Ingredients for Perfect RF Transceiver

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Outline

Focus of this Tutorial

- I will focus on a fairly common modern approach to building LLRF:
  - Heterodyne downconverters for input
  - Digital signal processor with ADCs, FPGAs, and DACs
  - Heterodyne upconverters at the output
- Several advantages of converting to intermediate frequency (IF) instead of DC:
  - Single downconverter and ADC per channel;
  - Insensitive to DC offsets and drifts.
- Why not direct sampling?
  - Downconversion translates phase at RF directly to phase at IF, producing $f_{\mathrm{RF}}/f_{\mathrm{IF}}$ improvement in ADC clock jitter sensitivity.

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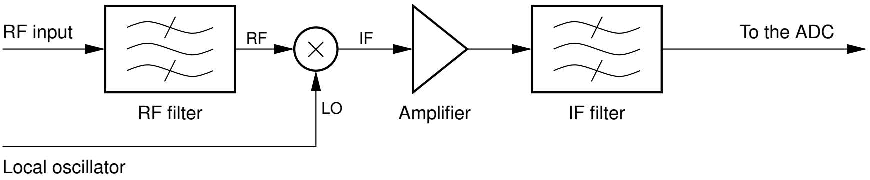
Generic Receiver Block Diagram



- RF filter is optional;
- As is IF amplifier.
- At the IF port of the mixer both desired signal (lower sideband) at $\omega_{\mathrm{rf}} - \omega_{\mathrm{lo}}$ and unwanted upper sideband at $\omega_{\mathrm{rf}} + \omega_{\mathrm{lo}}$ are present;
- For the mixer to perform well, both upper and lower sidebands must be well terminated.

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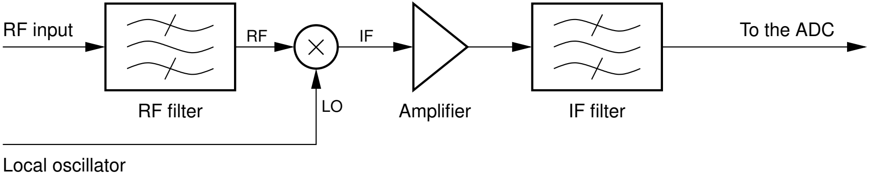

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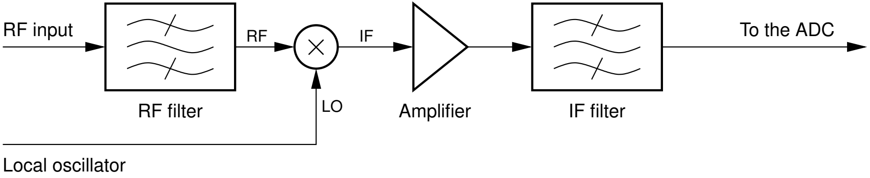

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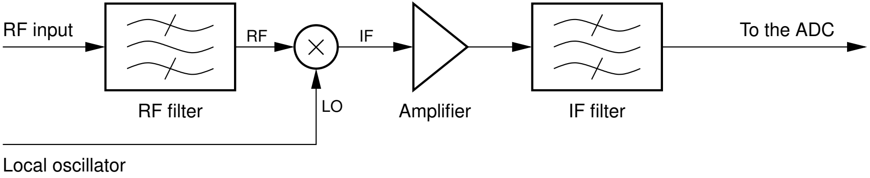

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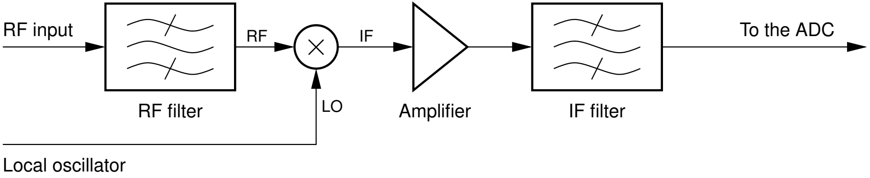

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Main Difficulty in LLRF Receivers

- The secret to building low noise receivers is well known.
- Friis equation for the noise factor: $F = F_1 + \frac{F_2-1}{G_1} + \frac{F_3-1}{G_1 G_2} + \ldots$
- Use a high gain low noise amplifier as the very first stage of your signal chain.
- Cascade noise figure is then dominated by the first stage, greatly relaxing the requirements for the rest of the chain.
- Unfortunately this approach assumes we start with very low amplitude signals;
- In LLRF we typically start with very large signals, so the first stage is often a 20–30 dB attenuator.

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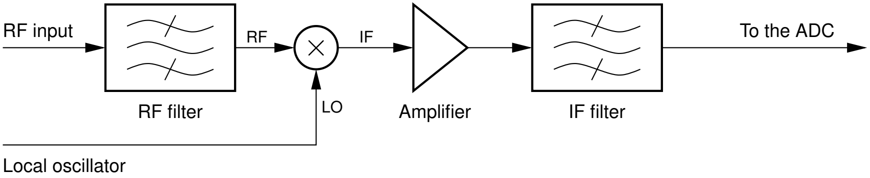

- To maintain linearity, RF port of the mixer has to stay 10–20 dB below the LO port;
- With 13 dBm mixers, you can't get much above 0 dBm without introducing significant distortion;
- 8 channel module with 13 dBm LO needs 27 dBm (0.5W) input;
- Going to 17, 23, or 27 dBm gets impractical very quickly;
- Mixer output is typically too small for the ADCs, some voltage gain is needed.

