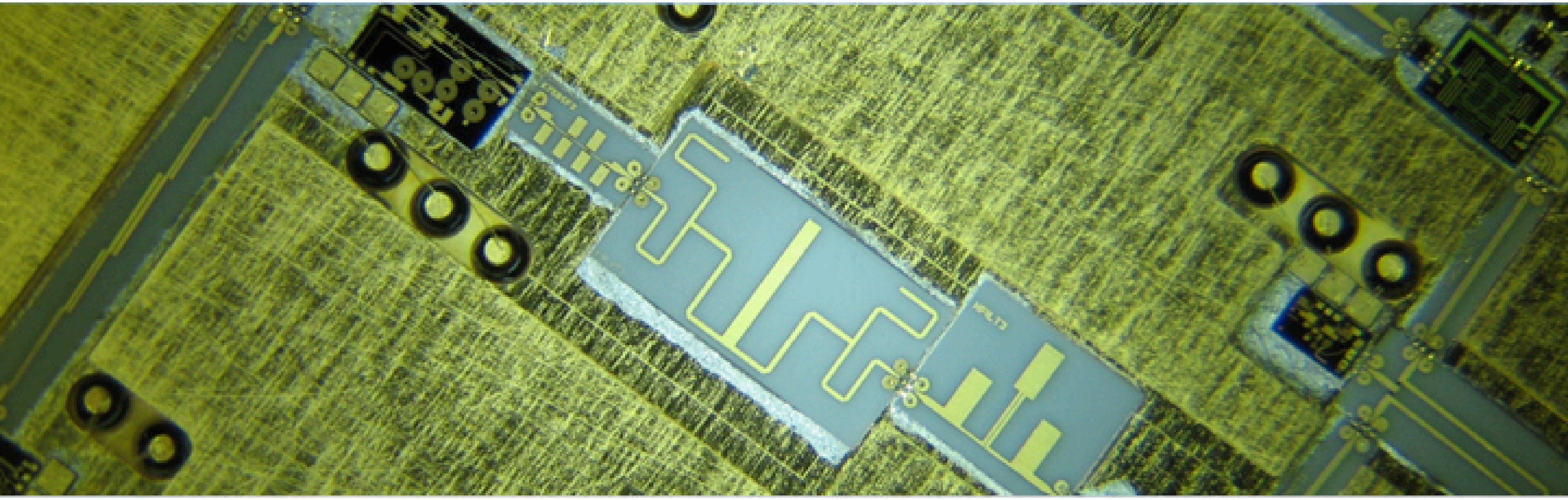
Integrated Analog-Digital-Photonic Receivers



Matt Morgan

US-China Workshop, 5/19/2014

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

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Integration of Analog, Digital, and Photonic Front-End Components

- Re-optimizes front-end architecture to leverage modern advances in:
  - Integrated technology, and
  - Digital Signal Processing (DSP).
- These concepts are *complementary*:
  - DSP delivers **precision** unmatched by analog techniques,
  - while integration ensures **stability** in both amplitude and phase
    - more accurate and longer-lasting calibrations
    - crucial to high-dynamic range imaging
- To that end, we
  - digitize as close to the antenna feed as possible,
  - transfer any functionality we can into the digital domain,
  - and integrate into the front-end everything needed to lock-in the analog amplitude and phase drift and to get the data physically off the telescope (i.e. analog, digital, and photonic).

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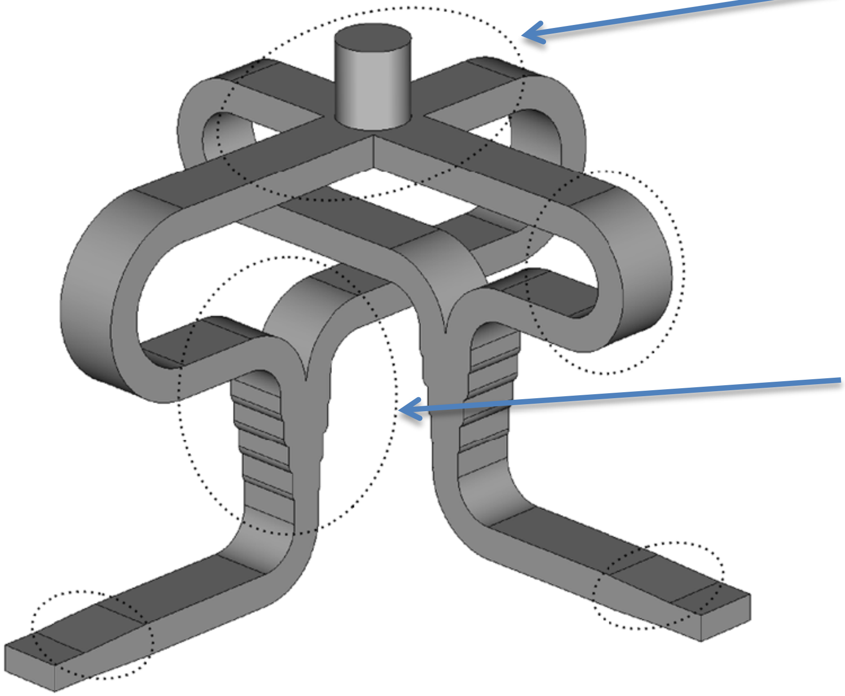
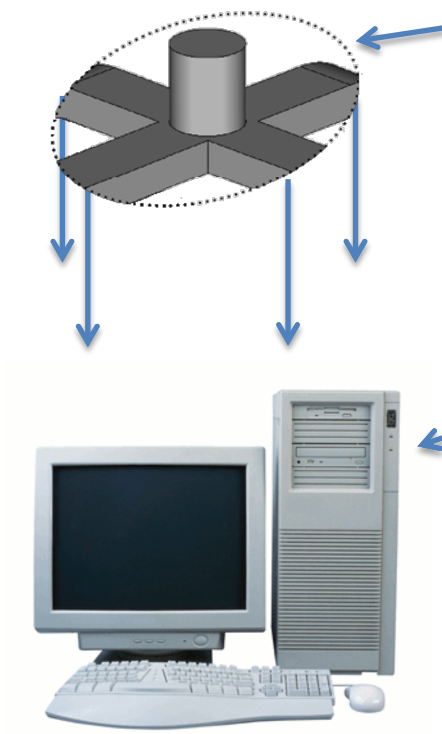
Orthomode Transducers (OMTs) Generally Work in Two Steps



- "Factorization"
  - separation of dual-polarized input into vector components
  - turnstile, Bøifot, etc.
- "Reconstruction"
  - Re-assembly of component vectors into orthogonal polarizations
  - Typically, E/H-Plane combiners, planar baluns, etc.

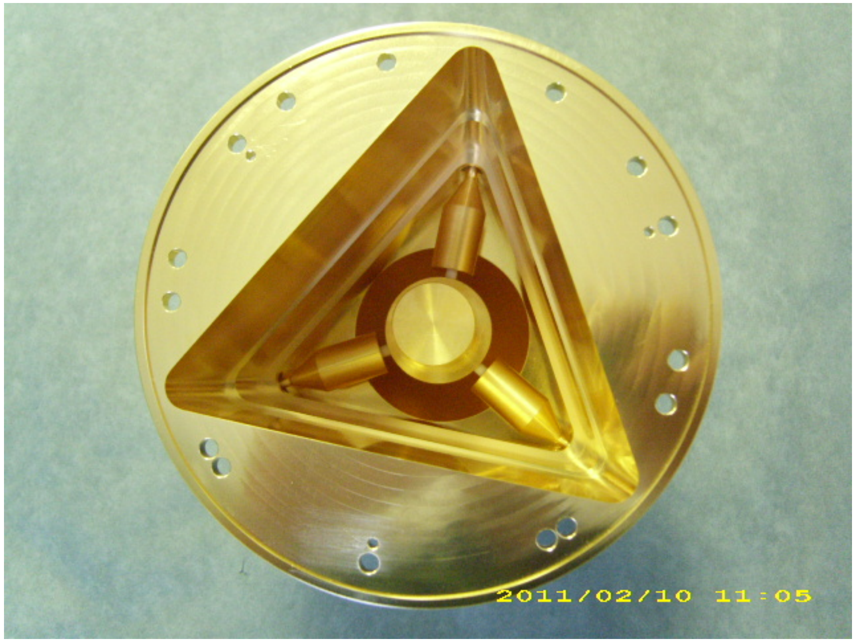
A. Navarrini, A. Bolatto and R. L. Plambeck, "Preliminary test results of the turnstile junction waveguide orthomode transducer for the 1 mm band," CARMA Memo #32, 15 Mar 2006.

Digital Polarization Synthesis



- "Factorization" is still done by analog means.
- But "Reconstruction" or synthesis can be done digitally
  - with greater accuracy, and
  - reduces loss in front of the cryogenic amplifiers.

Numerical Reconstruction Affords Additional Degrees of Freedom



- Center-probe couples in common-mode into all three channels, but *not* into a radiating mode on the sky.
- No added insertion loss (unlike calibration coupler).
- Signal drops out during digital polarization reconstruction.
  - Allows for strong omnipresent calibration signal that does not mask observations, and
  - pilot-tone stabilization of amplitude fluctuations.

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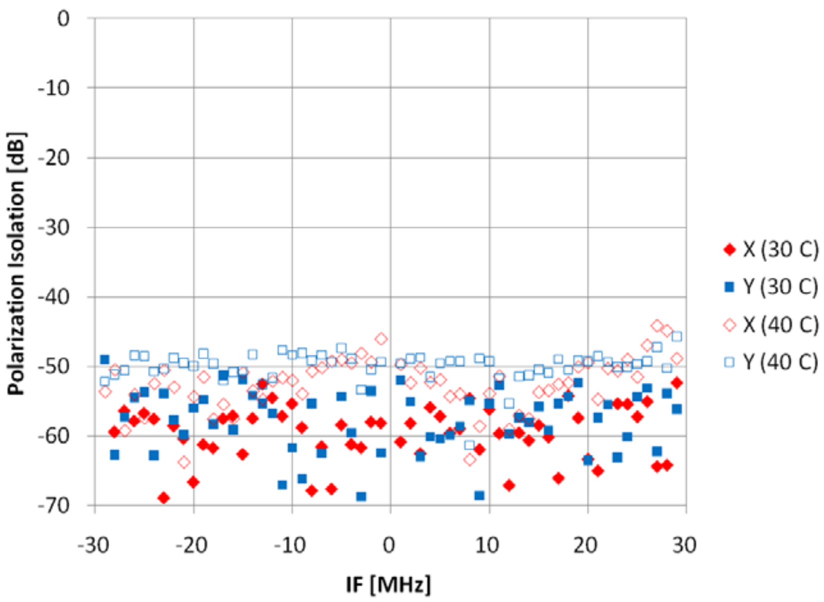
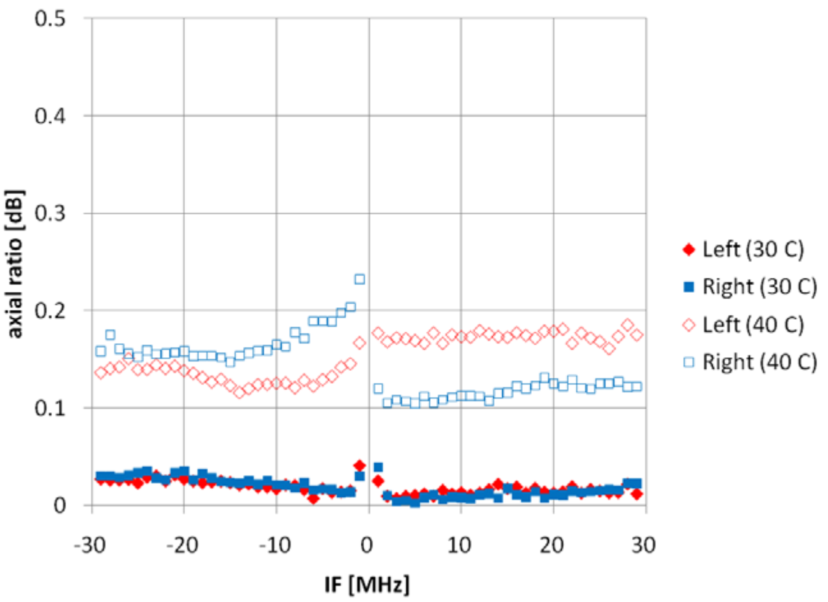
Polarization Performance and Stability

