LMX2594 Open Collector Outputs

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CAUTION!

A lot of the conclusions in this document are highly speculative and many of the measurements have many potential sources of error. Read this document with the intention of gaining insight and understanding, but be aware that this doccument may contain errors and erroneous conclusions are possible.

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Chapter 1 Introduction

Introduction

Many TI Devices such as the LMX2581, LMX2582/92, LMX2571, and LMX2594/95 offer open collector outputs. The traditional claim of benefits of open collector outputs that is often stated is that it makes the output voltage flexible to drive inputs of different voltage levels, but this is not really the motivating reason for these devices. For these high frequency devices, it has the advantages of dissipating the power outside the IC and also allows higher output power as the external pull-up component can be pulled up to Vcc, as opposed to a lower internally regulated voltage inside the chip.

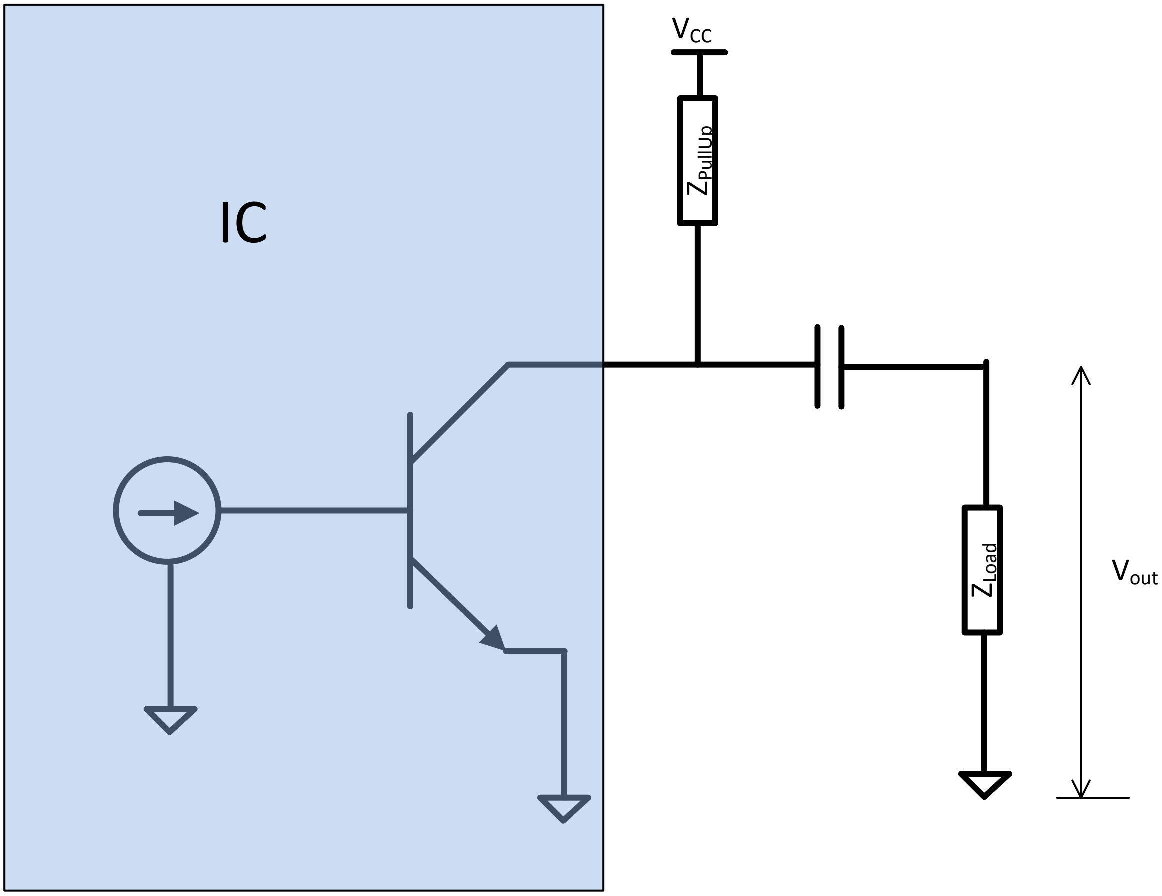
Why open Collector

Many TI Devices such as the LMX2581, LMX2582/92, LMX2571, and LMX2594/95 offer open collector outputs. The traditional claim of benefits of open collector outputs that is often stated is that it makes the output voltage flexible to drive inputs of different voltage levels, but this is not really the motivating reason for these devices. For these high frequency devices, it has the advantages of dissipating the power outside the IC and also allows higher output power as the external pull-up component can be pulled up to Vcc, as opposed to a lower internally regulated voltage inside the chip.

General Strategy

The general strategy for understanding the output buffer is as follows:

1. Understand the collector current, both DC and AC. Measure the AC current at lower frequencies to minimize impacts of unwated parasitics.
2. Study the theoretical output power with a known pull-up and know load assuming no parasitics or transmission line effects
3. Get a general idea of the out impedance of the buffer so one can have a general idea if it is high compared to the pull-up component.
4. Study the resistor pull-up case
5. Study the inductor pull-up case.
6. Conclude results and present a general strategy.



For high frequency, it also has several considerations. The choice and layout placement for the pull-up component is critical to output power and harmonics. Also, the assumption that the transistor output is high impedance is not necessarily true either. This paper attempts to bring some explanation to the behaviors of these open collector outputs through matching theoretical explanations to measured data.

Defining PWR

There are the programmable words called OUTA_PWR and OUTB_PWR. The minium value is 0 and the maximum value is 63. However, states 32-47 are redundant. State 32 is the same as state 16, state 33 is the same as state 17, and state 47 is the same as 31. So therefore it makes sense to cut out states 32-47 and redefine the new PWR that goes from 0 to 47 and define as follows:

$$PWR = \begin{cases} OUTx\_PWR & OUTx\_PWR \leq 31 \\ OUTx\_PWR - 16 & OUTx\_PWR > 31 \end{cases}$$

Chapter 2 Determining the Collector Current

Measuring the DC Current

The dual PLL EVM was used with a supply of 3.4V. A voltage of 3.18 V was measured at the board. PWR was then changed and the DC voltages were measured.

PWR	Fout=10M	Fout=7G	Fout=10G
0	2.91	2.92	2.88
5	2.74	2.78	2.70
10	2.58	2.62	2.54
15	2.41	2.28	2.38
20	2.25	2.04	2.23
25	2.09	1.88	2.09
31	1.95	1.80	1.96
32	1.94	1.73	1.94
34	1.91	1.72	1.92
39	1.86	1.63	1.88
44	1.83	1.58	1.78
47	1.82	1.57	1.80

Since there was a 50 ohm resistor, and assuming the pull-up was supplied to 3.18 V, the current (in mA) through the resistor can be found and modeled with the following equation:

$$I_C = \begin{cases} 0.65 \cdot PWR + 0.57 & PWR \ \leq 15 \\ 32 \cdot \left[1 - exp\left(-\dfrac{PWR}{22}\right)\right] & PWR > 15 \end{cases}$$

PWR	Fout=10MHz	Fout=10G	Model
0	5.4	6	5.70
5	8.8	9.6	8.95
10	12	12.8	12.20
15	15.4	16	15.45
20	18.6	19	19.11
25	21.8	21.8	21.73
31	24.6	24.4	24.18
32	24.8	24.8	24.53
34	25.4	25.2	25.18
39	26.4	26	26.56
44	27	28	27.67
47	27.2	27.6	28.22

AC Current Measurement

To determine the AC current, a 50 ohm pull-up resistor was used and an oscilloscope was set to high impedance and the output frequency was set to 200 MHz to hopefully avoid any high frequency effects. The voltage measured and recorded and modeled.

PWR	Measure Vpp	Measure Vrms
0	0.61	0.22
5	0.88	0.31
10	1.19	0.42
15	1.49	0.53
20	1.80	0.64
25	2.05	0.73
31	2.38	0.84
32	2.43	0.86
34	2.51	0.89
39	2.68	0.95
44	2.81	0.99
47	2.87	1.02

The next step was to divide this voltage by the 50 ohm pull-up value. Also, as this is AC current, we want to model with the RMS value

$$i_C = \begin{cases} 4.3 + 0.42 \cdot PWR & PWR \leq 30 \\ 23 \cdot \left[1 - exp\left(-\dfrac{PWR}{22}\right)\right] & PWR > 30 \end{cases}$$

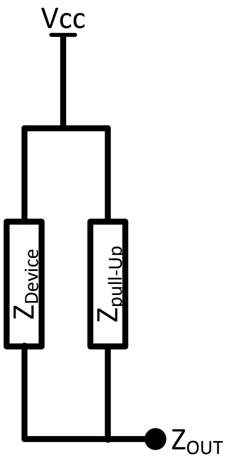
Below is the AC currents as a function of PWR.

PWR	Measure	Model
0	4.33	4.30
5	6.25	6.40
10	8.42	8.50
15	10.56	10.60
20	12.74	12.70
25	14.52	14.80
31	16.84	17.38
32	17.19	17.63
34	17.75	18.10
39	18.96	19.09
44	19.88	19.89
47	20.31	20.28

Chapter 3 Determining the Output Impedance

What is Meant by "Output Impedance"

As the output is really an open collector current source, some could get into some philosophical arguments as to what is really meant by the output impedance. Also, what is really going on is there is a transistor that is switching on and off, so in what state is the impedance measured? These questions will be left to the armchair philosopher and the output impedance will be treated as just simple impedance, Z_{Device}, which is in parallel witht the impedance of the Pull-Up, $Z_{Pull\text{-}Up}$.