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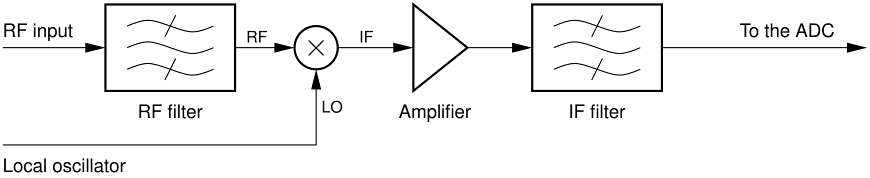

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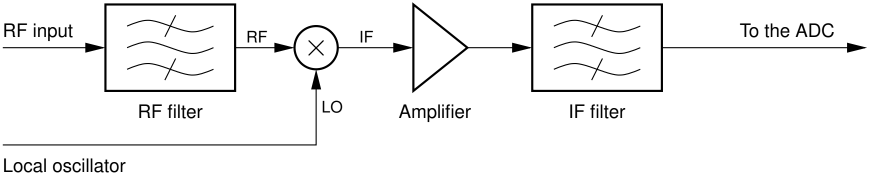

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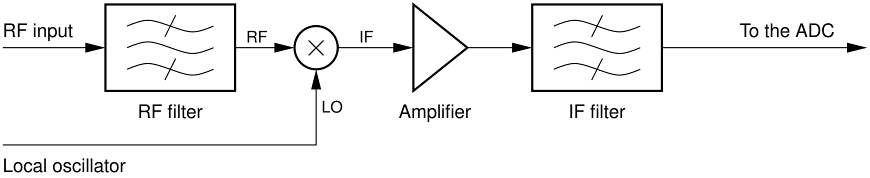

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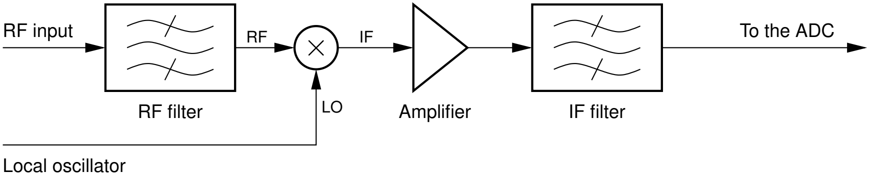

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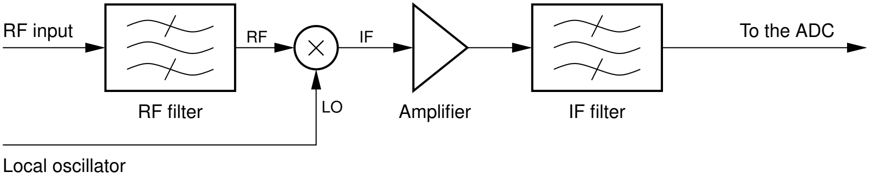

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Enemies of the Perfect Transceiver

- Channel to channel coupling;
- Spurious signals;
- Gain and phase drifts;
- Phase noise;
- Broadband noise;
- Distortion.

Outline

1 Introduction

2 Measurements and Surprises
- Single Tone ADC Characterization
- Spurs
- Amplifier Phase Noise
- Input Channel Coupling
- Output to Input Coupling
- Reflections

In This Section

- Learning from your mistakes is a good way to learn;
- But learning from the mistakes of others is even better;
- I will present here a mix of measurement techniques for quantifying transceiver performance;
- Many of these measurements have lead to discoveries of unwanted behavior;
- I'll try to explain the mechanisms and to offer solutions.

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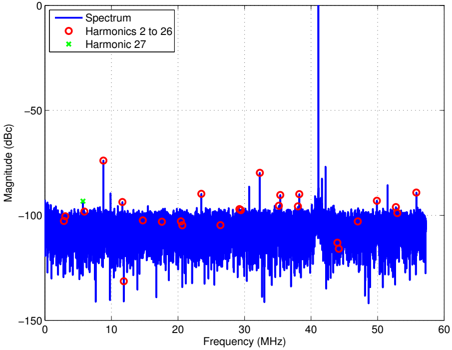
Basic Measurement



- Set input signal to CW frequency in an exact FFT bin;
- Capture 16–64k samples;
- Standard calculation to extract SNR, SINAD, ENOB, SFDR;
- Hardware check - identify stuck or shorted ADC bits.
- Rich harmonic content;
- Reference channel coupling at 41.7 MHz and an intermodulation line.

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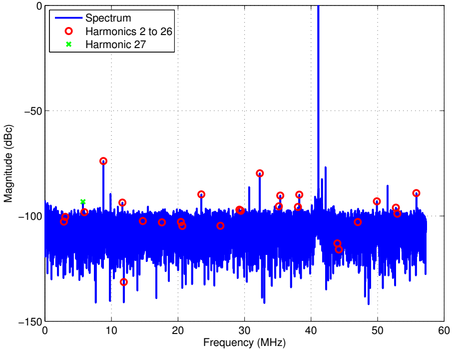

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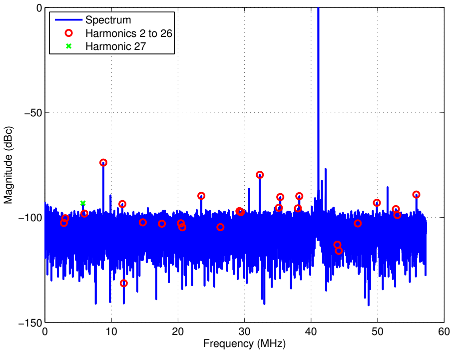

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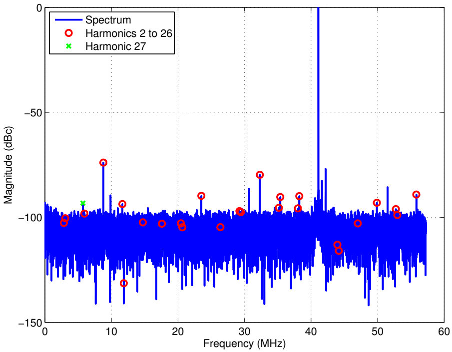

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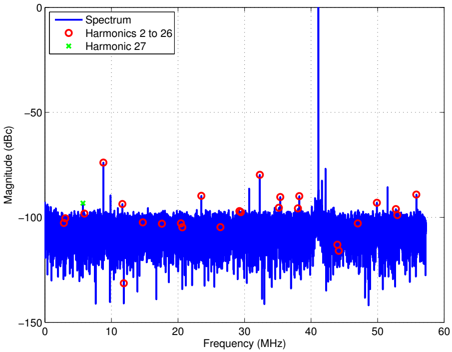

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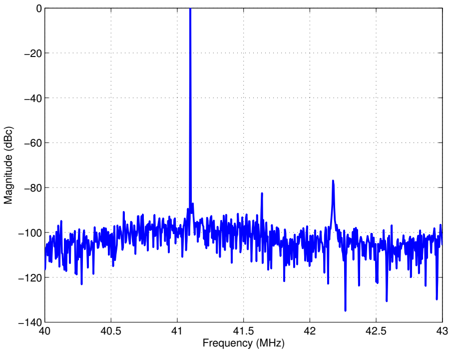

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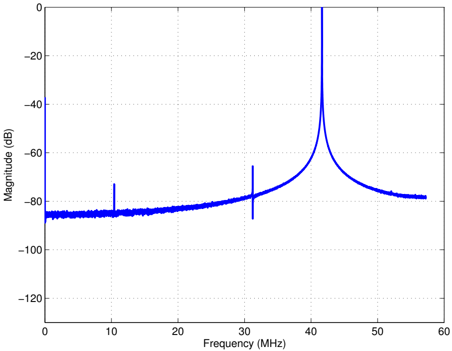

- Capture 24576 samples of CW IF signal;
- IF to sampling ratio 4/11;
- A lot of spectral leakage;
- Standard approach is to window time-domain signal (Blackman);
- Another way is to trim the data record to leave an integer number of periods ($24574 = 2234 * 11$).

