo No. 41, 2002-Jan-20.

[A2] S. Ellingson, "MAX210x chips," email to Dave DeBoer dated 2002-Feb-02.



Capacitors: Fractional values are in microfarads and integer values are in picofarads unless otherwise noted.

All microstrip lines: 50 ohms characteristic impedance.
Line widths for FR4 (k=4.5):
h=12 mils -> w=20 mils, min line spacing=40
h=20 mils -> w=35 mils , min line spacing=70
h=31 mils -> w=56 mils, min line spacing=100
h=62 mils -> w=114 mils, min line spacing=200

Mount bypass capacitors on top side of board, near corresponding Vcc or Vs pin. With 2 capacitors, put smaller valued one as close as possible to pin.

Title	DIGITIZER BREADBOARD --- ANALOG SECTION	
Size	Number	Revision
Tabloid		
Date: 15-Feb-2002	Sheet of	
File: C:\myfiles\ifProcessor\protel\digitizerBreadboard\digitizerBreadboard.ddb	Drawn By:	