To determine the output impedance, Z_{Device}, three approaches were used:

Approach 1: Theoretical Calculation of Output Impedance

The output impedance was calculated based on estimates of lead frame capacitance, bond wire inductance, ESD diode capacitance and a few other things.

Approach 2: Direct Measurement of Output Impedance

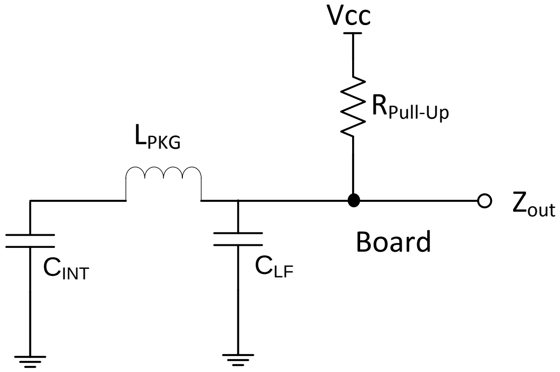
The output was hooked directly to a network analyzer and the output frequency was tuned away from any frequency of interest being measured.

Approach 3: Indirect Measurement of Output Impedance

A stub tuner was used and the setting for maximum output power was found. Then the output impedance was determined to be the complex conjugate.

Of the three approaches used, the indirect measurement is the one that I trust toe most.
The following sections go into more details on these approaches

Approach 1: Theoretical Calculation of Output Impedance



The above model was used to model the package impedance. Note that these are not exact values, but rather coarse estimates.

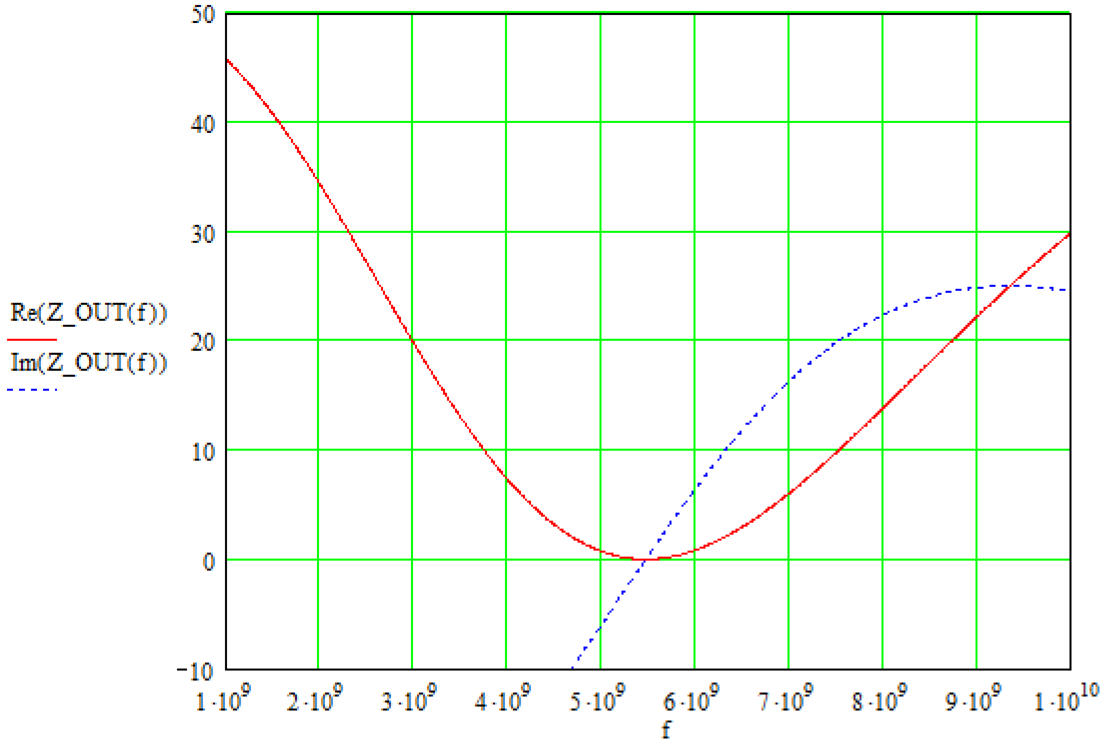
Symbol	Value	Comments
$R_{Pull\text{-}Up}$	50 Ω	This is the pull-up on the board
C_{LF}	0.1 pF	Lead frame capacitance
L_{PKG}	1 nH	Bond wire inductance of package. This might not be a very accurate assumption for high frequency.
C_{INT}	0.85 pF	Sum of capacitances after bond wire due to package and die. ESD protection diode is one major contributor.

$$\text{C\_INT} := 0.850 \cdot \text{pF} \qquad \text{C\_LF} := 0.1 \cdot \text{pF}$$

$$\text{L\_PKG} := 1 \cdot 10^{-9} \cdot \text{H} \qquad \text{R\_PullUp} := 50 \cdot \Omega$$

$$\text{Z1}(s) := \text{L\_PKG}s + \frac{1}{s \cdot \text{C\_INT}} \qquad \text{Z2}(s) := \frac{\text{R\_PullUp}\left(\frac{1}{s \cdot \text{C\_LF}}\right)}{\text{R\_PullUp} + \frac{1}{s \cdot \text{C\_LF}}}$$

$$\text{Z\_OUT}(f) := \frac{\text{Z1}(2 \cdot \pi \cdot i \cdot f) \cdot \text{Z2}(2 \cdot \pi \cdot i \cdot f)}{\text{Z1}(2 \cdot \pi \cdot i \cdot f) + \text{Z2}(2 \cdot \pi \cdot i \cdot f)}$$



The thing to take not of specifically is that around Note around 5 GHz, impedance is theoretically low for this example using a 50 ohm pull-up. Note also that this is where C_{INT} resonates with L_{PKG}. So this low impedance is likely to be an issue for just about any pull-up at 5 GHz.

So the key take-away from this mathematical exercise is to see if there is any sort of dip in output power or output impedance for the measured data. This comes next.

Approach 2: Direct Measurement of Output Impedance

One way to measure output impedance is to hook the output to a network analyzer and look at a frequency other than the oscillation frequency. I tried this method and the value changed a lot based on the output frequency, but here are some rough numbers.

TAKE THESE WITH A GRAIN OF SALT!

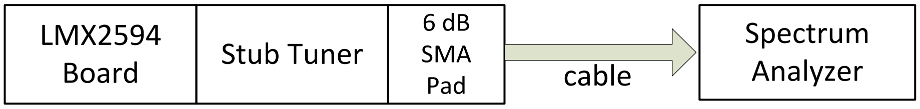
Fout (GHz)	OUTA_PWR=20			
	CHDIV Bypassed		CHDIV Engaged	
	R	jX	R	jX
1	47	-11	46.9	-12.9
5	4.3	13.7	4.8	15.6
10	106.8	40.5	109.1	46.7
15	22	-20.3	22.3	20.6
20	41	22.8	40.3	22.5

Fout (GHz)	OUTA_PWR=50			
	CHDIV Bypassed		CHDIV Engaged	
	R	jX	R	jX
1	41.8	-13.4	44.3	-13.2
5	17.5	18.5	7.6	19.6
10	100.8	26.2	105.6	43.4
15	25	-17.7	22.1	-19.3
20	42.3	20.4	40.5	22.5

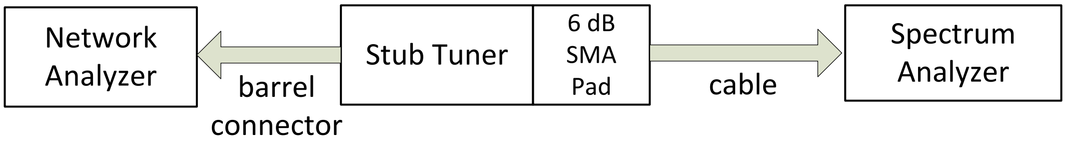
I didn’t try to take this much farther because I saw too much variation based on what the output frequency was. However, the one thing worth observing is that at 5 GHz, the output impedance sharply drops. Note that this agrees with the simulation.

Approach 3: Estimating Output Impedance by Indirect Measurement

The output of the LMX2594 is a current source, so measurement of the impedance of that is complicated. So the first step is to define the impedance as what it should be treated as for matching purposes.



To do this, the approach was to take the output to a stub tuner through a pad and cable to a spectrum analyzer. The stub was then tuned to maximize the output power. Theoretically, the value that maximizes the output power would have the complex conjugate for impedance. The next step is to measure the setup on a network analyzer.



So the first step is to take the measured impedance (table has already taken complex conjugate). To go one step further, the pull-up structure was measured without the LMX2594 under "Pull-Up Structure". Finally, the true buffer impedance is shown. For the true buffer impedance, don't take the R and jX part to the bank so seriously, but rather focus o the magnitude and note that it is not necessarily large next to 50 ohm.