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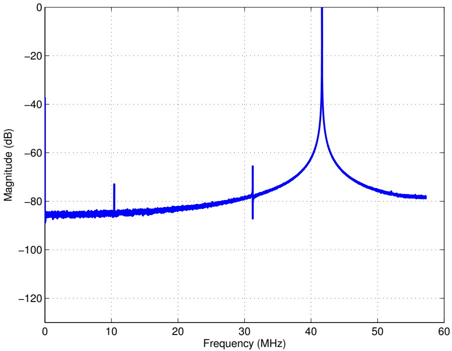

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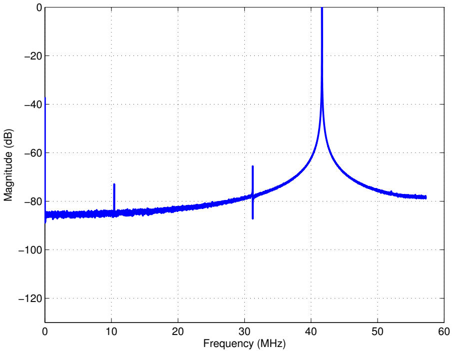

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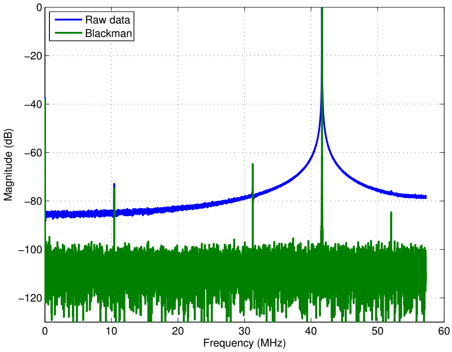

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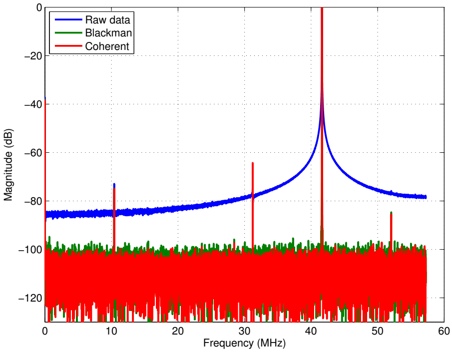

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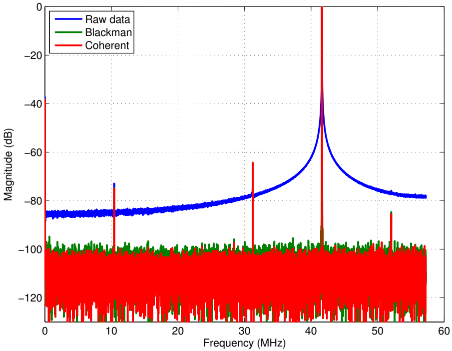

- This is called coherent sampling;
- Not much difference between windowed spectrum and coherent sampling one;
- What if we zoom in?
- Log scale vs. offset frequency;
- Coherent sampling gives us a way to measure noise density within one FFT bin of the carrier!

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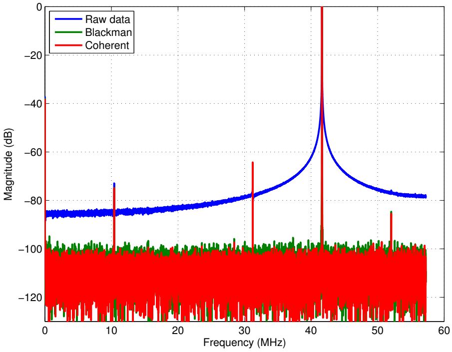

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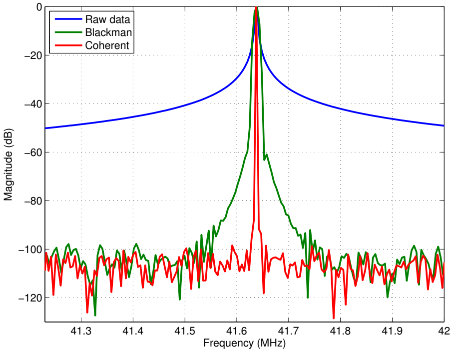

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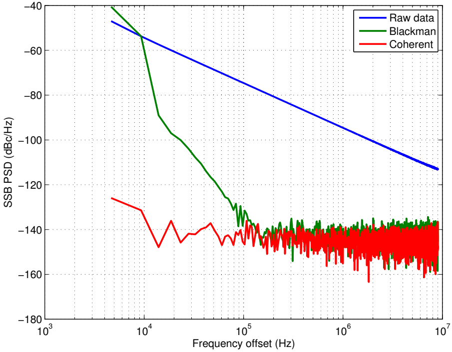

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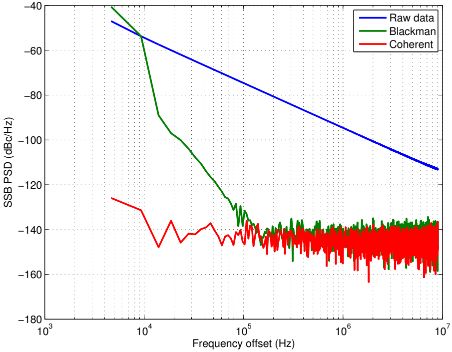

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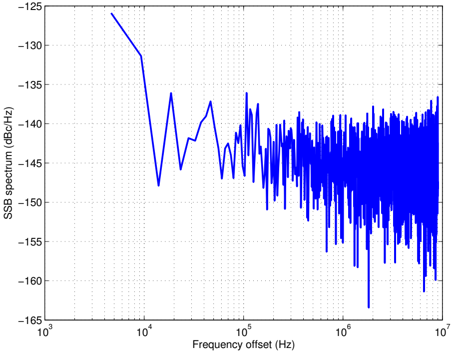

- FFT of a single acquisition;
- An average of 1000 acquisitions;
- Use two channels, average of 1000 cross-correlated acquisitions;
- Uncorrelated noise sources are averaged out
  - Averaged out: channel thermal noise, ADC quantization and aperture jitter;
  - Remain: source noise, common LO and clock noise.