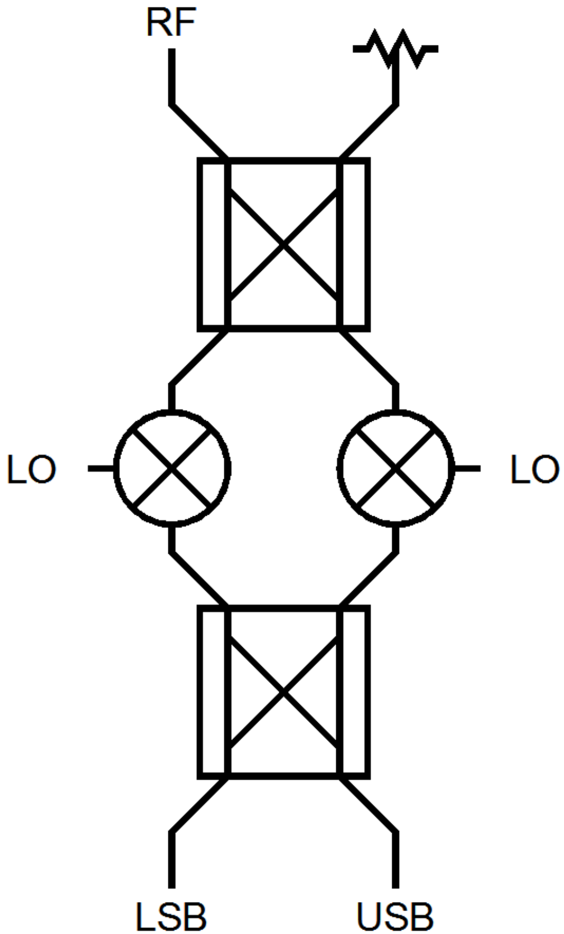
Isolation (Linear Pol.)

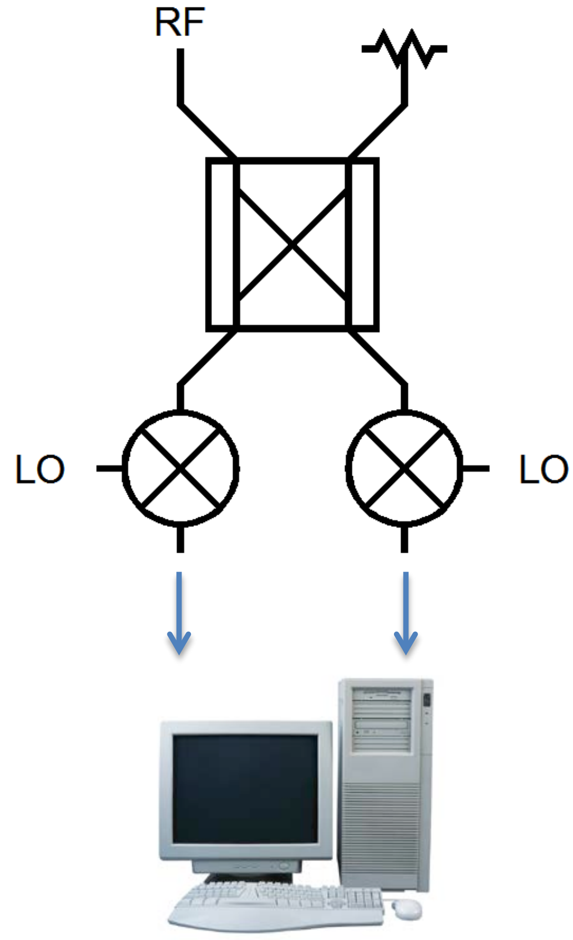


Axial Ratio (Circular)



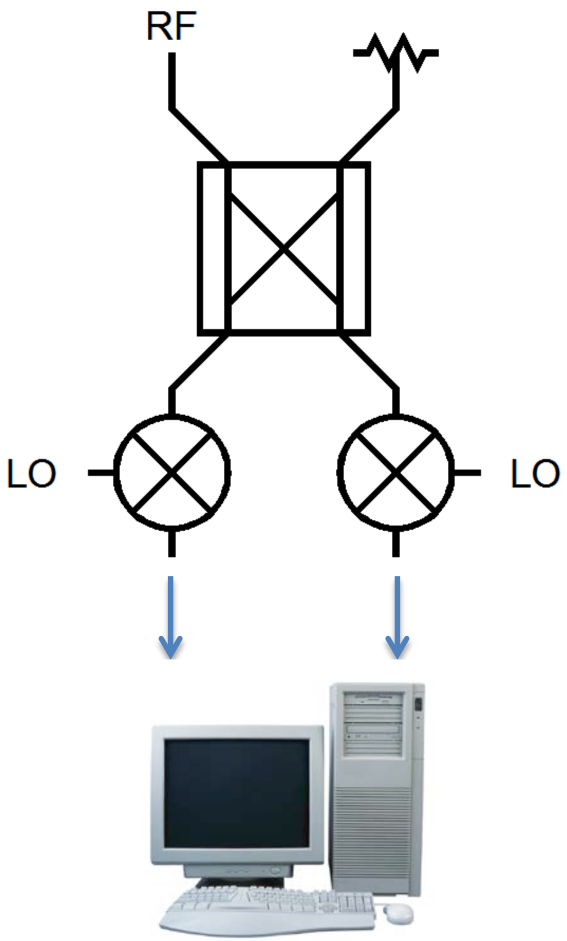
Digital Sideband-Separating Downconversion





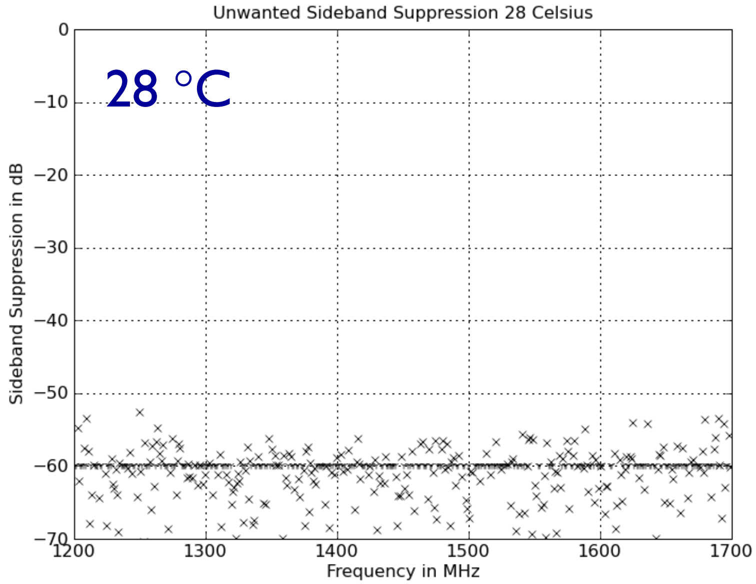
Benefits of Numerical Reconstruction

- Digital IF Hybrid is "better than ideal" in that it can compensate for analog RF-circuit imbalances.
- Allows precise, single-stage downconversion to baseband with only one system-wide LO.
  - Guards against spurious mixing products which integrated receivers are especially sensitive to.

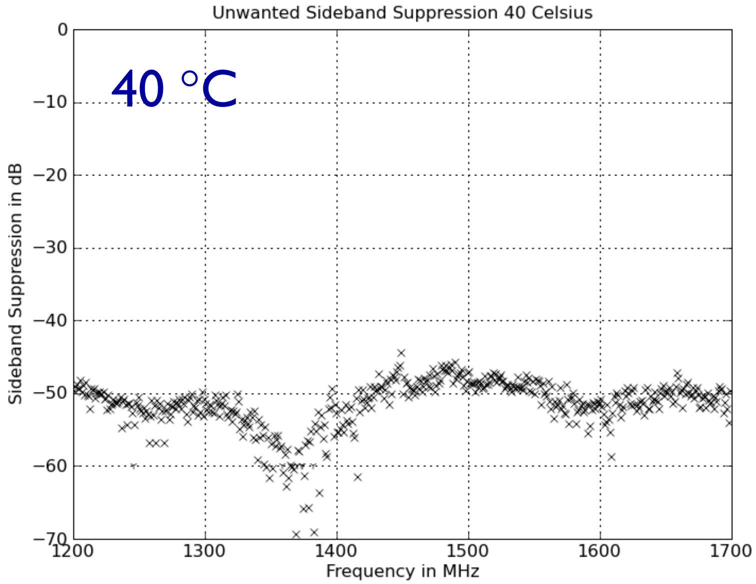


Sideband-Separation Performance and Stability

Initial Calibration



After Temp. Excursion



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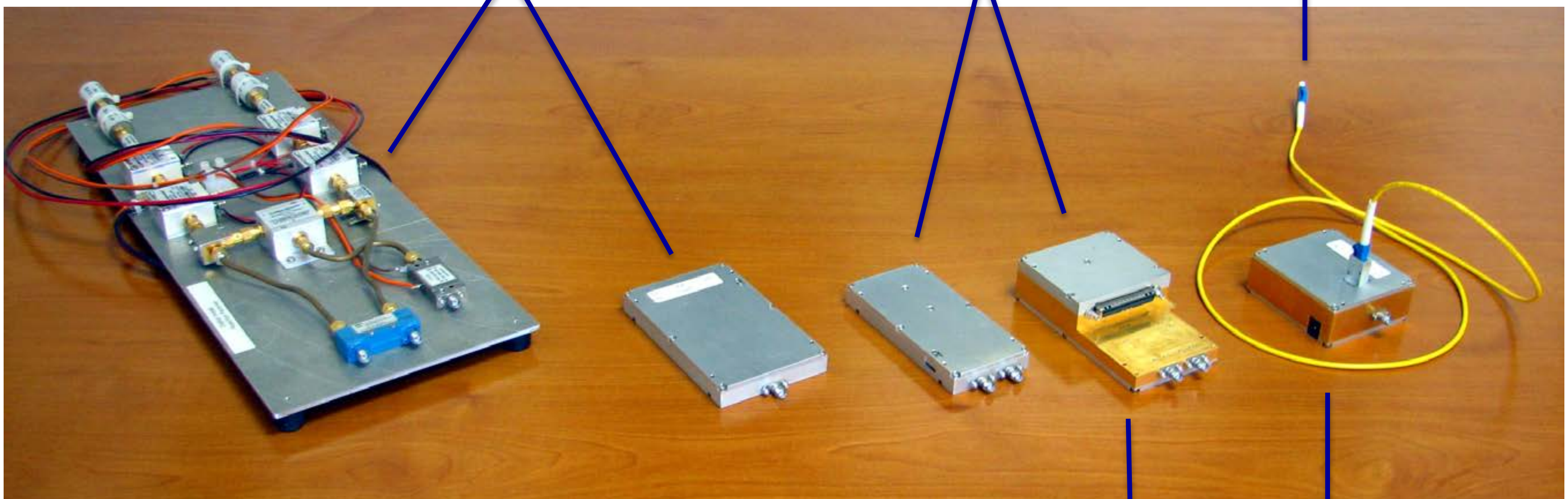
Careful Step-by-Step Development