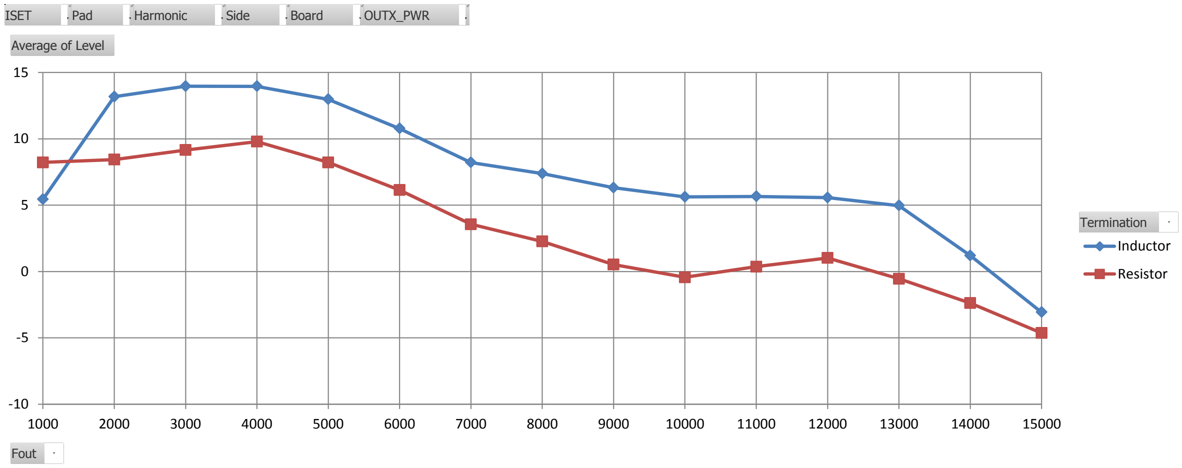
Fout	OUTxPWR	Measured Impedance		Pull-Up Structure		True Buffer Impedance		
		R	jX	R	jX	R	jX	Magnitude
2000	20	40.9	21.5	49.1	-4.3	-7.5	83.8	84.1
2000	50	38.2	15.2	49.1	-4.3	19.6	88.6	90.7
5000	20	58.3	13.6	34.4	3.2	-79.0	7.0	79.4
5000	50	60.4	30.7	34.4	3.2	-59.9	15.3	61.9
10000	20	88.7	-32.3	59.7	-28.1	-169.8	127.8	212.6
10000	50	91.3	-8.3	59.7	-28.1	-75.0	143.8	162.2
15000	20	29.9	5.3	27.1	52.4	35.5	-13.4	38.0
15000	50	28.2	3.5	27.1	52.4	31.9	-12.6	34.3

As the output buffer contains a current source, maybe this is why the true buffer impedance can be negative. But don't focus on this. Focus on the magnitude and see it is not large next to 50 ohms. Also note that near 5 GHz, there is a small dip in the magnitude, although not as pronounced as found by the other methods.

Conclusion Regarding Output Impedance

The models and measurements both have uncertainty and this is why three approaches were presented. That being said, all three methods suggest a lower output impedance around 5 GHz and also that it is not fair to assume the output impedance of the device it self next to a 50 ohm pull-up is high.

This is not the chapter on output power, but as a sanity check, this begs the question if anything happens around 5 GHz. The plot below shows for both inductor and resistor pull-up and we see roll-off start to happen around 5 GHz. So maybe it means something, maybe not. Realize that this output power does not account for board losses or matching th the load.



So key points from this chapter to remember are:

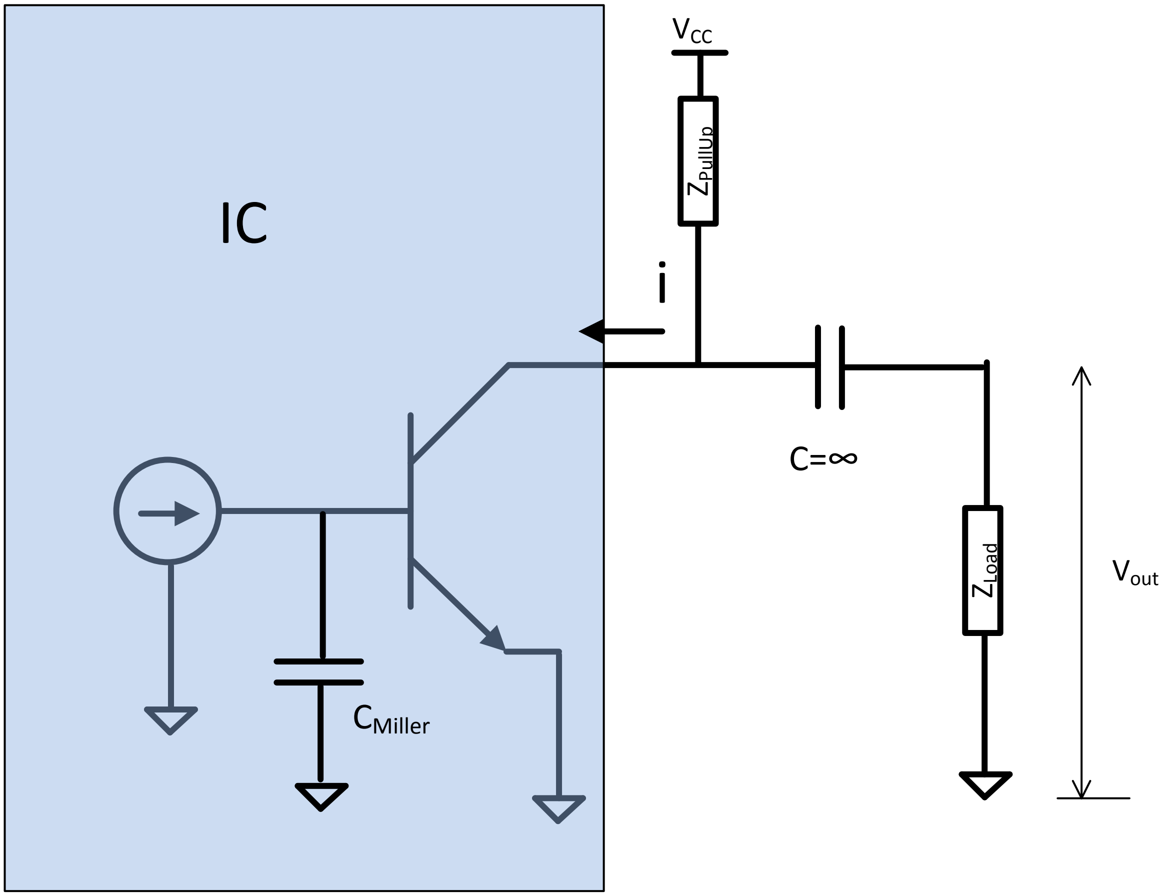
- Output Impedance near 5 GHz theoretically is low for this device
- Above 2 GHz, not really fair to assume output buffer impedance is high next to 50 ohm
- Output impedance theoretically might start to recover a little after 5 GHz, but then other parasitics and high frequency effects may cause output power to not recover.
- In general, some of the measurements in other sections at 5 GHz seem flakey for output power, so these will be de-emphasized as the output impedance is suspect.

Chapter 4 Signal Swing

Introduction and Miller Capacitance

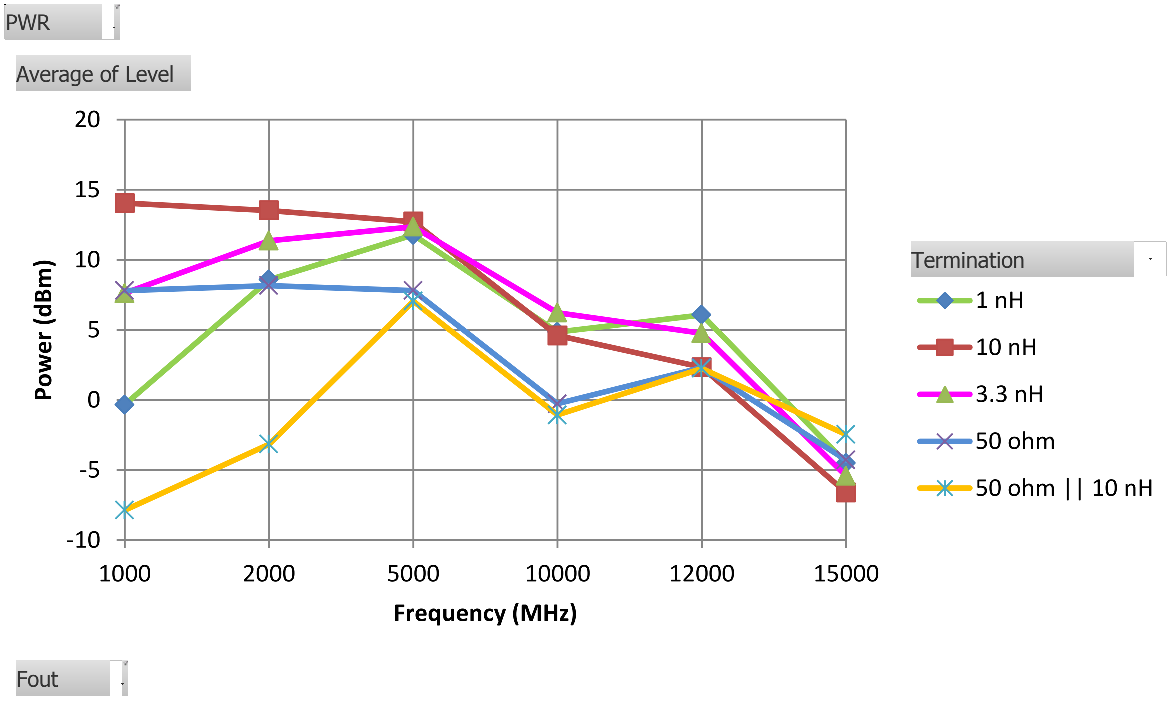
Consider the case of a known load and pull-up with no transmission line effects or parasitics. Z_{PullUp} represents the impedance of the pull-up component in parallel with the output impedance of the device. As this output impedance is typically large relative to $Z_{PullUp} \parallel Z_{Load}$, this chapter will just treat it as the pull-up impedance.