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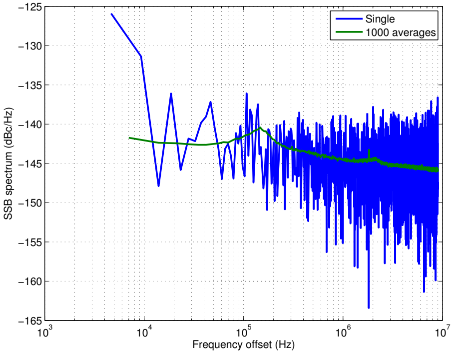

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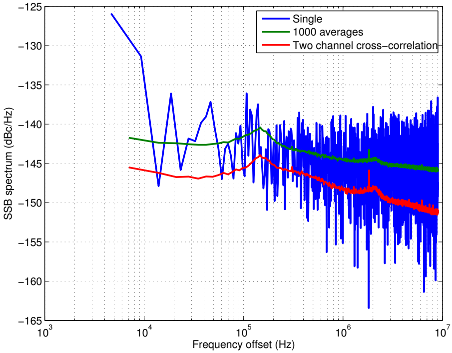

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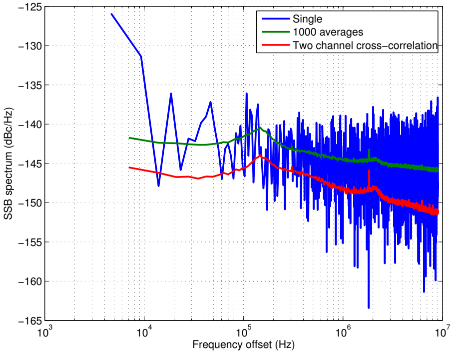

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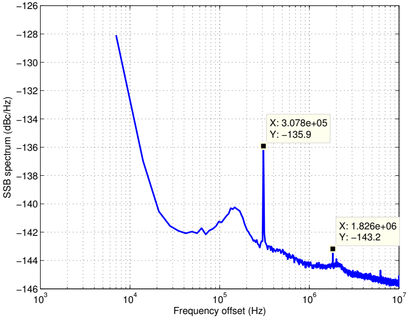

- Single channel spectrum, 308 kHz spur;
- Comes from DC-DC converter driving LO generator bulk supply;
- Between DC-DC converter and RF supplies:
  - An RC filter;
  - Low-noise LDO regulator;
  - Tens of bypass capacitors.
- Lower ESR RC filter, 2.2 dB improvement;
- 10 2.2 μF LDO input capacitors replaced with 22 μF.

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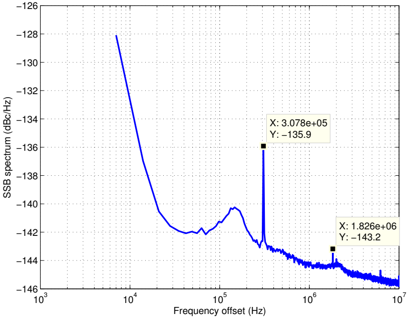

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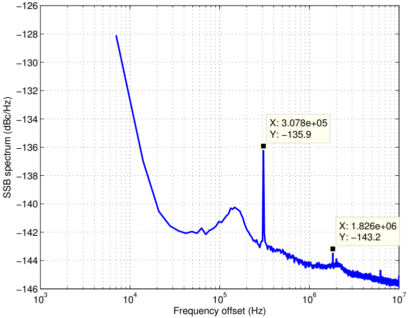

- Single channel spectrum, 308 kHz spur;
- Comes from DC-DC converter driving LO generator bulk supply;
- Between DC-DC converter and RF supplies:
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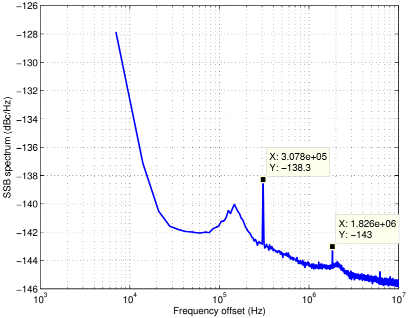

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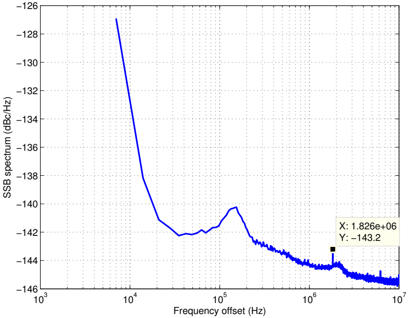

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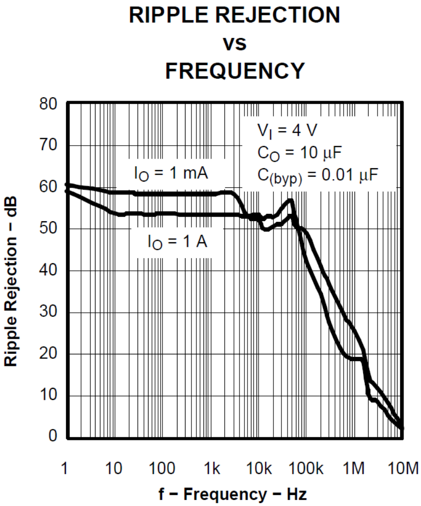