2008 2009 2012



Analog only

Analog
& Digital

Analog,
Digital,
& Photonic

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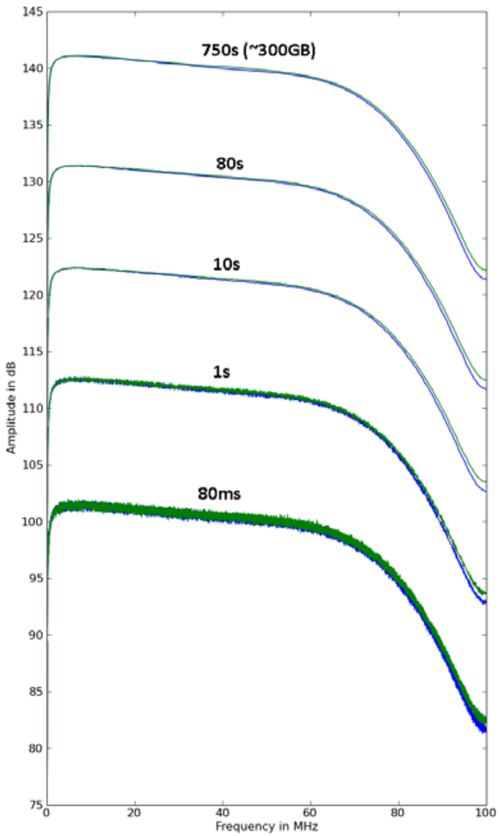
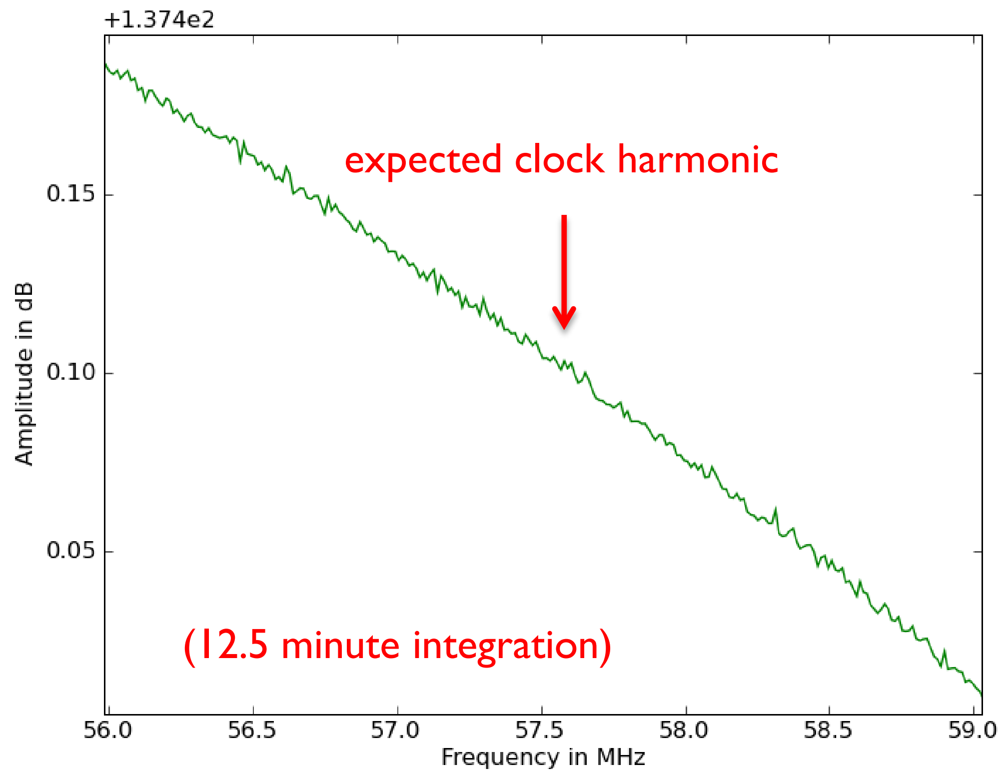
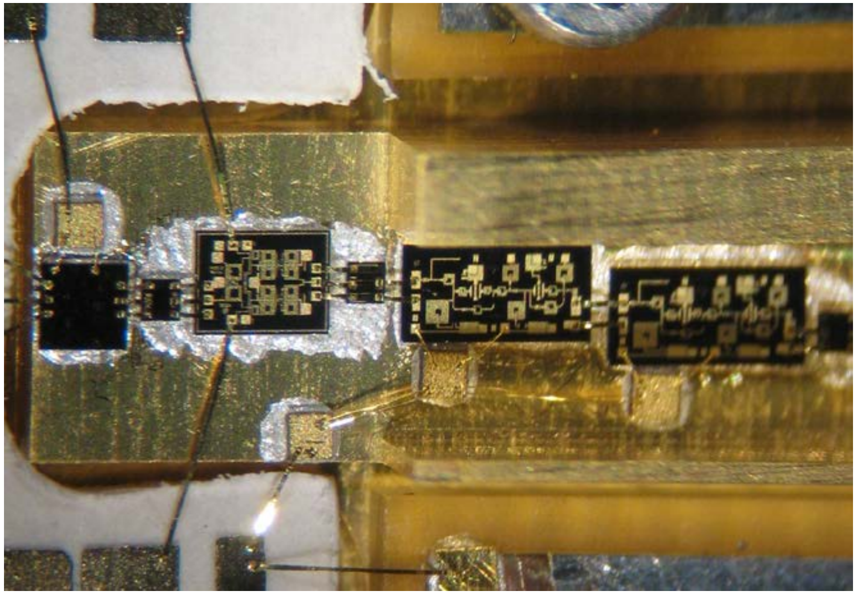
Internal ADCs Introduce No Measurable Interference



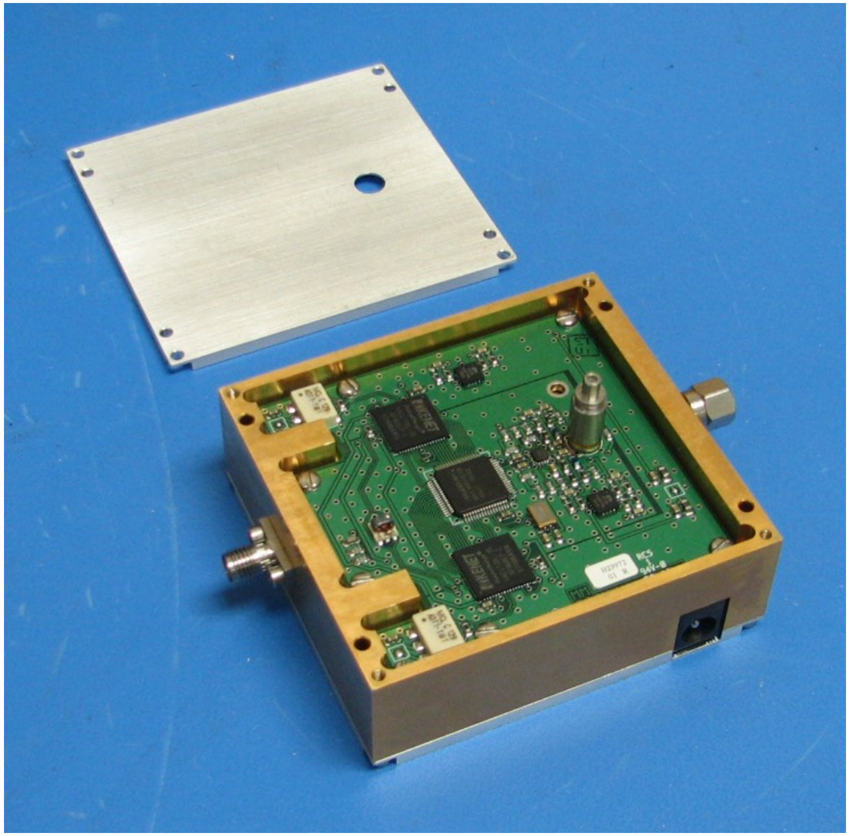


MMICs and Integration

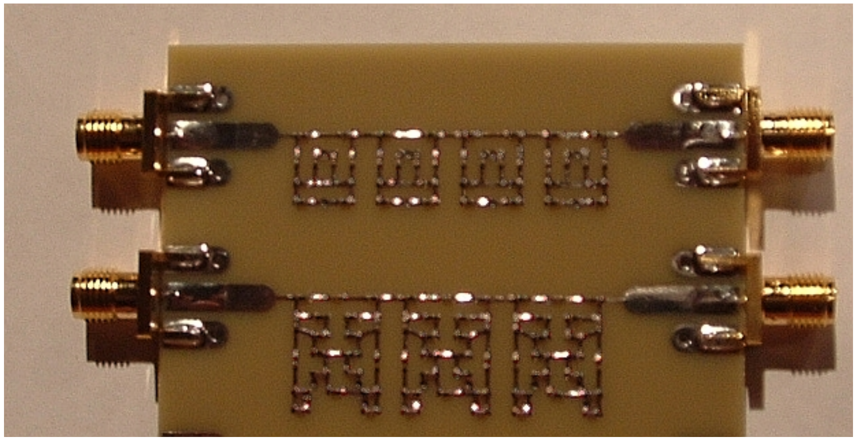
Analog

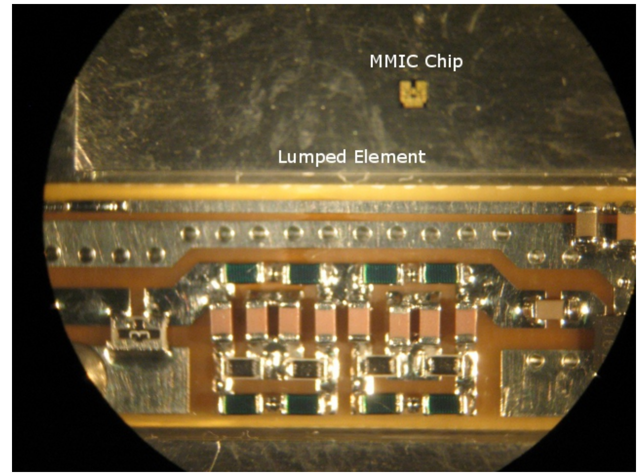


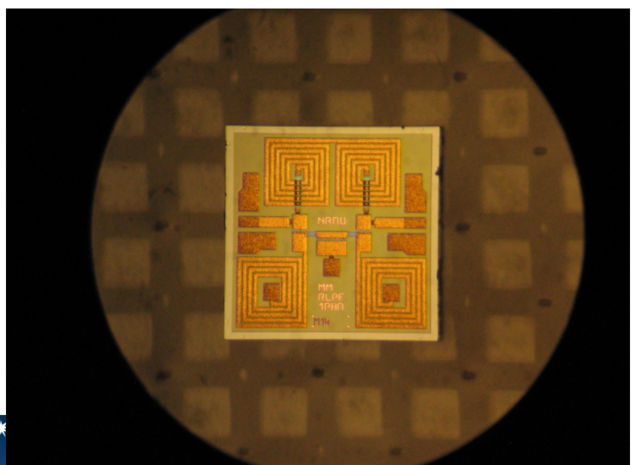
Digital & Photonic

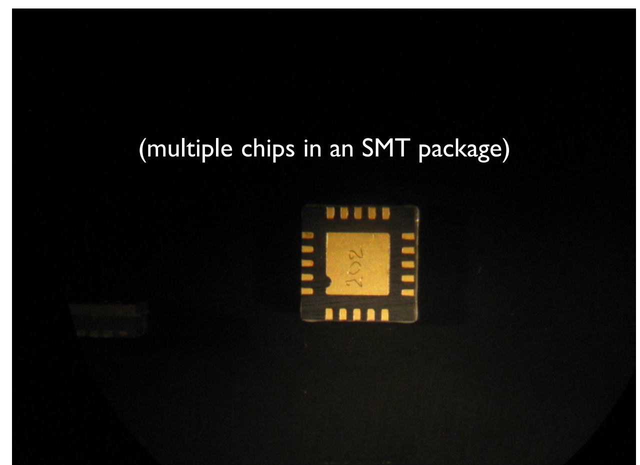


Miniaturization








(multiple chips in an SMT package)