The basic idea is to take the AC current calculations from the previous section and see the results for the output power. One additional factor is the Miller capacitance. It is known that this capacitance will be greater when PWR is increased. This will impact power at higher frequency measurements.



Pull Up component Experiments

Several experiments were done with resistors and inductors to get a feel of how the output buffer behaves. The following figure gives a summary:



Let's start with the straight 50 ohm. We see flat power and then it starts to roll off. Recal that at 5 GHz, there is a dip in output impedance. After this, it is likely impacted by losses and parasitics. Now look at the 50 ohm || 10 nH. The basic idea here was to eliminate the DC drop across the resistor, but it only seemed to make things worse.

Now looking at the inductors, we see the 10 nH starting high and sort of flat, but then rolling off. Now compare the 10 nH to the 50 ohm. It looks about 6 dB higher at lower frequencies. Perhaps this has nothing to do with the DC drop, but rather there is twice the signal swing. The 10 nH in parallel with the 50 ohm spectrum analyzer has twice the amplitude as the 50 ohm in parallel with 50 ohm at low frequencies. 10 nH at 1 GHz is already 62 ohms.

Calculate the Output Voltage

From an AC perspective, the voltage across the pull-up and the voltage across the load are the same as they are both AC grounded and they are AC shorted together. It therefollows that the voltage

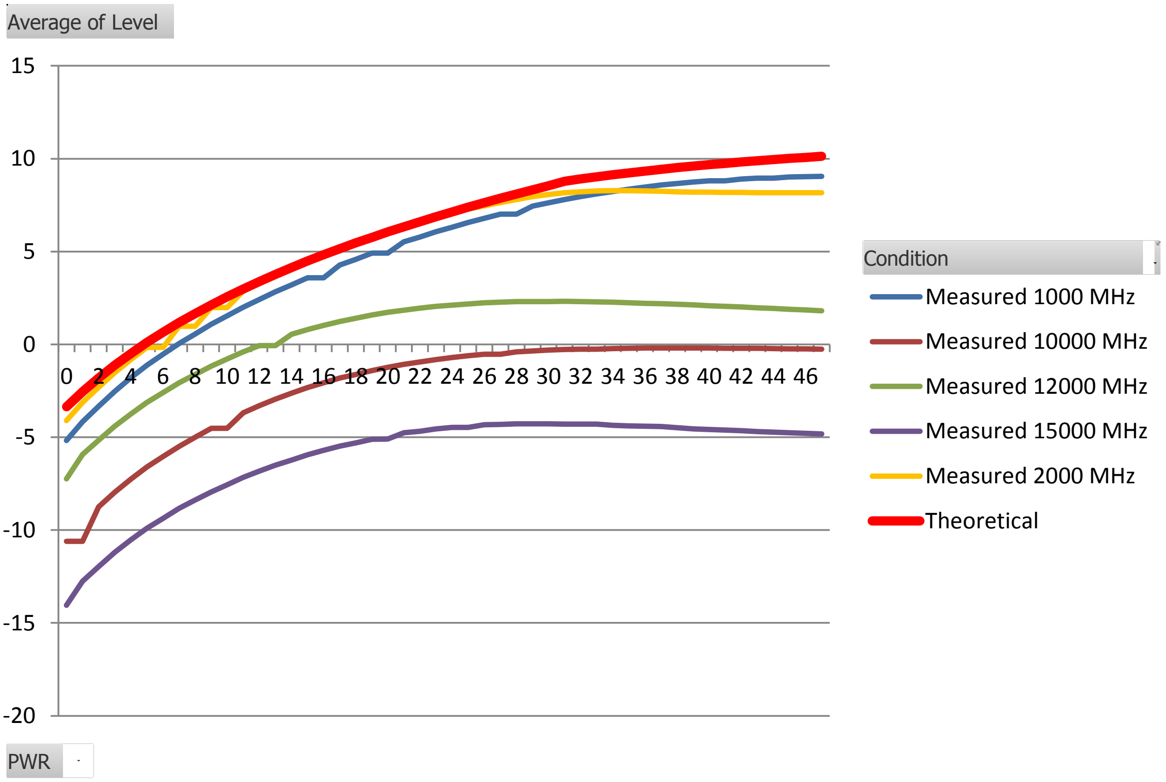
$$V_{OUT} = i \cdot Z_{Load} || Z_{PullUp} = i \cdot Z_{Load} \cdot \frac{Z_{PullUp}}{Z_{PullUp} + Z_{Load}}$$

Now this implies to just blindly crank up OUTx_PWR to the max to for the max current. However, it turns out that there is another restriction to consider.

Resistive Pull-Up Case

One common and important case to consider is when the pull-up and load are both 50 ohm resistors. In this case, we get the relationship:

$$V_{OUT} = i \cdot 25\Omega$$



At 1000 MHz, the measured power is actually lower. This could be because the AC coupling capacitor was too small and there was some loss. At 2000 MHz, there is very good match up to PWR=30, but then we see saturation occurring earlier than predicted by the model. Then at 10,12, and 15 GHz, we see some saturation even earlier, possibly due the the Miller capacitance, which increases with PWR.

Inductor Pull-Up Case

For the 50 ohm resistor, this was a specialized RF resistor that I could trust as 50 ohm. For an inductor, it's harder to trust this just based on the label. So for starters, I tried some various components and tried some sweeps over frequency and PWR.

Inductor	Manufacturer	Part #	Q	SRF (MHZ)	RDC (ohm)
1 nH	Toko	LL1005-FH1N0S	10	13599	0.1
3.3 nH	Toko	LL1005-FH3N3S	10	6800	0.19
10 nH	Toki	LL1005-FH10NU	12	3750	0.46

For later reference, let's calculate the output impedance in j ohms for various frequencies. Frequencies above self resonalt frequency (SRF) are greyed out.

Fout (MHz)	1 nH	3.3 nH	10 nH
100	0.6	2.1	6.3
1000	6.3	20.7	62.8
2000	12.6	41.5	125.7
5000	31.4	103.7	314.2
10000	62.8	207.3	628.3
12000	75.4	248.8	754.0
15000	94.2	311.0	942.5

Note that when the inductor impedance has the same magnitude as the load impedance, there is a 3 dB (not 6 dB) reduction in power. In other words, consider a 50 ohm pull-up with 50 ohm load. This is effectively a load with magnitude 25 ohm. Now consider a 2.4 GHz output with 3.3 nH pull-up, which has j50 ohm. This effectively has a magnitude of 35 ohms, which is only a 3 dB reduction. Another interesting frequency is where the magnitude is the same as the load impedance. In other words:

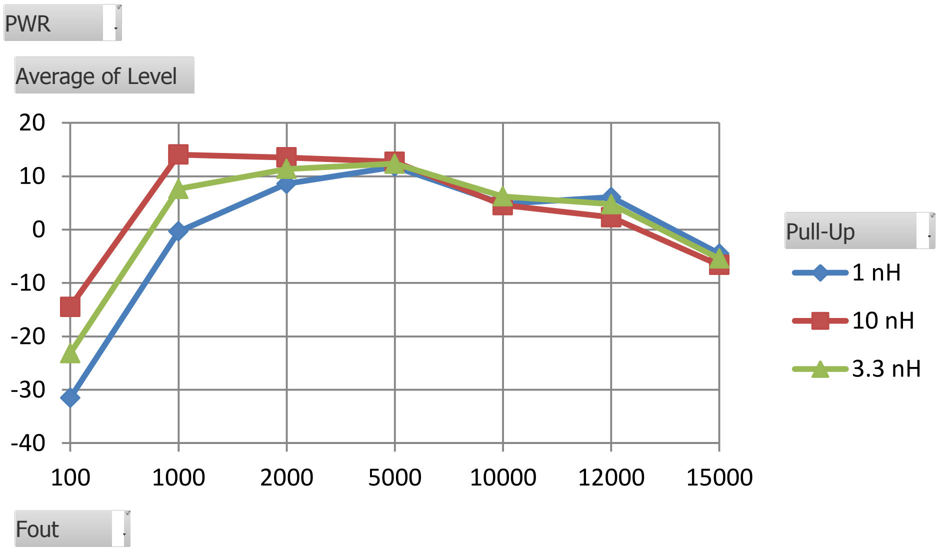
$$\frac{x \cdot R_{Load}}{x^2 + (R_{Load})^2} = \frac{R_{Load}}{2}$$

This has a solution of:

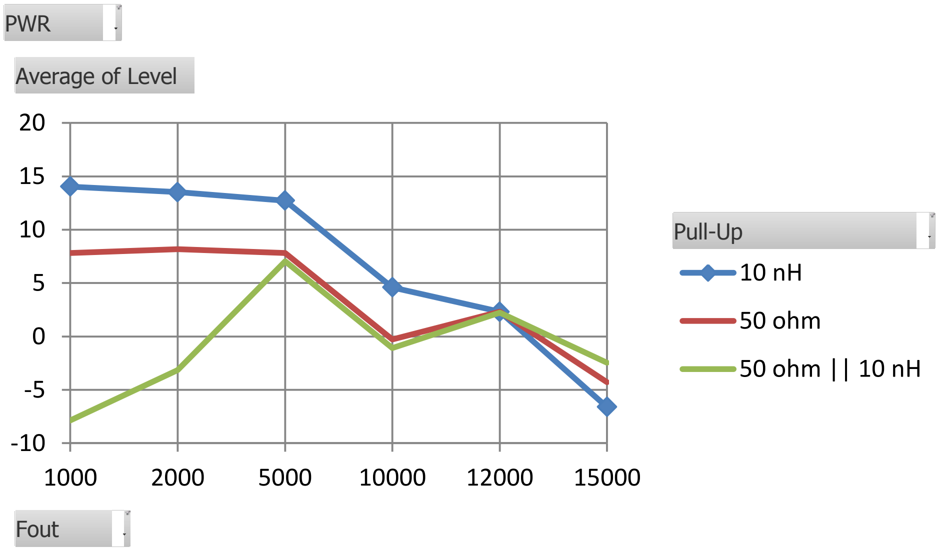
$$x = 2 \cdot L \cdot f_{OUT} = \frac{R_{Load}}{\sqrt{3}}$$

For instance, for a 50 ohm load, the impedance would be j28.9 ohm. If we take this in paralle with 50 ohm, it has a magnitude of 25 ohm. This would be the same as a 50 ohm resistor pull-up in parallel with 25 ohm.