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- LDO might have 60 dB power supply rejection at low frequencies;
- But at 300 kHz you are lucky if you get 30 dB PSRR;
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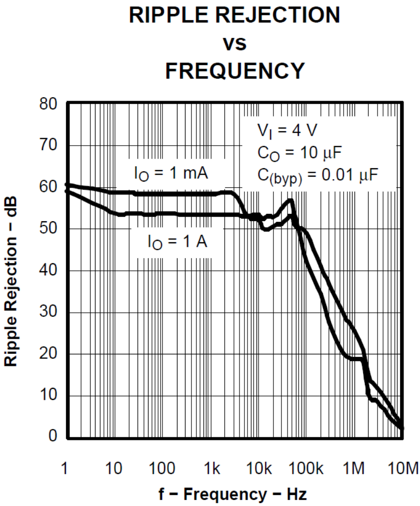

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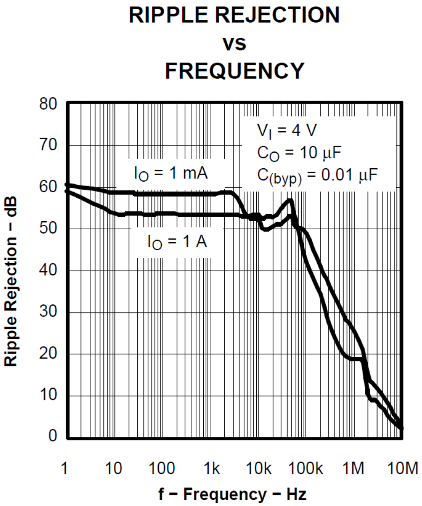

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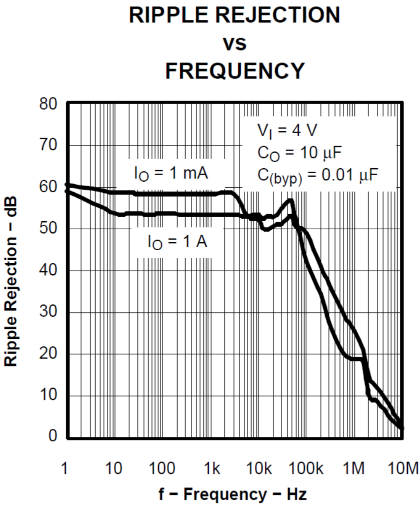

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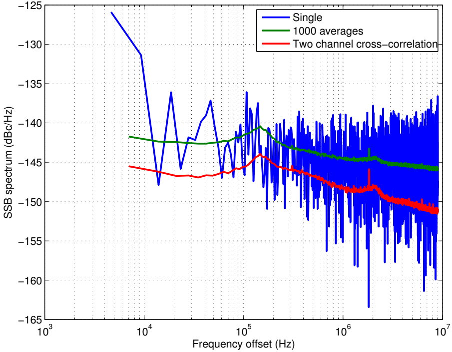
Measuring Additive Phase Noise



- This is not a demodulated signal, so both amplitude and phase noise are included;
- Comparison with demodulated phase noise measurements on the same system shows that phase noise dominates below 100 kHz;
- Use the setup to investigate additive phase noise contribution of amplifiers.

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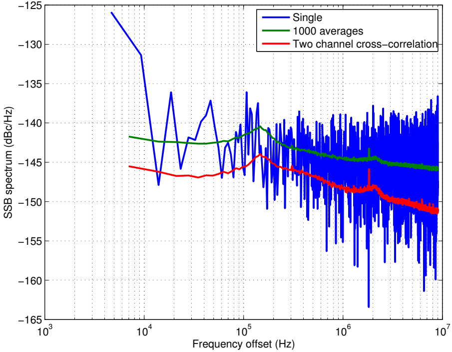

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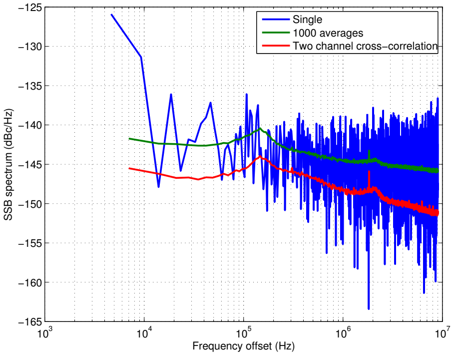

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Two Amplifiers

Measured Parameters

Device	Gain (dB)	NF (dB)
MGA-31589	19.9	1.15
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- Two amplifiers (LO drive candidates);
- Phase noise is dramatically different between the two;

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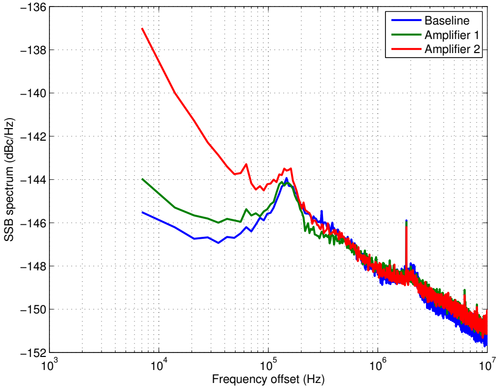

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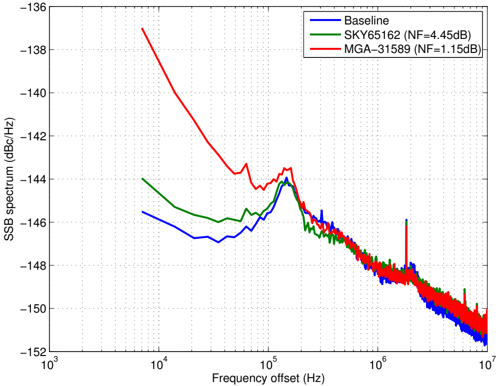

- Two amplifiers (LO drive candidates);
- Phase noise is dramatically different between the two;
- Wideband noise figure tells you little about the phase noise performance;
- Manufacturers rarely (never) talk about phase noise performance.

Outline

Channel to Channel Coupling: Measurements

Standalone board

0	−77	−90	−101
−69	0	−75	−90
−79	−76	0	−70
−89	−89	−83	0

Cold plate, thermal gap filler

0	−61	−61	−63
−58	0	−60	−64
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- A typical coupling matrix for four channels (dB);
- The same board is mounted 1.27 mm above the cold plate;
- A different gap filler magically fixes the problem.