Integration of Optical Transmitter

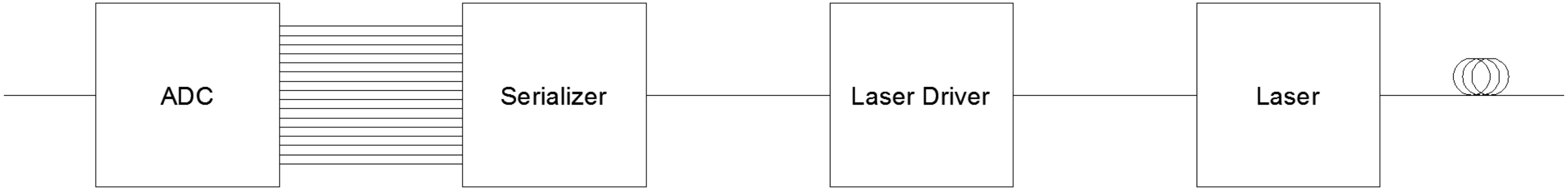
- Conventional digital fiber optic links come with a great deal of complex logic
  - bit scramblers
  - 8/10 encoding
  - packetizing/framing

- These functions add to the bulk and power dissipation of the front-end while increasing the risk of digital self-interference.

- But the known statistics of our signal may work to our advantage:
  - Well-characterized by Gaussian-distributed white-noise.

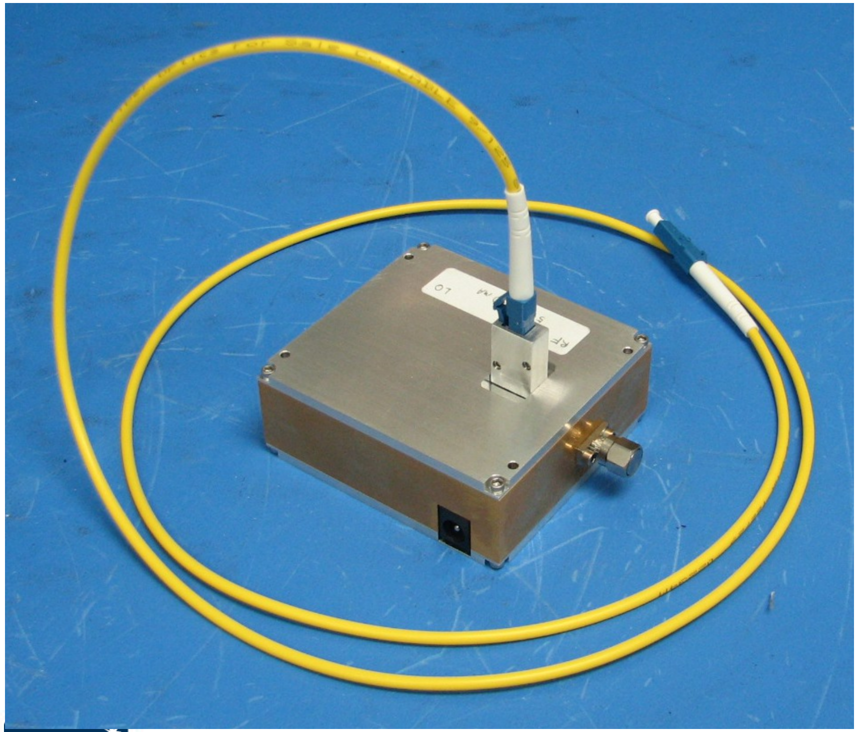
Unformatted Digital Fiber Link

- To realize a digital fiber-optic data link with minimal overhead, we use only
  - a sampler,
  - a serializer,
  - a laser driver,
  - and a laser.
- Known statistics of radio astronomy signals allow link management to be performed entirely at the receive end.
  - 1st Challenge: DC Balance
  - 2nd Challenge: Clock Recovery
  - 3rd Challenge: Word-Alignment
  - (also channel synchronization, power, interleaving...)

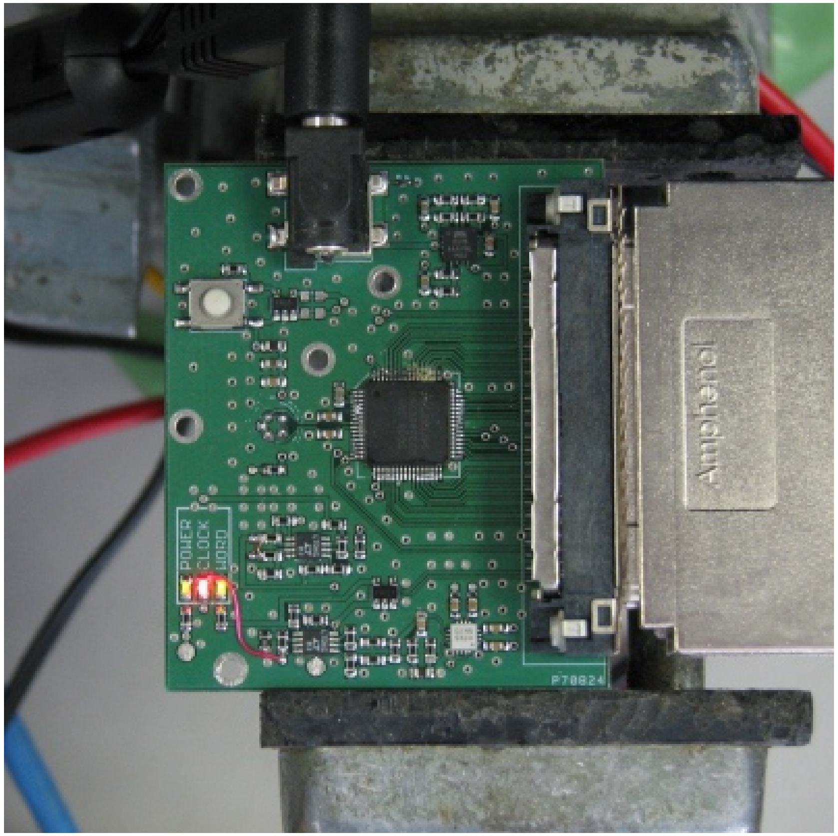


Implementation

Analog-Digital-Photonic Front-End



Photonic Data Receiver



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- J. Fisher and M. Morgan, "Analysis of a Single-Conversion, Analog/Digital Sideband Separating Mixer Prototype," Electronics Division Internal Report #320, June 2008.
- M. Morgan, "Compact Integrated Receivers Using MMIC Technology," China-US Bilateral Workshop on Radio Astronomy, Beijing, China, April 2008.

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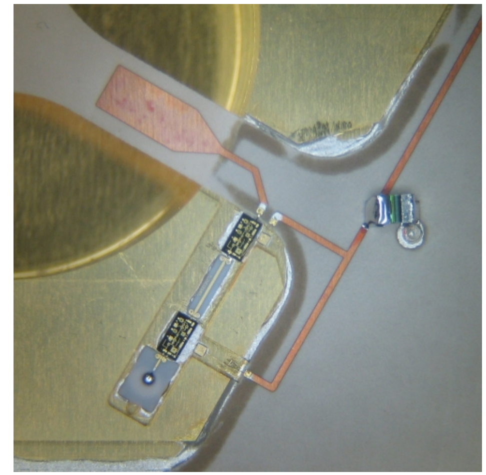
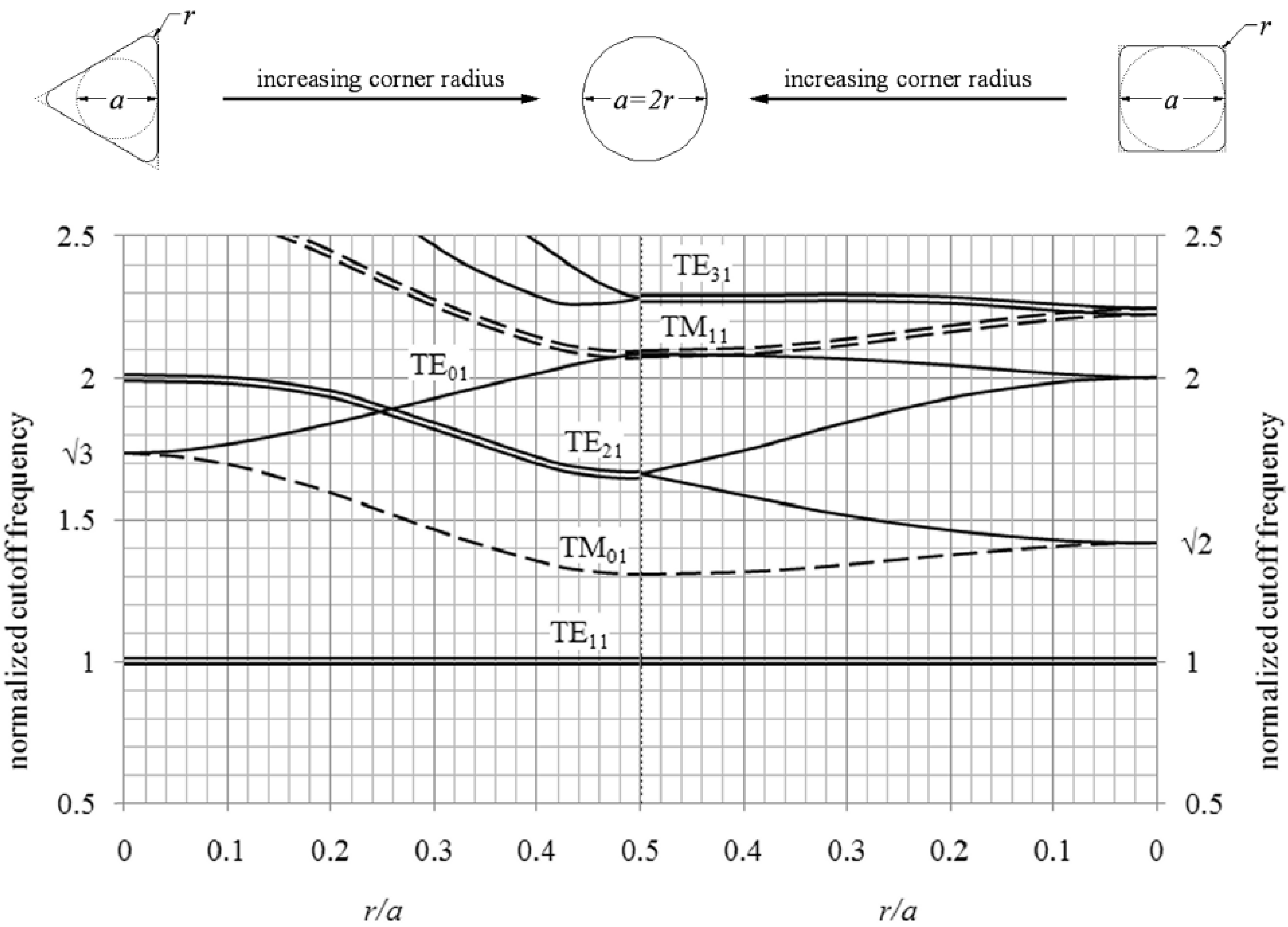
Want to know what's under the hood? (Backup slides follow...)