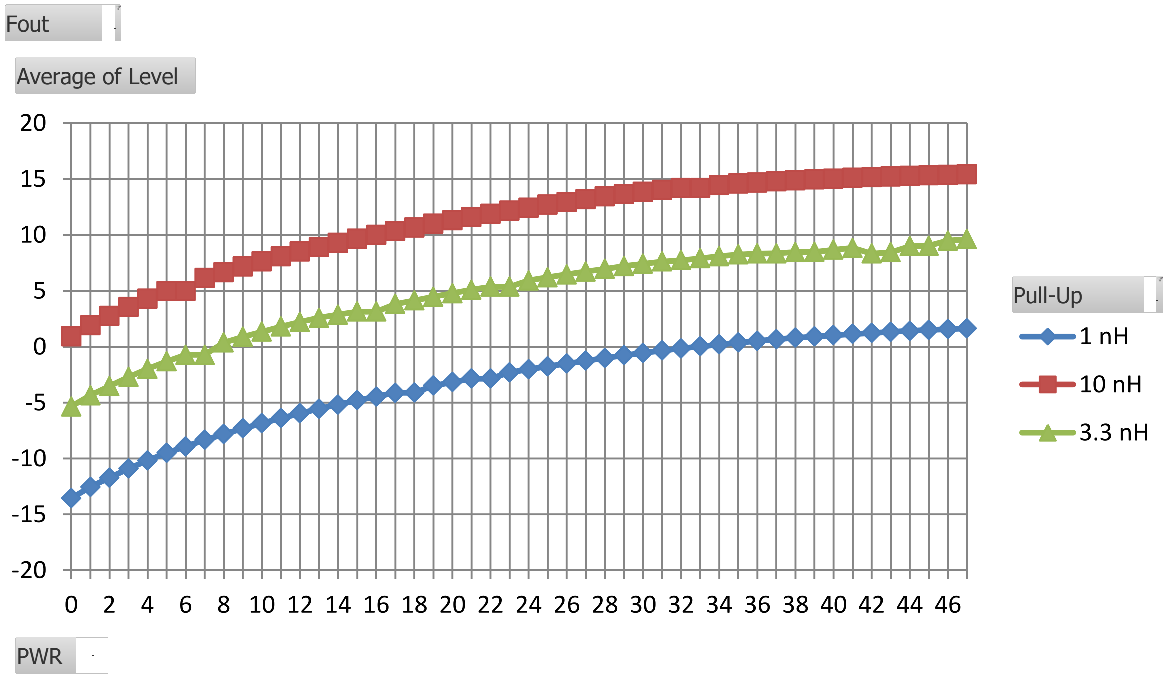
Now, lets measure this for PWR=31 and sweep across frequency. Realize the load is the 50 ohm spectrum analyzer and when the impedance is j 50 ohm, there is theoretically 3 dB lower power from infinite output power. Also remember we are ignoring matching.



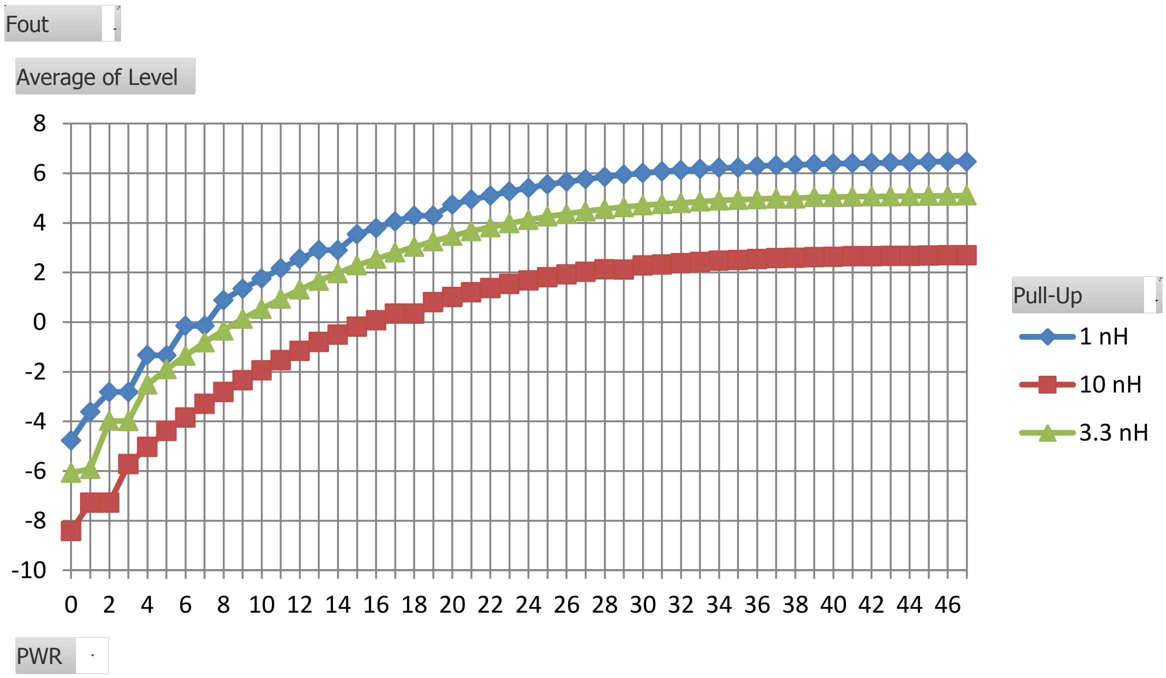
At 1 GHz and below, the inductor size matters, as it is much less than the 50 ohms. At 2 GHz, we see the 10 nH is getting lower, but we are also getting maybe too close to the self-resonant frequency for that. But we see higher power for the 1 and 3.3 nH inductors. At 5 GHz, the theoretical pull-up inductor impedance is high enough, but now we are near the point where the device output impedance is low. Beyond this, it seems that other effects dominate.



Now let’s compare inductor to resistor. Around 1-5 GHz, the inductor impedance is high enough relative to the 50 ohm spectrum analyzer and we see 6 dB improvement. I think it’s because there is twice the signal swing. Also, I put 50 ohm parallel 10 nH and it did not improve the resistor power level anywhere, suggesting the theory that the bias voltage drops is not the reason; it's that the load (pull up in parallel with spectrum analyzer) is twice for the inductor.



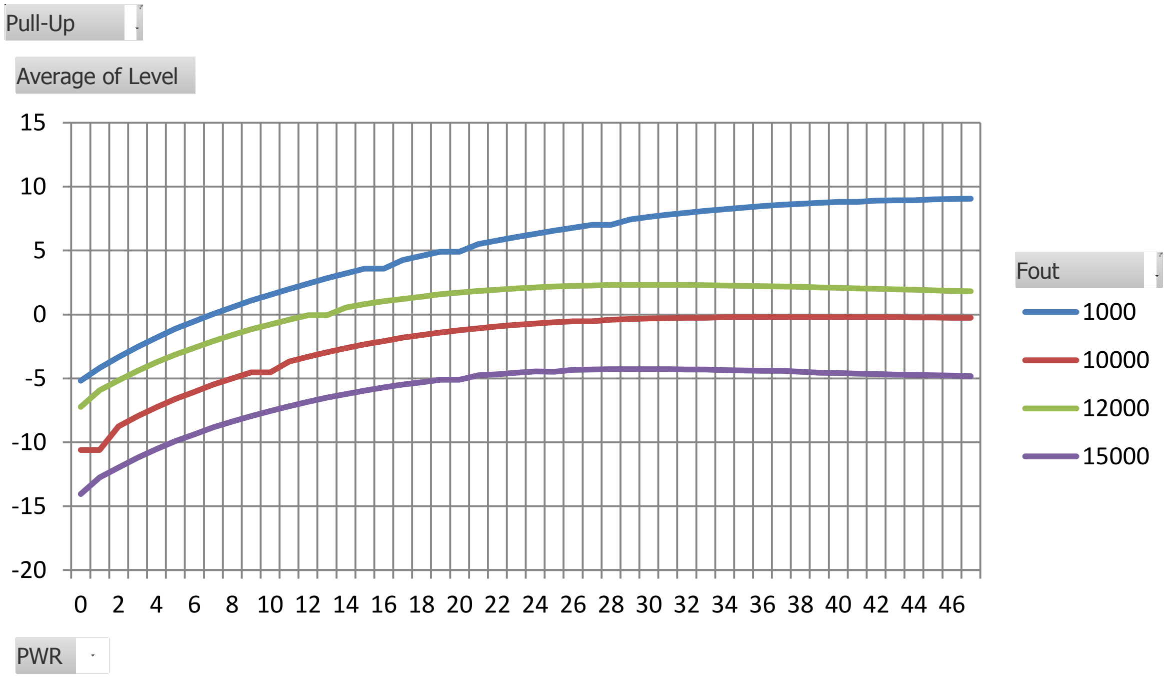
Now if we look at 1 GHz and sweep PWR, we see the curves are parallel, implying the AC drop across the pull-up does not cause any gain/bias issues at the transistor. I see similar results at 2 GHz. At 5 GHz, they are close to parallel,but the 10 nH looks a little different, but this is the frequency where our device output impedance is low. Below shows 12 GHz.