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0	−77	−88	−91
−68	0	−74	−88
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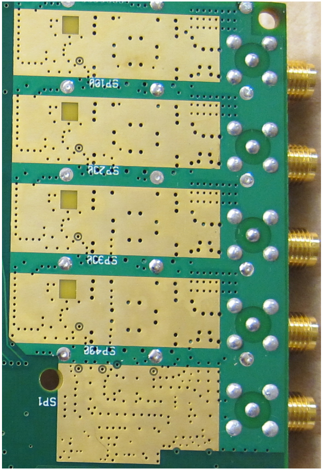
Channel to Channel Coupling: Investigation



- What causes coupling and why do different materials behave differently?
- Increased coupling is due to the thermal gap filler in the area under four input SMA connectors.
- Dielectric constants:
  - Bergquist GP3000S30-0.060: 7@1 kHz
  - Laird Tflex 660 DC1: 3.31@1 MHz
- 2 mm center conductor pad, parasitic capacitance to the plate:
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- Clearly there is more going on: ε_r change with frequency, etc.

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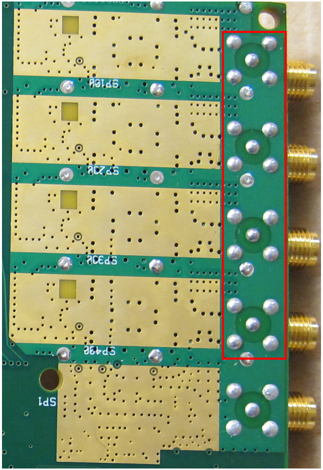

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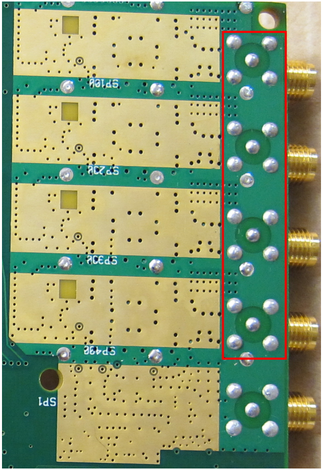

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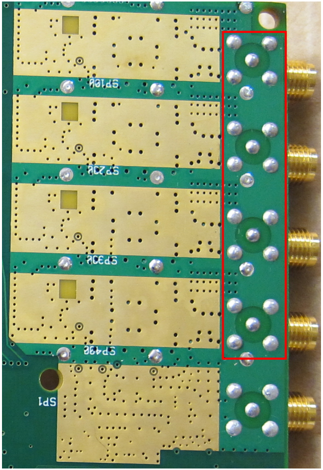

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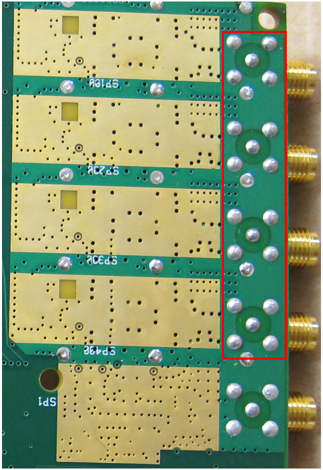

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Learning from Mistakes

- Important point: when we design our systems, we necessarily simplify things and make assumptions;
- However carefully you simulate your design, there are always features you leave out;
- There is no substitute for the physical test bench and methodical troubleshooting;
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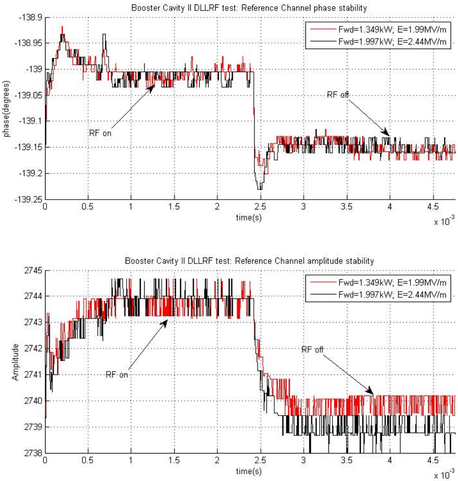
Example of Strong Coupling



- Reference channel shifts during the output pulse;
- Change of 0.15%, 0.15°, −50 dB error vector;
- Coupling path — LO distribution:
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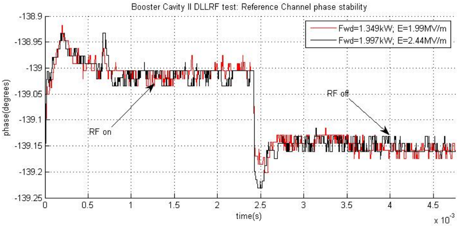

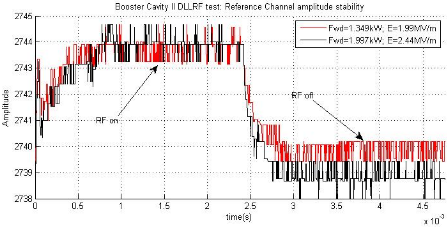

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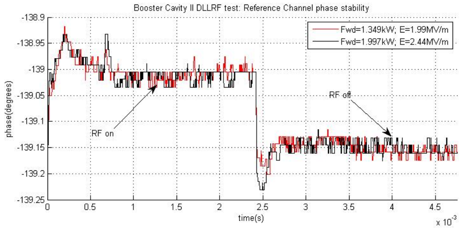

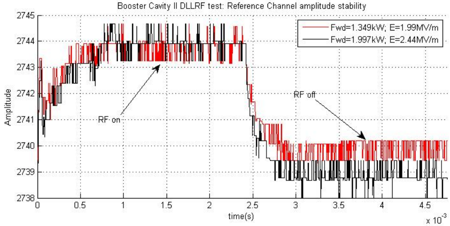

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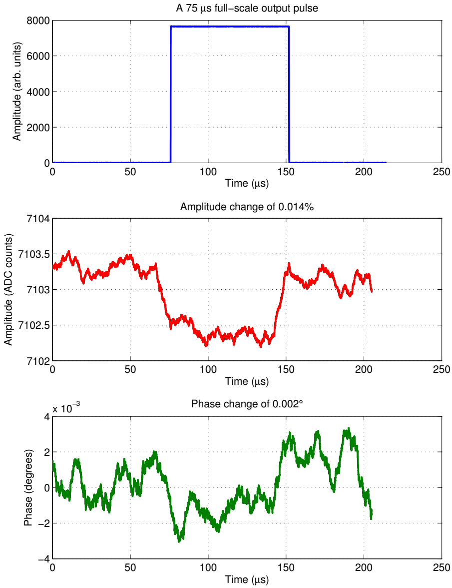