Vector Components Need Not Be Orthogonal/Independent

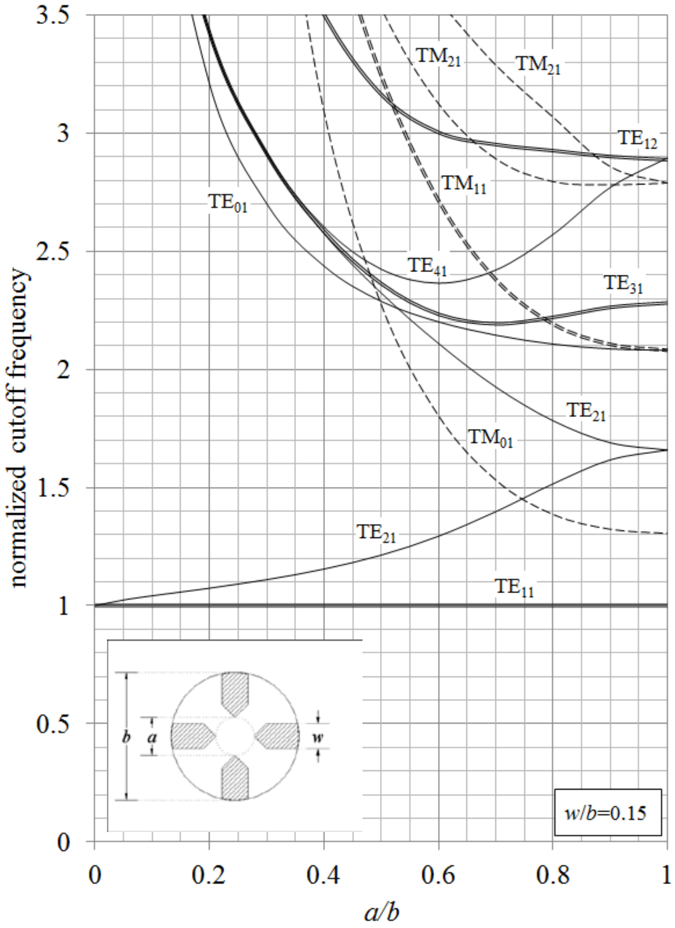


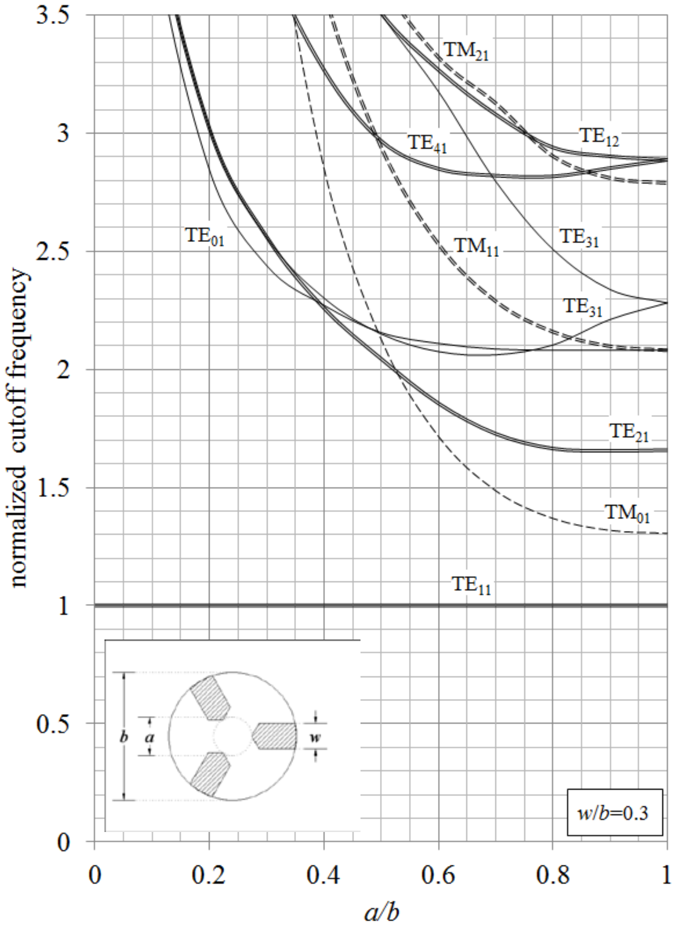
- Three-channel systems have advantages:
  - triangular/triple-ridged waveguides have broader mode-free bandwidth
  - extra degree of freedom permits common-mode calibration channel

Broad Mode-Free Bandwidth



Broad Mode-Free Bandwidth (cont'd)



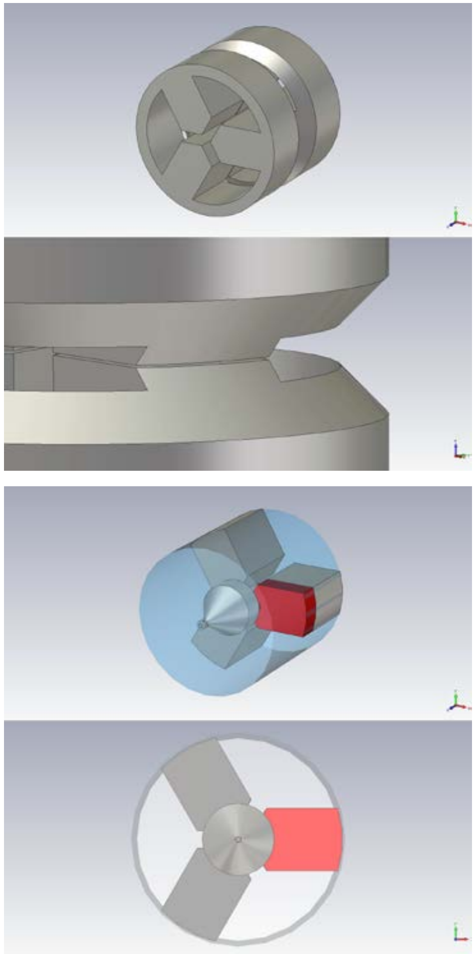


N-Wire Model For Ridged Waveguides

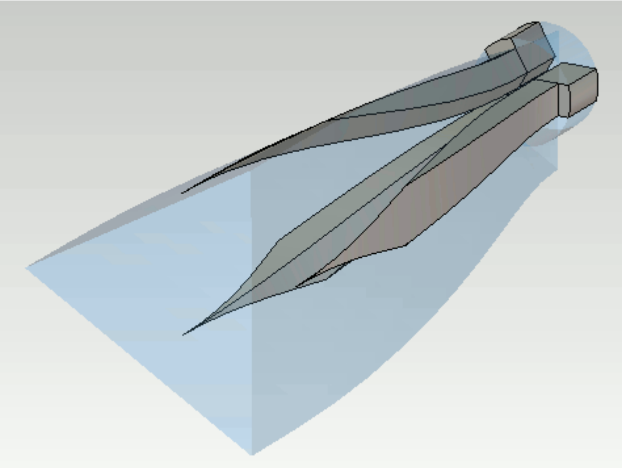
- In the limit, all the fields are concentrated in the gaps.
- *N*-ridges become *N*-wires.
- Outer walls become "infinitely" far away.

- Low-order modes become like TEM modes.
- Their number is simply the number of ways you can assign currents to the wires while maintaining DC balance.

Triple-Ridged for Ultra-Wideband AND Low Noise?



- "Unlimited" single-mode bandwidth makes it easier to realize compact, abrupt transitions (e.g. thermal and vacuum)
- These junctions, along with smaller mass enable cryogenic cooling of electromagnetic components where other approaches cannot.