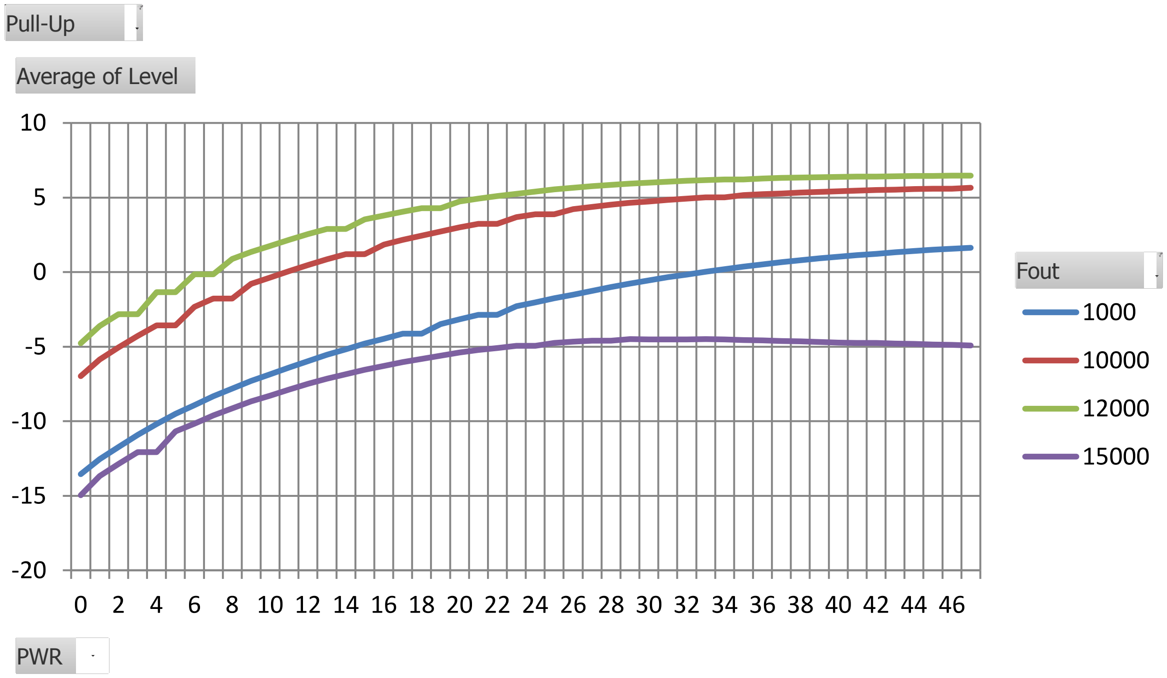
So yes, the output impedance curve changes form over frequency, but it's not the pull-up inductor.

Miller Capacitance and PWR

At higher frequencies, we see a tendency for the output power to actually DECREASE with higher PWR at some point. For the resistor pull-up case below, note at 10 GHz, it saturates around PWR=32, at 12 GHz, it slightly starts to decrease, and at 15 GHz, it is most noticeable.



For the 1 nH inductor, we see something to very similar to the inductor



So although the collector current may increase with PWR, at some point (dependent on output frequency, but not pull-up), increasing PWR does not increase the output power and actually decreases it. Here's a general table guideline for this:

	Inductor		**Resistor**	
Frequency	**PWR_1dB**	**PWRMax**	**PWR_1dB**	**PWRMax**
100	33	47	30	47
1000	37	47	33	47
2000	29	47	25	47
5000	23	46	20	11
10000	29	47	21	36
12000	24	47	18	31
15000	19	33	18	29

The table above gives a guideline for setting the PWR. Note at 5 GHz, there is odd behavior due to the self-resonance discussed in the output impedance chapter. PWR_1dB is the output power you set that gets you to within 1 dB of the maximum power that I got. PWRMax is the setting that gives the maximum power.

Conclusion

It has been shown that the output power is a function of PWR and the impedance of the load, which would be the pull-up in parallel with the load. Note a spectrum analyzer isa 50 ohm load. The Miller capacitance causes the power level to be lower than expected when the frequency is high for higher PWR settings. So therefore, it makes sense to restrict the PWR at higher settings and not always blindly assume higher is better.

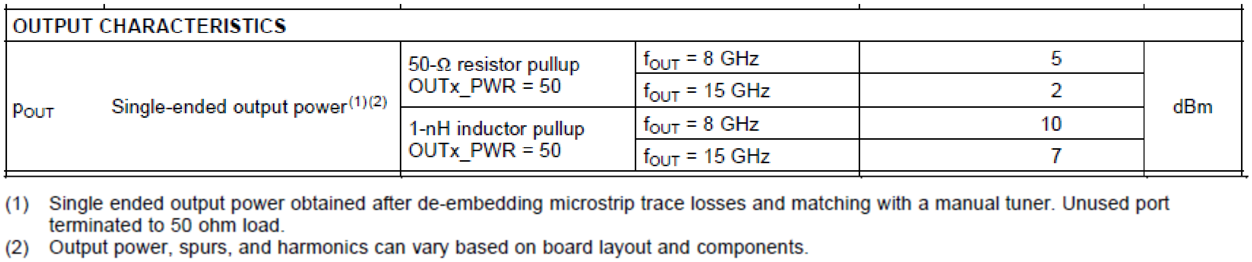
Chapter 5 LMX2594 Absolute Output Power

Introduction

Other chapters have ignored losses and loss due to mismatch. For this chapter, the focus is to figure out the output power that would be achieved with perfect matching and zero losses; these are the numbers in the datasheet. The setup conditions for measurement of output power are key. This document describes the setup conditions used to achieve the numbers as reported in the datasheet. There are a few key points to keep in mind:

- Output power in datasheet has losses de-embedded.
- The LMX2594 EVM routing is sub-optimal for output power.
- Output power setting for OUTx_PWR is non-linear and has a discontinuity between 31 and 32.
- Output power will be lost due to bad match

LMX2594 Datasheet Output Power



OUTPUT CHARACTERISTICS					
P_{OUT}	Single-ended output power(1)(2)	50-Ω resistor pullup OUTx_PWR = 50	f_{OUT} = 8 GHz	5	dBm
			f_{OUT} = 15 GHz	2	
		1-nH inductor pullup OUTx_PWR = 50	f_{OUT} = 8 GHz	10	
			f_{OUT} = 15 GHz	7	

(1) Single ended output power obtained after de-embedding microstrip trace losses and matching with a manual tuner. Unused port terminated to 50 ohm load.

(2) Output power, spurs, and harmonics can vary based on board layout and components.

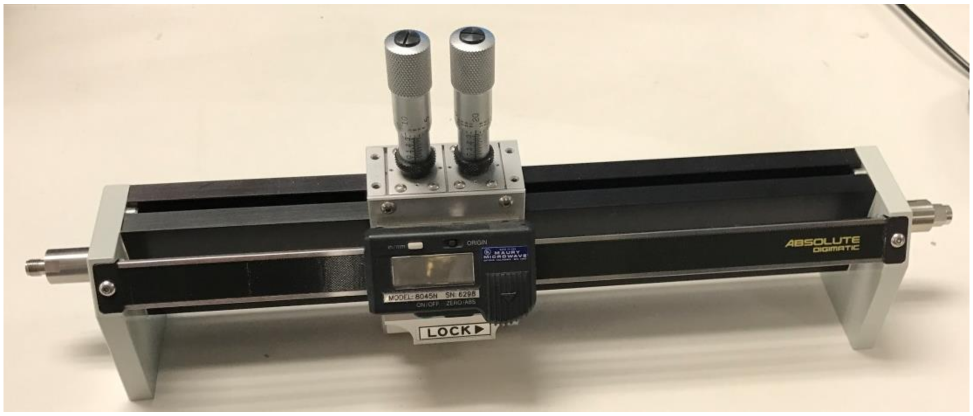
The numbers reported in the datasheet assume that the losses are de-embedded and that the load is matched.

Board Used for Output Power

The placement for the pull-up component is absolutely critical and must be close to the chip or else there is loss in output power. However, the LMX2594EVM accommodates many features including differential outputs. For the best possible output power measurement, it is better to use a single-ended routing and take the complimentary side to 50 ohm on the back side of the board as done in reference design TIDA-01410. Note in layout that pullup is as close as possible. Also best possible connector and decoupling capacitor is used.