- 75 μs output pulse (full scale);
- Isolation is around 77 dB;
- Connect the output to one of the inputs, still 74 dB;
- 8-way splitter: 3 stages of 90° hybrids;

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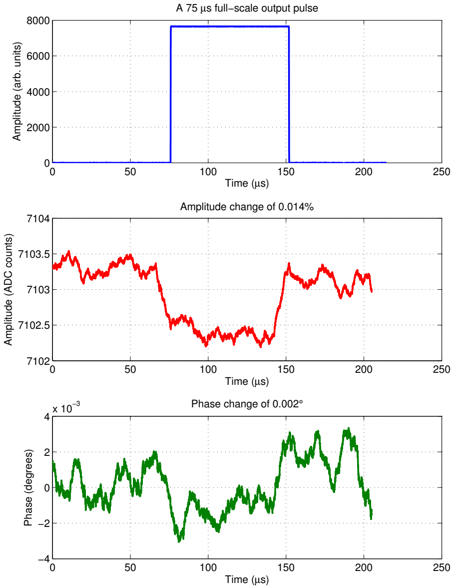

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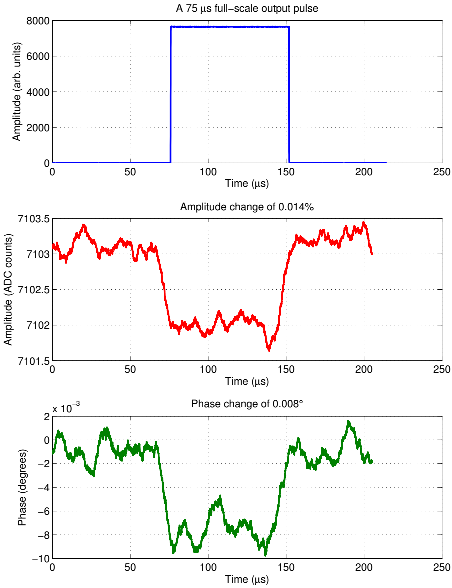

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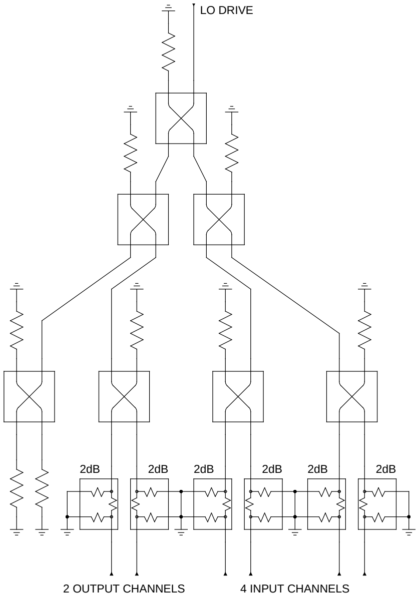

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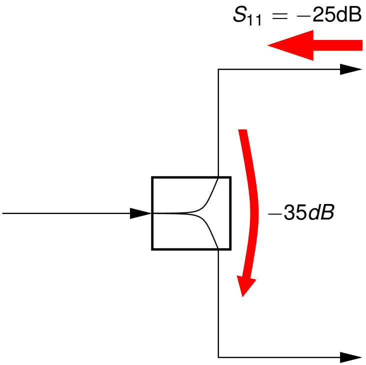
2. Measurements and Surprises
   - Single Tone ADC Characterization
   - Spurs
   - Amplifier Phase Noise
   - Input Channel Coupling
   - Output to Input Coupling
   - Reflections

Tricky Power Splitters



- Power splitters are extremely common in LLRF;
- Datasheets will quote 20–40 dB isolation between output ports;
- That spec assumes that the input port is perfectly matched;
- Due to the sum port mismatch the isolation is 41 dB instead of 60 dB.

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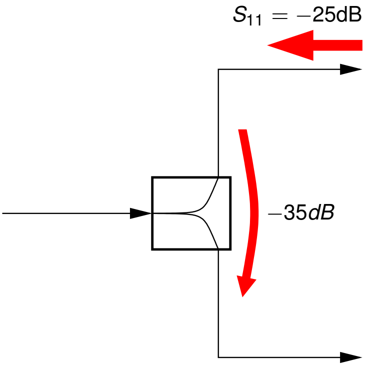

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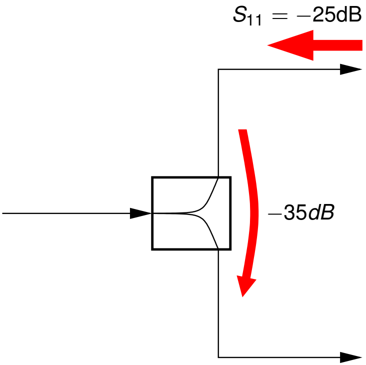

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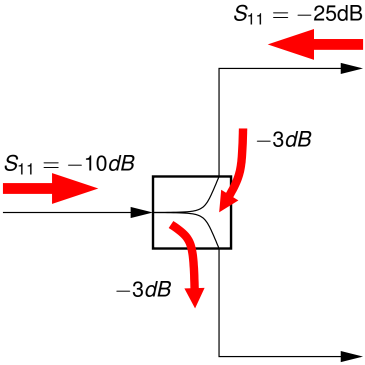

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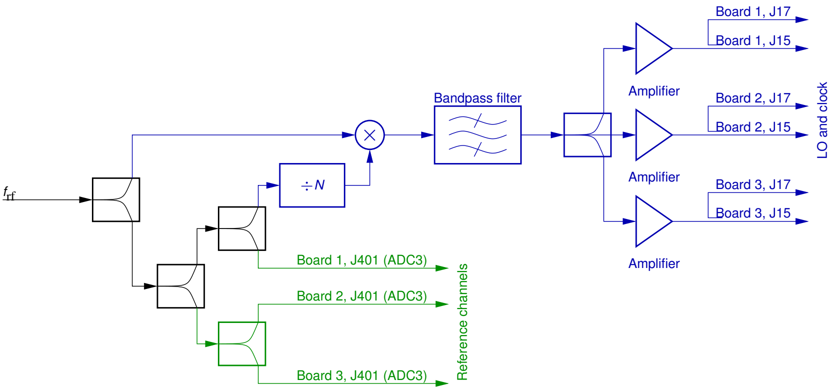
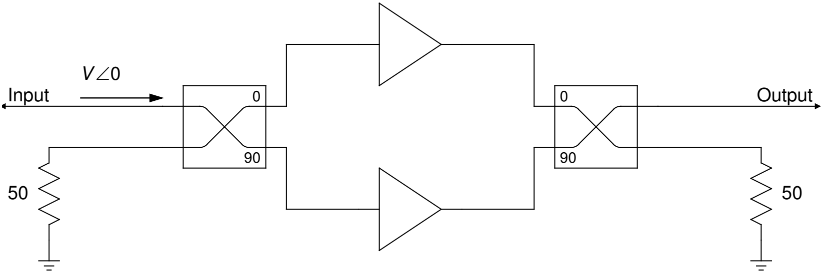
Real Life Example: Divide and Mix LO Generation