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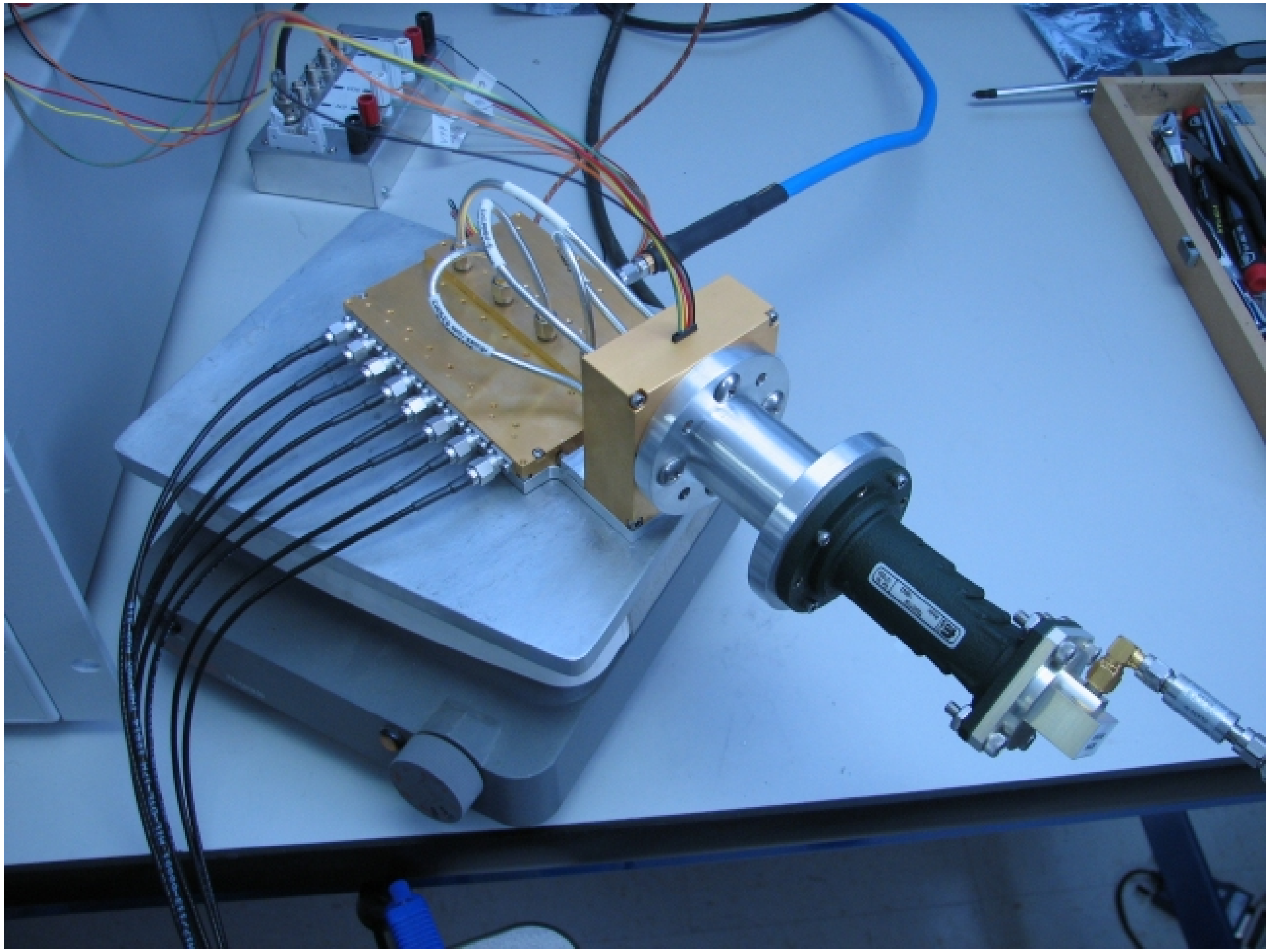
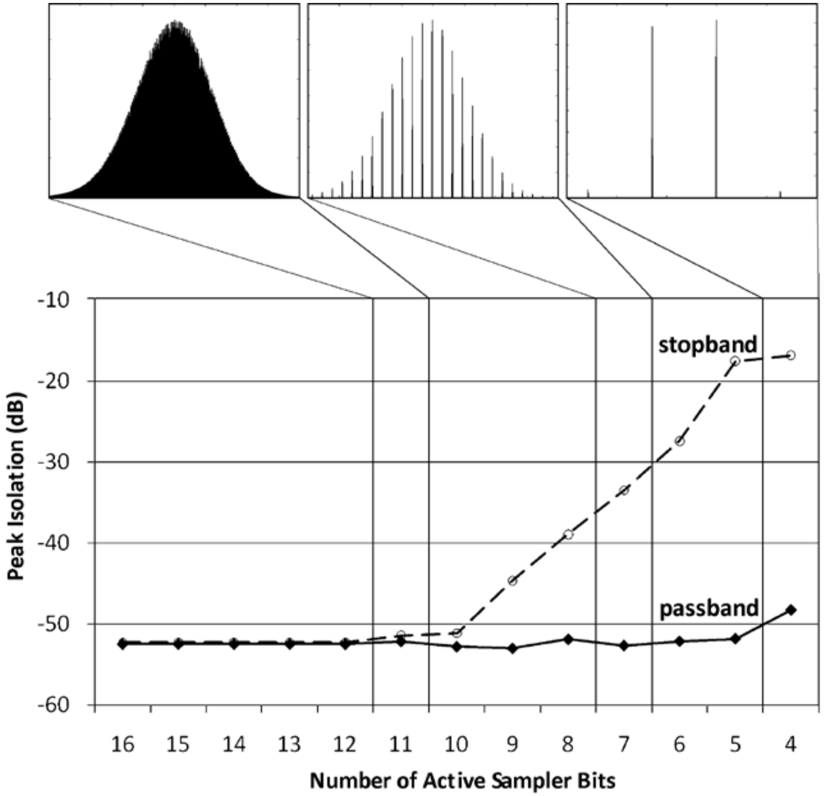
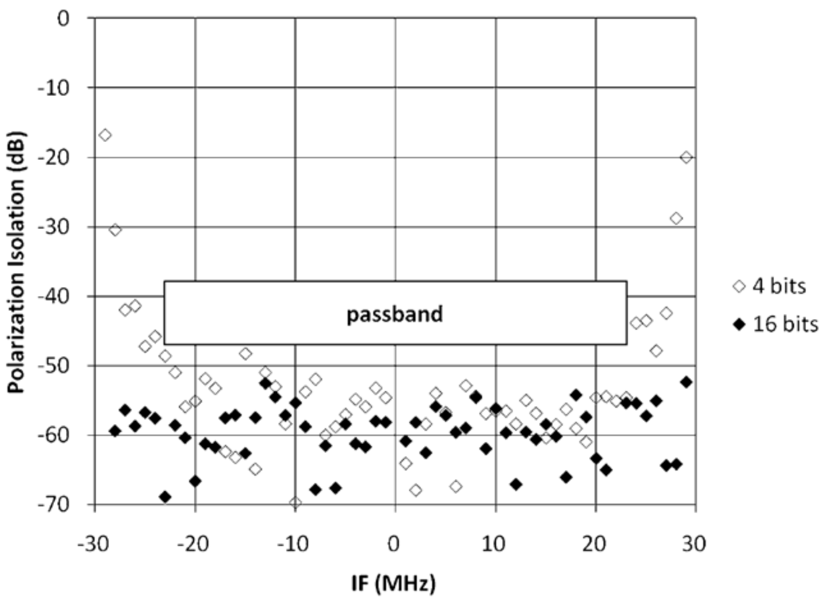
Laboratory Measurement Setup

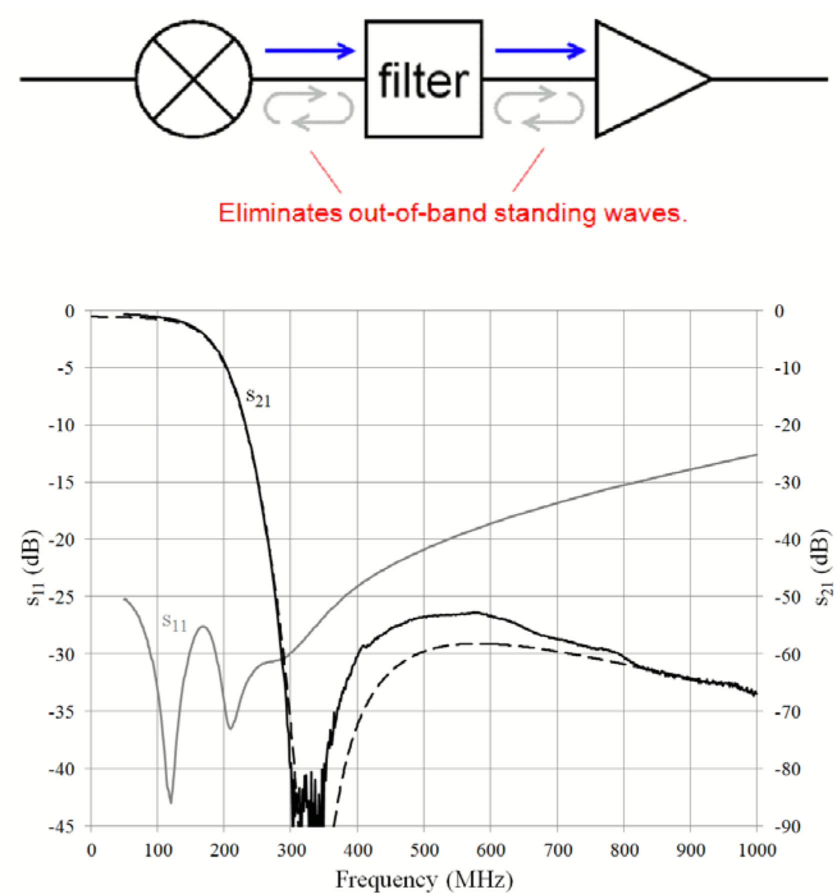


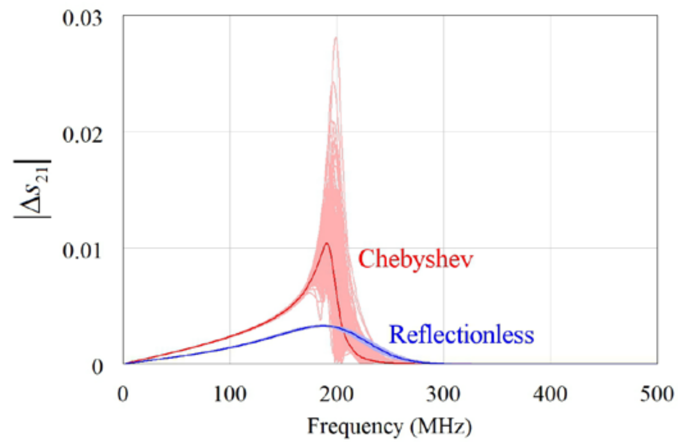
Not Dependent on Bit Resolution





Reflectionless Filters Enhance Stability



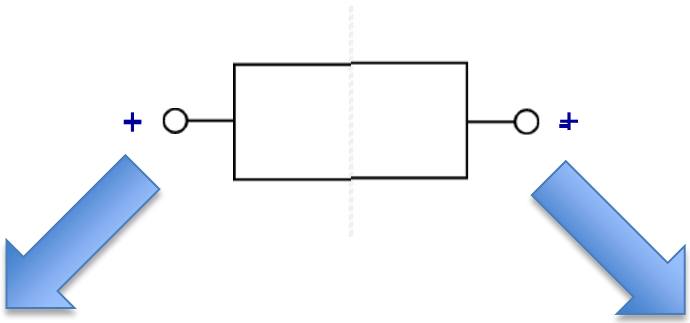


- New filter topology changes less with temperature (lower peak above) and more consistently with component values (less spread) than conventional designs.
  - fewer calibration points are required
  - calibration is far more stable

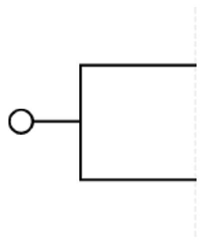
Design a Reflectionless Filter: Even-/Odd-Mode Analysis (backwards)

Odd-Mode excitation:

symmetric
two-port network

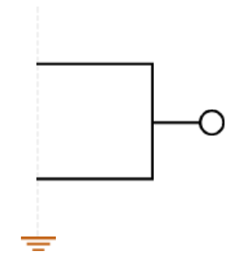


Even-Mode
equivalent circuit



(open)

Odd-Mode
equivalent circuit



(short)

Allows you to solve two 1-port networks instead of one 2-port network.

Reverse application: Instead of solving for the performance of a given circuit, let us first *prescribe* the desired performance and then derive a circuit that achieves it...