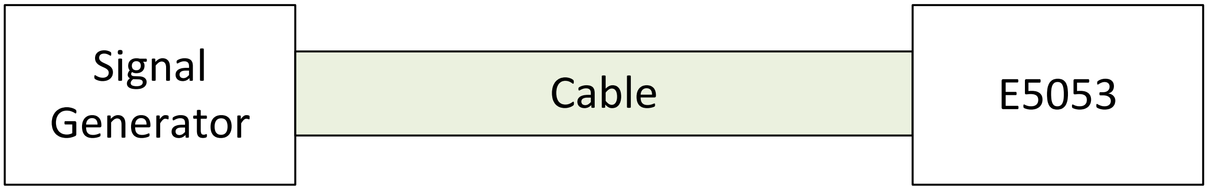
Matching the Load

If the load is not matched, then there is loss of power. The matching may change with frequency. In the case of the resistor pull-up, the matching helped only slightly. However, in the case of the inductor pull-up, the output impedance is far from 50 ohms and matching is not very good. In both cases, a sliding microwave tuner was used from Maury Microwave.

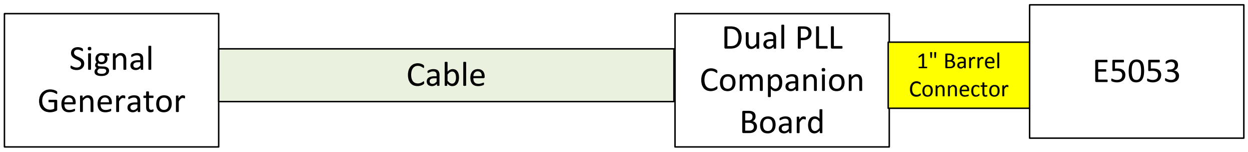


Determining the Loss due to SMA Connectors and Traces on the Board

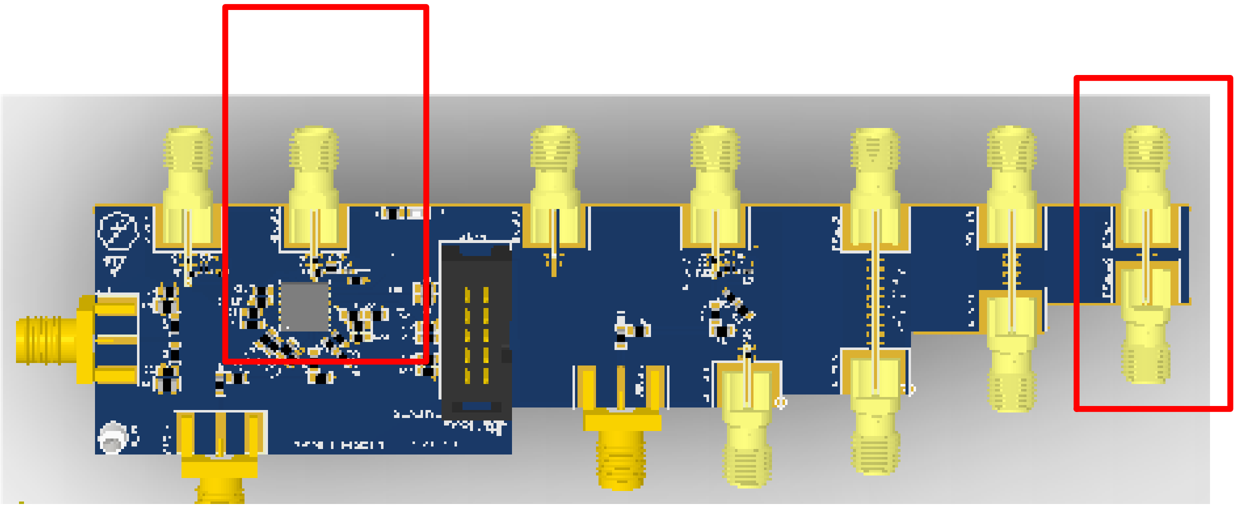
For the actual measurement, a signal generator of known power and frequency was attached to the E5053 and the signal generator frequency was swept.



The next step was to repeat this with a specialized board that had one output that was two copies of the output trace placed back to back and including the SMA connectors. Then this was connected with a barrel connector that was assumed to have no loss. The change in the output power observed on the E5053 is therefore twice the loss.



The actual board used was specialized for this purpose and served many functions, but a diagram of this is shown below. Note that he path on the far right is twice the length of the path attached to the LMX2594.



The loss of this board was measured over frequency and it was found to be about 0.2 dB. Although this board was not the dual PLL board (TIDA-01410), the PLL on it was a copy of this layout and therefore it can be assumed that the losses would be the same.

Measurements for Resistive Load

50 ohm Resistor Pull-Up						
Fvco	OUTA_PWR	Measure	Board Loss	Tuner Loss	Connector Saver	Output Power
3000	50	7.7	0.2	0.1		8.0
4000	50	8.8	0.2	0.1		9.1
5000	50	8.6	0.2	0.2		9.0
6000	50	6.6	0.2	0.2		7.0
7000	50	3.2	0.2	0.2		3.6
8000	50	4.7	0.2	0.3		5.2
9000	50	3.8	0.2	0.3		4.3
10000	50	2.3	0.2	0.3	0.1	2.9
11000	50	3	0.2	0.4	0.2	3.8
12000	50	1.7	0.2	0.4	0.3	2.6
13000	50	2.8	0.2	0.4	0.4	3.8
14000	50	3.1	0.2	0.5	0.4	4.2
15000	50	1	0.2	0.5	0.5	2.2

1 nH Inductor Pull-Up (High Frequency), Maybe 10 nH Below 5 GHz						
Fvco	OUTA_PWR	Measure	Board Loss	Tuner Loss	Connector Saver	Output Power
3000.0	50	10.6	0.2	0.1		10.9
4000.0	50	11.9	0.2	0.1		12.2
5000.0	50	12.1	0.2	0.2		12.5
6000.0	50	10.6	0.2	0.2		11.0
7000.0	50	7.9	0.2	0.2		8.3
8000.0	50	9.4	0.2	0.3		9.9
9000.0	50	8.5	0.2	0.3		9.0
10000.0	50	7.6	0.2	0.3	0.1	8.2
11000.0	50	6.8	0.2	0.4	0.2	7.6
12000.0	50	6.2	0.2	0.4	0.3	7.1
13000.0	50	6.1	0.2	0.4	0.4	7.1
14000.0	50	6.2	0.2	0.5	0.4	7.3
15000.0	50	5.6	0.2	0.5	0.5	6.8

Note that this matches the datasheet claims fairly closely.

Adding High Frequency Correction Factor to Output Power Model

	Resistor		
Fout	**Actual**	**Model**	**Correction**
3000	8	6.4	1.6
4000	9.1	6.4	2.7
5000	9	6.4	2.6
6000	7	6.4	0.6
7000	3.6	6.4	-2.8
8000	5.2	6.4	-1.2
9000	4.3	6.4	-2.1
10000	2.9	6.4	-3.5
11000	3.8	6.4	-2.6
12000	2.6	6.4	-3.8
13000	3.8	6.4	-2.6
14000	4.2	6.4	-2.2
15000	2.2	6.4	-4.2

	Inductor		
Fout	**Actual**	**Model**	**Correction**
3000	10.9	3.3	0
4000	12.2	5.4	0
5000	12.5	6.9	0
6000	11	8	0
7000	8.3	8.8	-0.5
8000	9.9	9.4	0.5
9000	9	9.9	-0.9
10000	8.2	10.2	-2
11000	7.6	10.5	-2.9
12000	7.1	10.8	-3.7
13000	7.1	11	-3.9
14000	7.3	11.2	-3.9
15000	6.8	11.3	-4.5

As these measured results have been corrected for board losses, the remainining error can be assumed due to the the device. Recall that the collector currents were derived at low frequency. So at higher frequencies, the approach is to simply compare the model to the measured result to get a correction factor that can be added in for the purposes of calculating output power.

Note that the inductor power seems suspiciously high for the actual at low frequencies; maybe that was 10 nH for lower frequencies. Also, resistor seems to get lower power, maybe that was the AC couplin capacitor

Output Power Below 3 GHz

In the datasheet and these measurements, the lower frequency reported is 3 GHz. This is NOT because there is something to hide below 3 GHz, but rather the impedance of the 1 nH inductor is too low at this frequency and for some of the measurements, the AC coupling capacitor was too small for this.

Chapter 6 Matching Strategies

Introduction

Now that the impedance and behavior has been explained, it's time to discuss what to do with the PCB

Use resistor pull-up when:
- You want to deal with very low frequencies where the inductor impedance is not very high
- You don't want to deal with putting a pad to match
- You can sacrifice power

Use Inductor followed by resistive pad when:
- You want to have a good broadband solution that is robust
- You want flexibility (resistive pad can be tweeked)

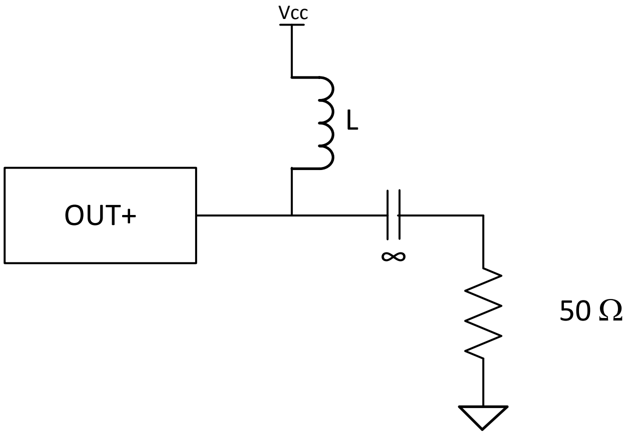
Use Inductor with no pad (but maybe tuned circuit) when:
- You absolutely want the last dB of output power AND you are willing to do measurements with trial and error.
- You have a narrowband design
- You have an inductor with resistive pad accomondated for the layout on your board and you want to tinker with replacing resistors with capacitors and inductors to see if you can do higher

Some other ideas to experiment with that were not tried:
- Resistor and inductor in series for pull-up
- Baluns and combining both outputs for higher power.