- Reflections in the splitter network change depending on the source impedance;
- Changes in reference level lead to changes in mixer RF and LO port matching.

Stabilizing Mixer Match



- Inspired by the idea of balanced amplifier matching;
- Drive two identical devices in quadrature;
- Combine outputs appropriately;
- If $\Gamma_1 = \Gamma_2$, reflection vanishes;
- In practice, expect 17–20 dB return loss;

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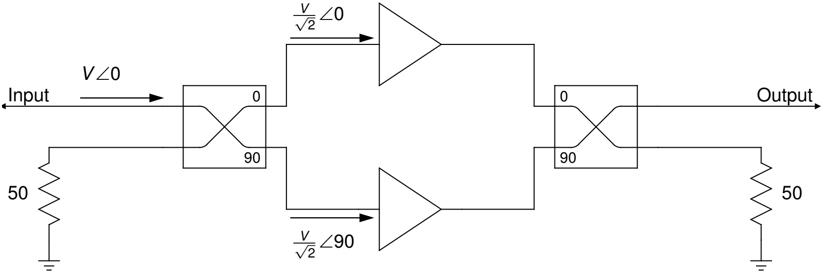

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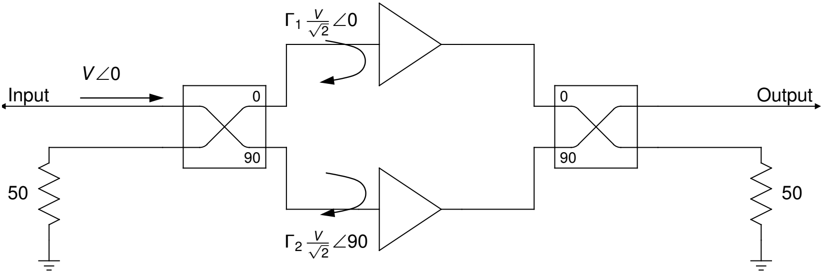

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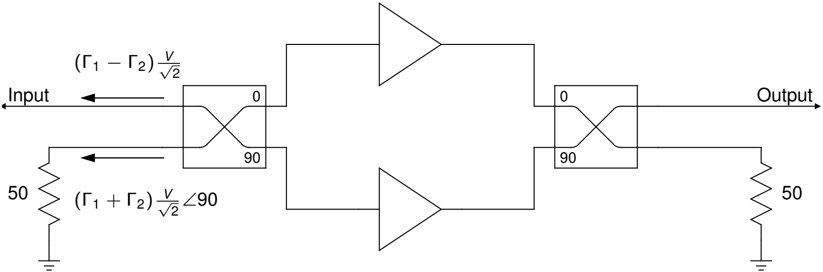

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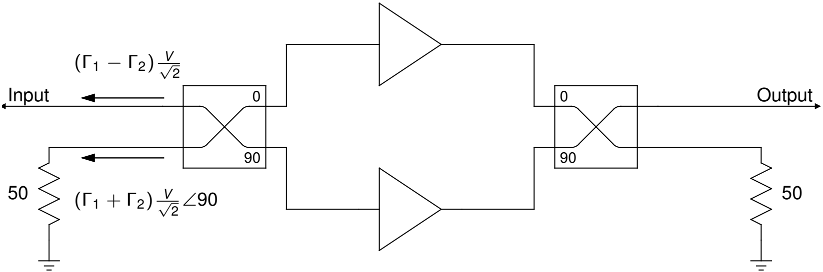

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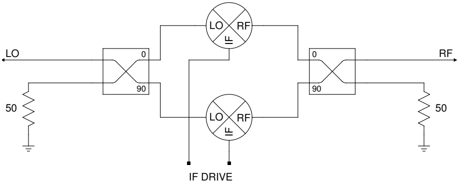
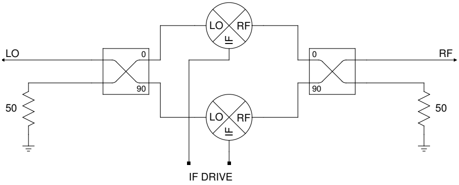
Stabilizing Mixer Match: Termination Insensitive Mixer



- Two options for IF drive: common mode or differential;
- Differential also reduces LO-to-RF coupling by 20 dB;
- Reflection coefficient on LO and RF ports is around 0.1 and shows very little change with incident power;
- Turns out this design is called Termination Insensitive Mixer;
- A figure from MITEQ Application Note on TIMs.

Stabilizing Mixer Match: Termination Insensitive Mixer



- Two options for IF drive: common mode or differential;
- Differential also reduces LO-to-RF coupling by 20 dB;
- Reflection coefficient on LO and RF ports is around 0.1 and shows very little change with incident power;
- Turns out this design is called Termination Insensitive Mixer;
- A figure from MITEQ Application Note on TIMs.

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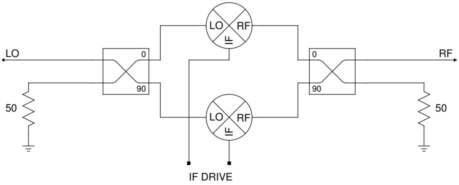

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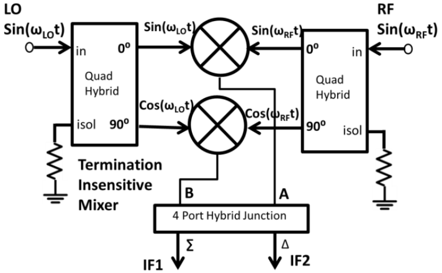

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