Even-/Odd-Mode Equations for a Reflectionless Filter

$$s_{11} = \tfrac{1}{2}\left(\Gamma_{even} + \Gamma_{odd}\right) = 0$$

$$\Gamma_{even} = -\Gamma_{odd}$$

$$\frac{z_{even} - 1}{z_{even} + 1} = \frac{y_{odd} - 1}{y_{odd} + 1}$$

$$\therefore z_{even} = y_{odd}$$

$$s_{21} = \tfrac{1}{2}\left(\Gamma_{even} - \Gamma_{odd}\right) = \Gamma_{even}$$

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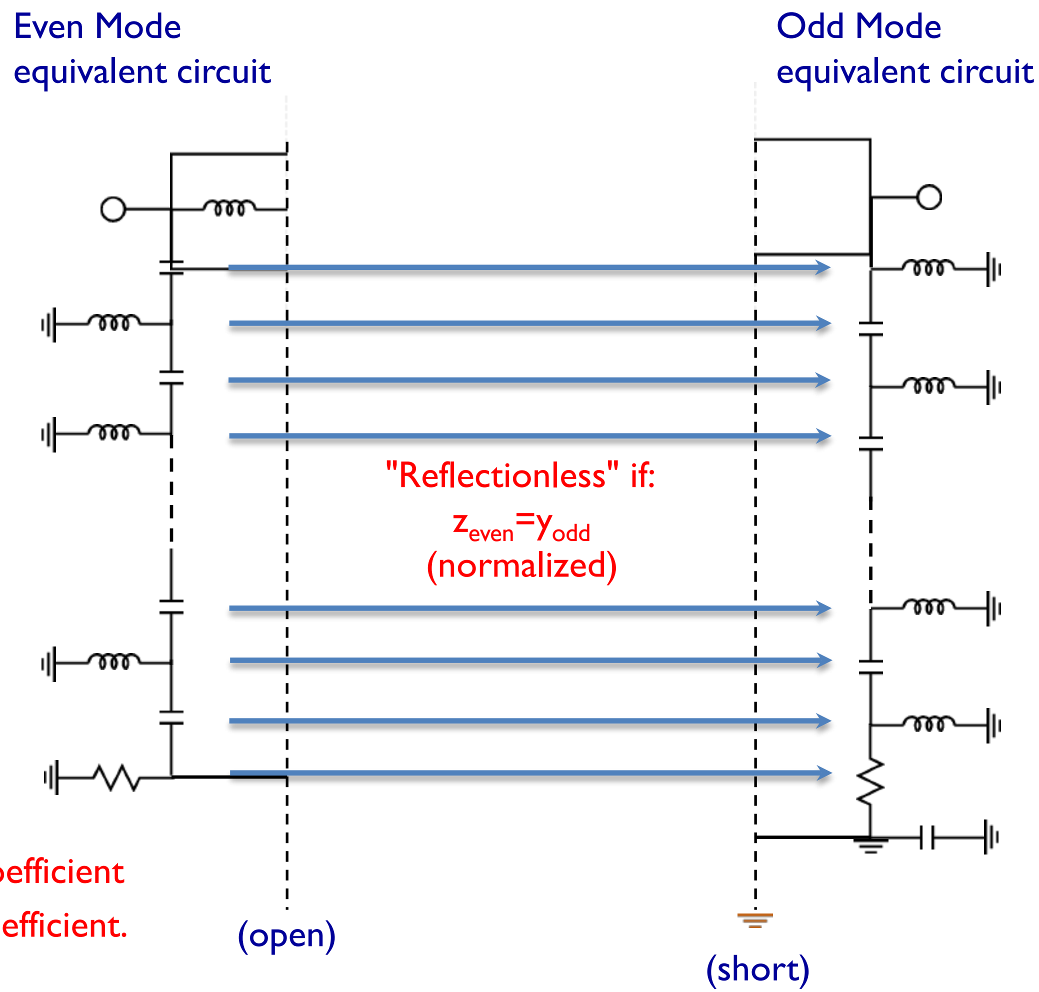
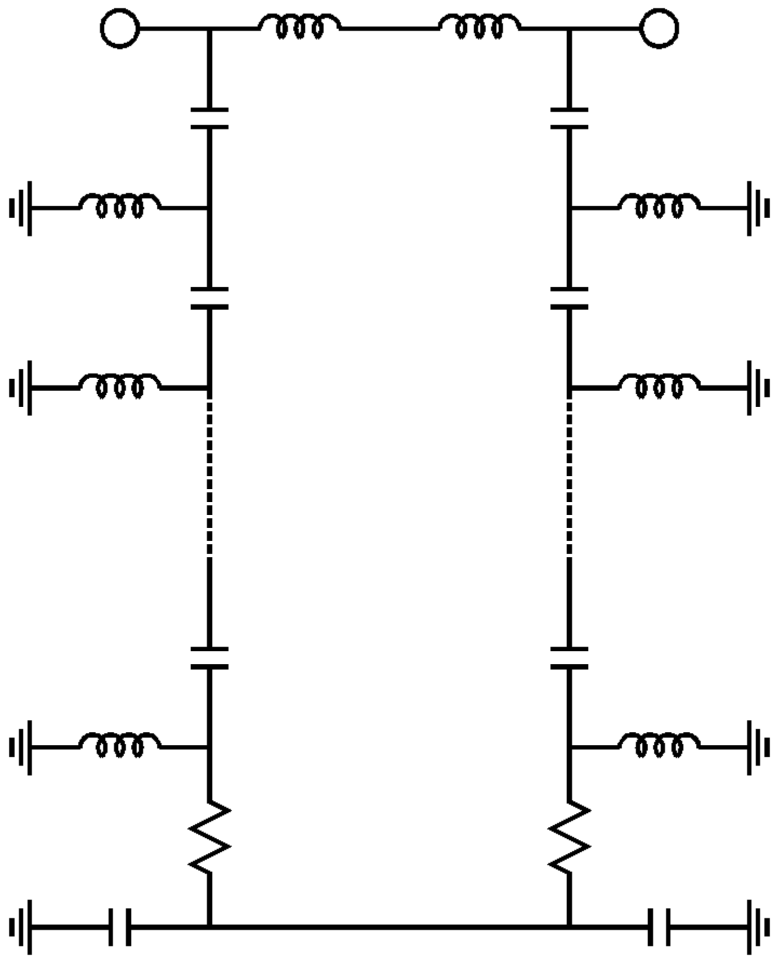
Design a Reflectionless Filter

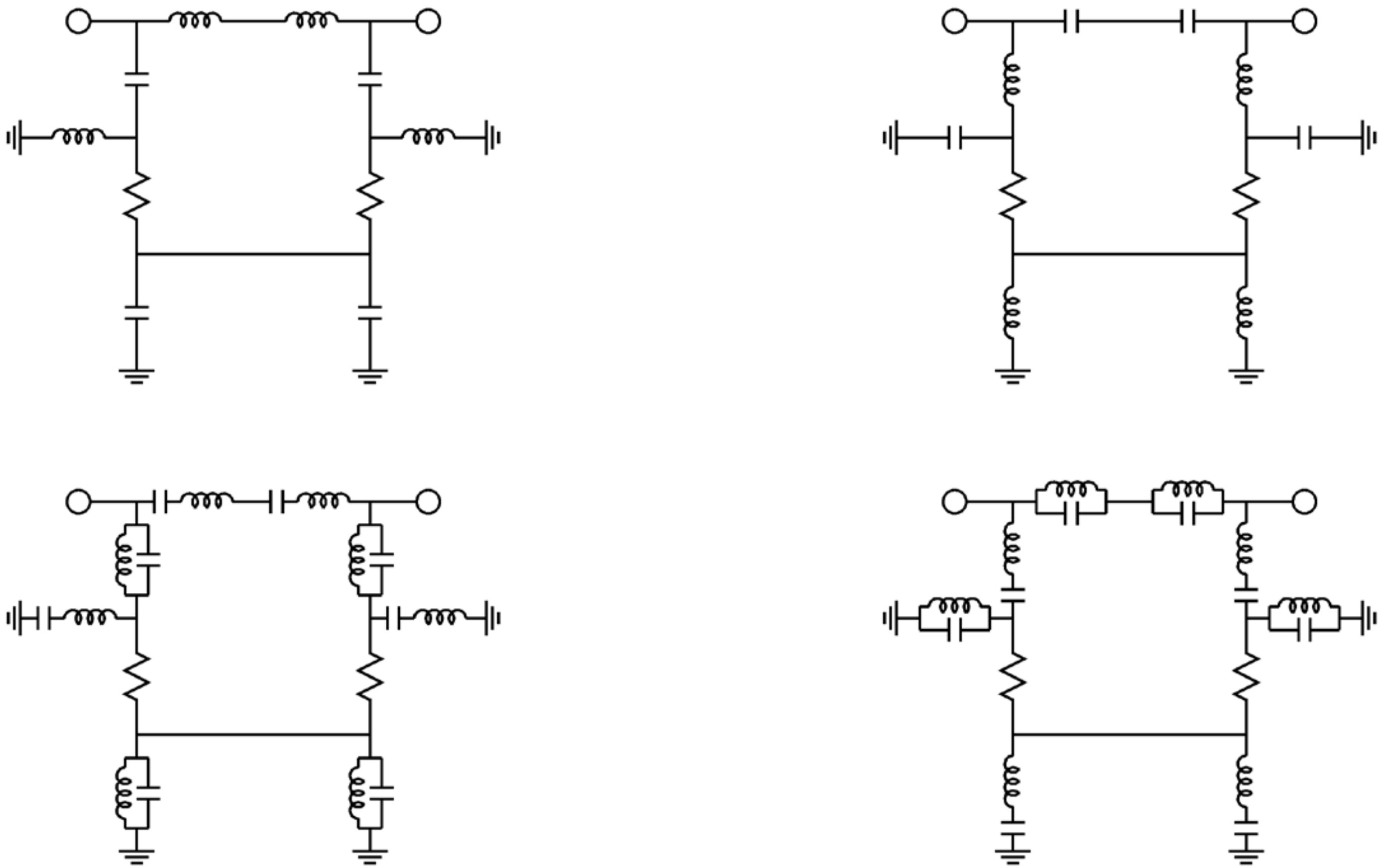


Full-circuit transmission coefficient
= even-mode reflection coefficient.

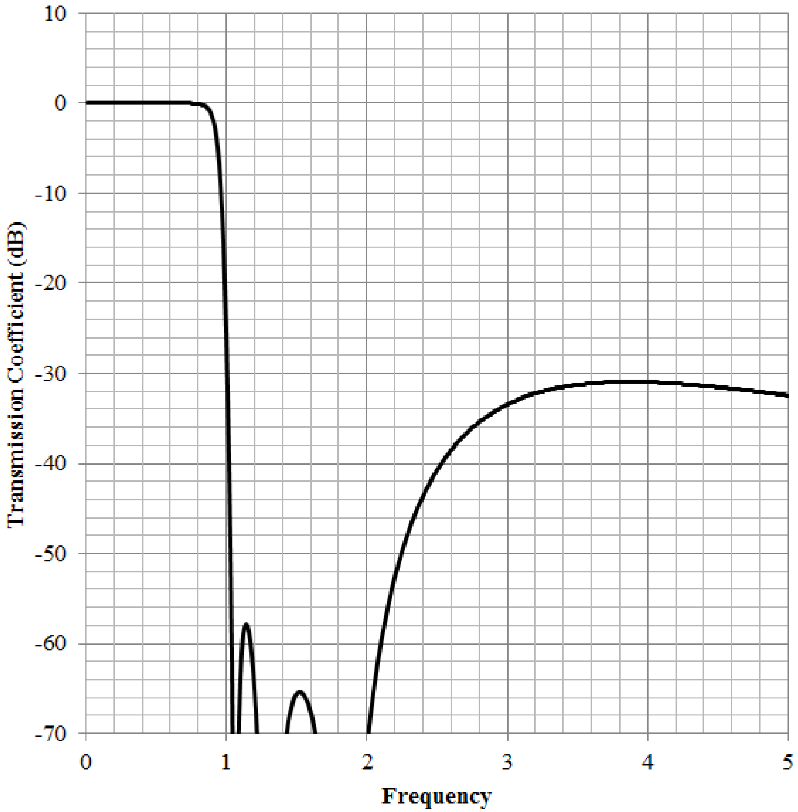
You Now Have a Symmetric Low-Pass Reflectionless Filter!