The rest of this chapter discusses some of these ideas.

What NOT to do --Futility of Inductor Impedance Matching

The idea of the pull-up inductor is to have high impedance; there is no point needing to make it to have a matched j50 ohm impedance. 50 ohm and j50 ohm are not the same. But just to prove the point, this section goes through the exercise.



For the purposes of matching the inductor, one may think that there is an "optimal" value (assuming the output buffer to be high impedance) for the purposes of impedance matching. Nevertheless, it's good to through the exercise. Calculate the reflection coefficient.

$$\Gamma = \frac{Z_A - Z_0}{Z_A + Z_0} = \frac{j \cdot \omega \cdot L - Z_0}{j \cdot \omega \cdot L + Z_0}$$

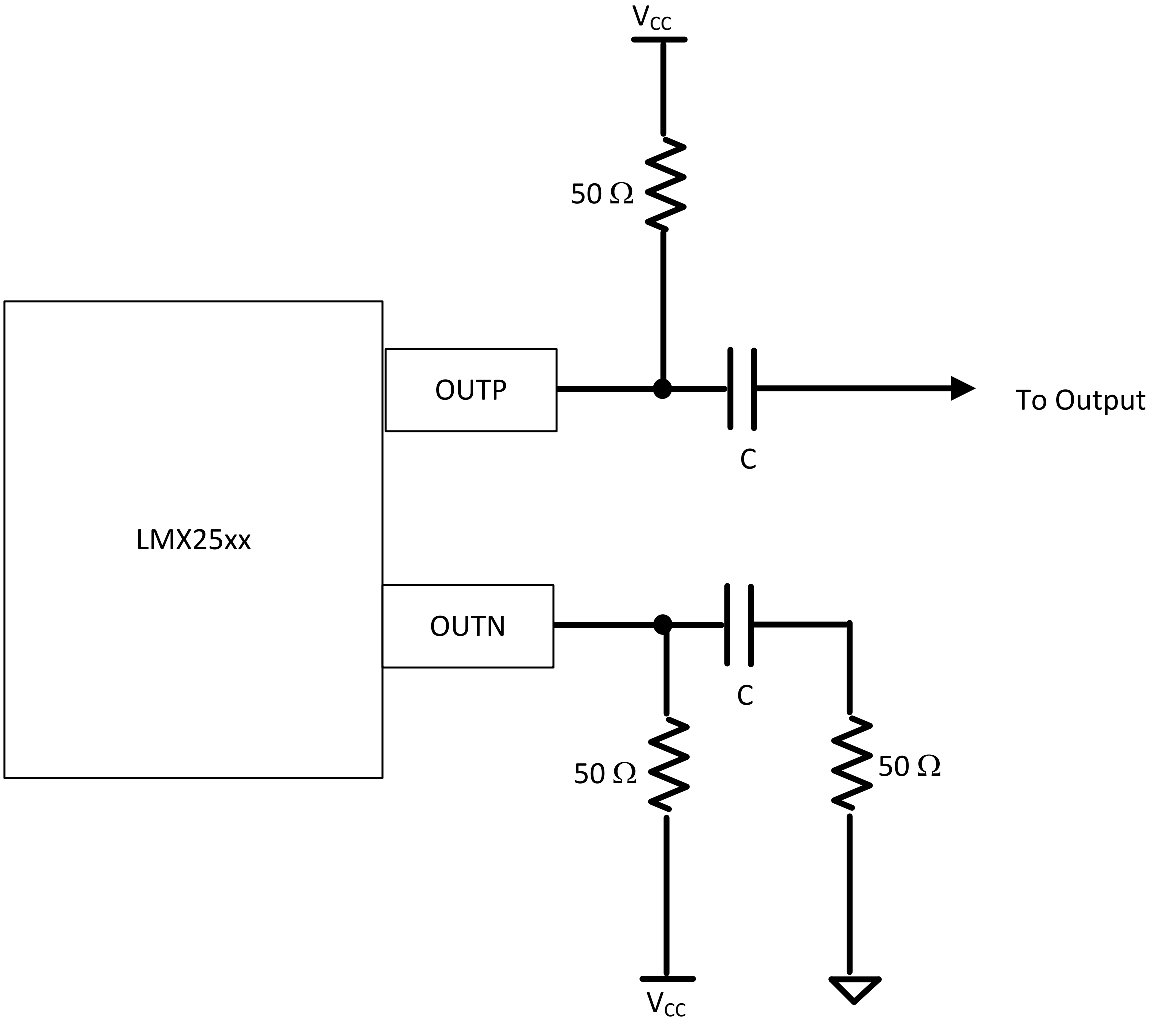
Note that the magnitude of this reflection coefficient is always one

$$|\Gamma| = \left|\frac{Z_A - Z_0}{Z_A + Z_0}\right| = \left|\frac{j \cdot \omega \cdot L - Z_0}{j \cdot \omega \cdot L + Z_0}\right| = \frac{\sqrt{(j \cdot \omega \cdot L)^2 + {Z_0}^2}}{\sqrt{(j \cdot \omega \cdot L)^2 + {Z_0}^2}} = 1$$

So in other words, the choice of inductor is not about the matching, but about the signal swing.

Resistor Pull-Up

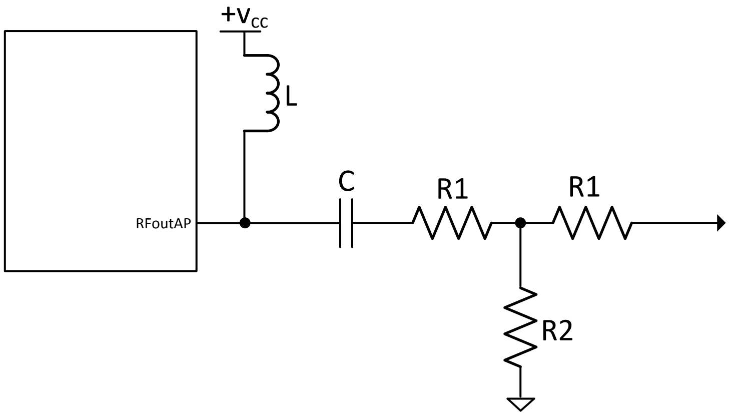
The resistor pull-up offers fairly good matching across all frequencies. Also at very low frequencies, it may be hard to find inductors large enough.



This is pretty straightforward. The output needs to be balanced for the negative. So this assumes the output is a 50 ohm load. If you are feeling adventurous, you could technically terminate the 50 ohm on OUTN to Vcc, but this has not been tried.

Inductor Pull-up with Pad

Provided the frequency is not too low for the inductor size, the inductor offers good output power, although the matching is not very good. The resistive pad mitigates this impedance issue. Note that there is a AC coupling cap in the bottom of the pad. The thinking is that this you need two caps and this is one less cap in the critical high frequency RF path. If one is feeling adventurous, you could use Vcc instead of ground for the pad.

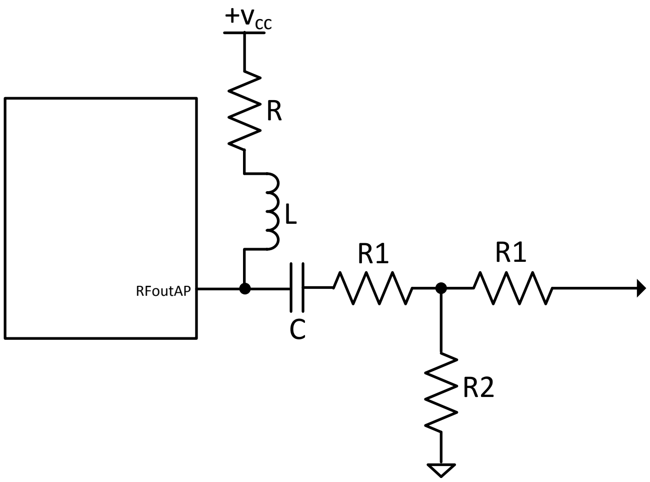


Here are some resistor values for common T pads:

Atten	R1	R2
1	2.7	420
2	5.6	220
3	8.6	150
4	12	100
5	15	82
6	18	68

Combination

The resistor pull-up seems to give good low frequency response, but seems to have lower power because there is less impedance and therefore less signal swing across this. Also, there is a DC voltage drop across the resistor, which could impact the transistor biasing, but an experient in this paper shows that putting 10 nH in parallel with the 50 ohm resistor did not help. So maybe it's more just the signal swing. The inductor has the problem of low impedance at lower frequencies and near the self-resonant frequency. By putting both components in series, it seems to help with the self-resonant frequency and low frequency response.



R is the pull-up resistor. In this case, 50 ohm might be a good choice, but maybe 25 ohm is a good choice at higher frequencies. Note that there are high frequency resistors available for both 50 and 25 ohm. For the inductor, 1 nH to 3 nH might be a reasonable choice. R1 and R2 form a resistive T pad. For the AC couping cap, C, one was put on the bottom of the pad instead of the junction of L and R1 in order to put less components in the high frequency path.