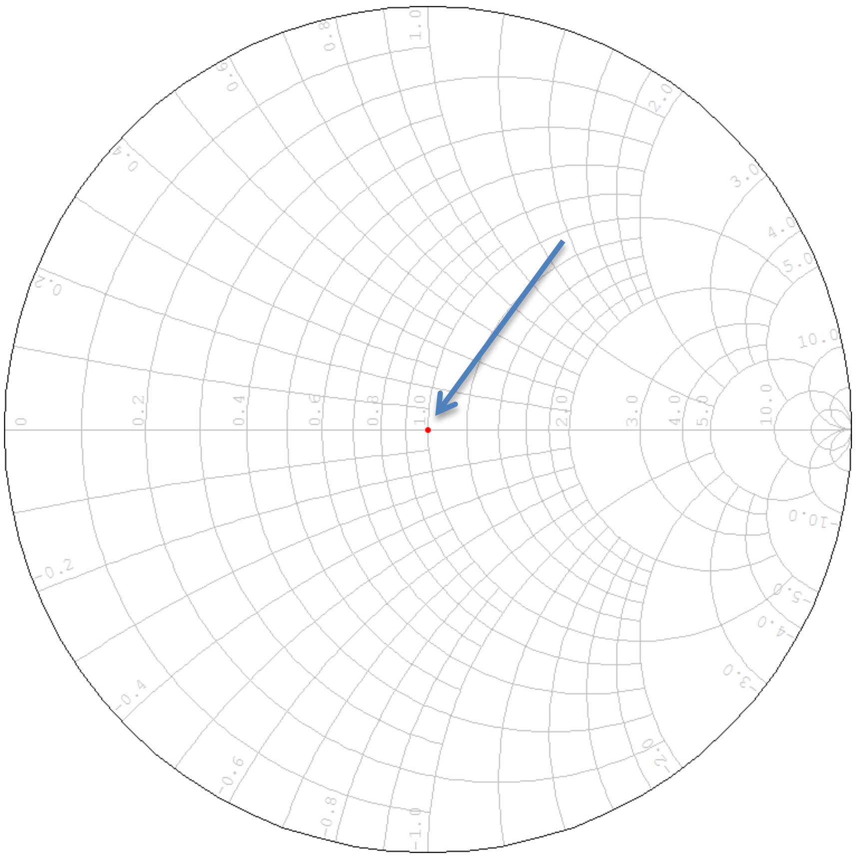


Low-Pass, High-Pass, Band-Pass, and Band-Stop



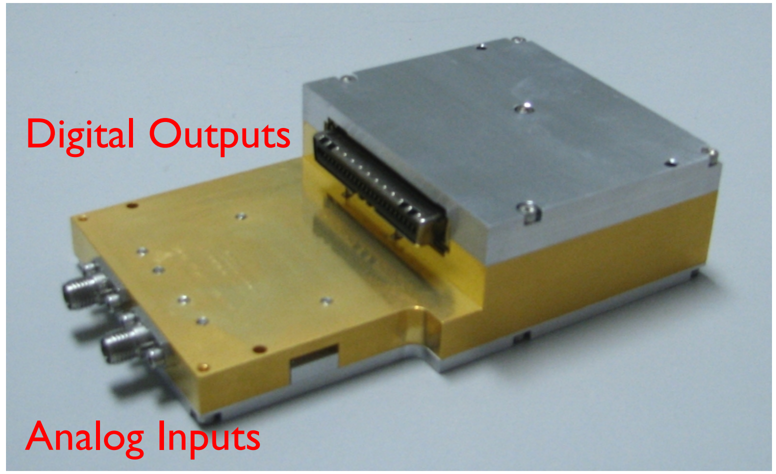
High-Order Designs are Possible as Well…



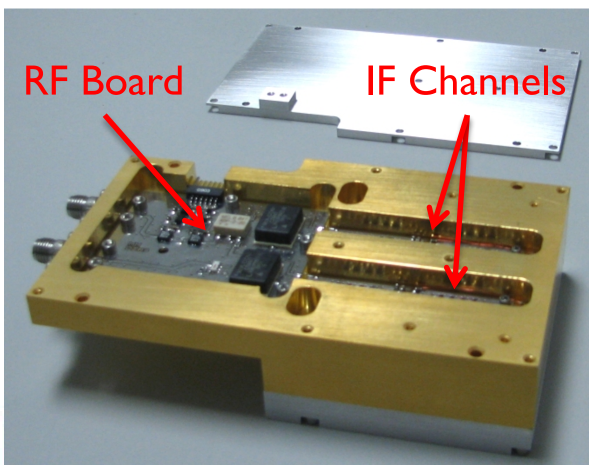


Integration of Samplers

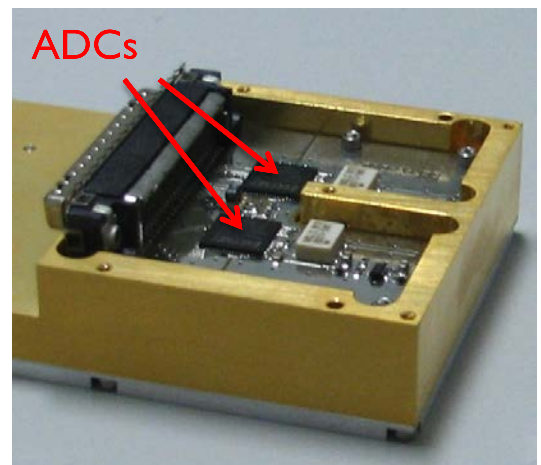
L-Band Module



Analog Side

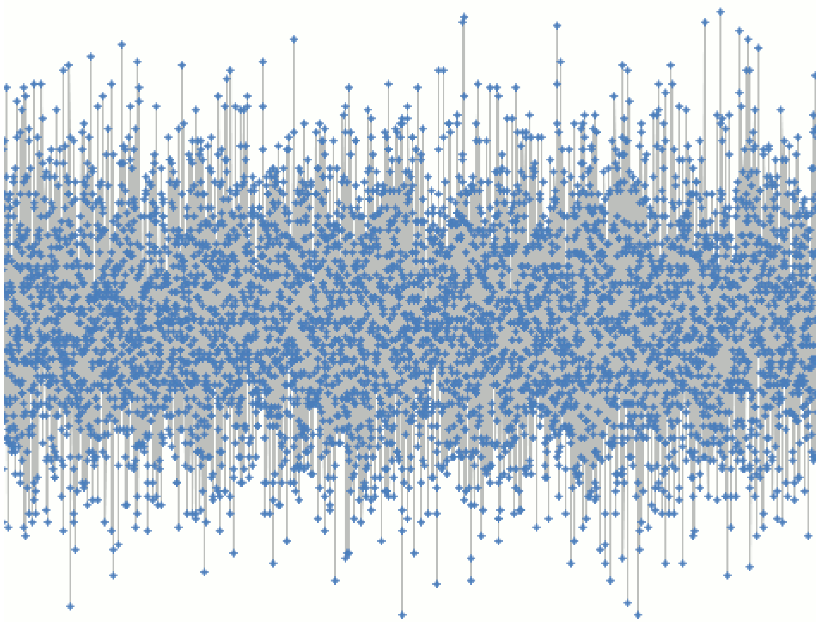


Digital Side

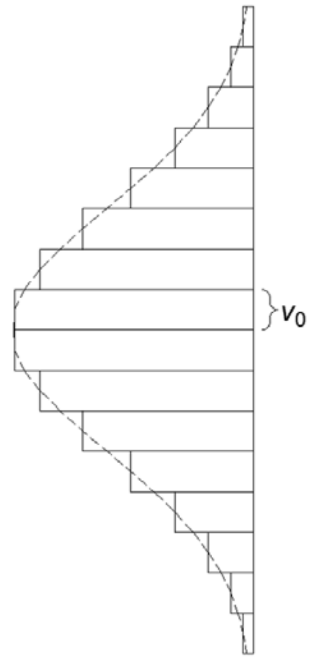


1st Challenge: DC Balance

Instantaneous Voltage vs. Time



Proability Density Function



Straight/Offset Binary

1	1	1	1
1	1	1	0
1	1	0	1
1	1	0	0
1	0	1	1
1	0	1	0
1	0	0	1
1	0	0	0
0	1	1	1
0	1	1	0
0	1	0	1
0	1	0	0
0	0	1	1
0	0	1	0
0	0	0	1
0	0	0	0
b_3	b_2	b_1	b_0

Two's Complement

0	1	1	1
0	1	1	0
0	1	0	1
0	1	0	0
0	0	1	1
0	0	1	0
0	0	0	1
0	0	0	0
1	1	1	1
1	1	1	0
1	1	0	1
1	1	0	0
1	0	1	1
1	0	1	0
1	0	0	1
1	0	0	0
b_3	b_2	b_1	b_0

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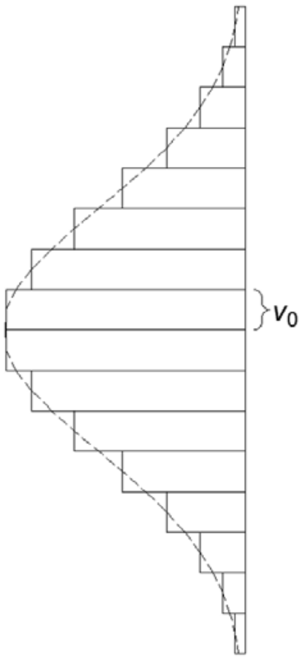
1st Challenge: DC Balance

- Actually, this is not a problem.
  - Individual samples are random with zero mean value.
- Common binary codes are symmetric about center.
  - Positive sample codes are mirror images of negative sample codes.
  - Thus, any given bit for any given sample has an equal chance of being a 1 or a 0.
- Only requires ADCs to have reasonably low offset voltage.
  - Small offsets lead to correspondingly small level shifts in the eye diagram.
  - Unlikely to break the serial link.



Straight/Offset Binary				Two's Complement			
b_3	b_2	b_1	b_0	b_3	b_2	b_1	b_0
1	1	1	1	0	1	1	1
1	1	1	0	0	1	1	0
1	1	0	1	0	1	0	1
1	1	0	0	0	1	0	0
1	0	1	1	0	0	1	1
1	0	1	0	0	0	1	0
1	0	0	1	0	0	0	1
1	0	0	0	0	0	0	0
0	1	1	1	1	1	1	1
0	1	1	0	1	1	1	0
0	1	0	1	1	1	0	1
0	1	0	0	1	1	0	0
0	0	1	1	1	0	1	1
0	0	1	0	1	0	1	0
0	0	0	1	1	0	0	1
0	0	0	0	1	0	0	0

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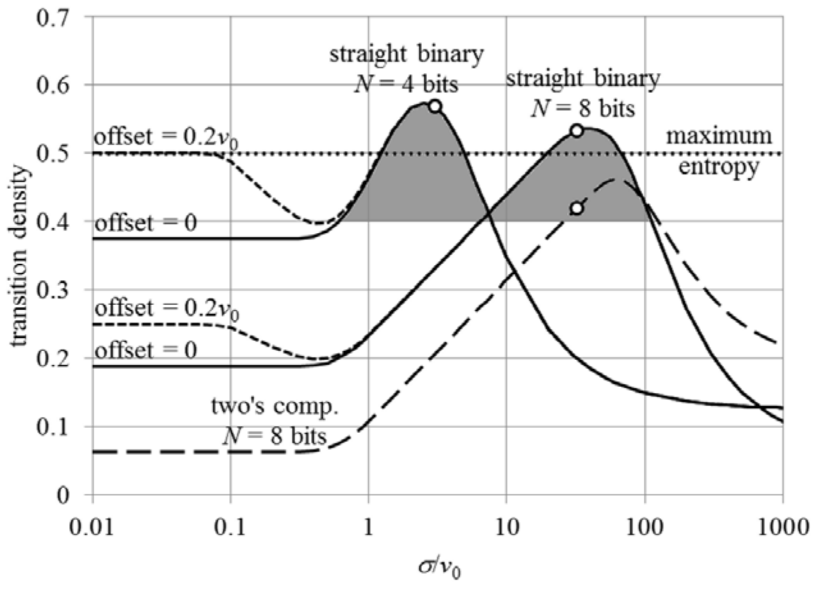
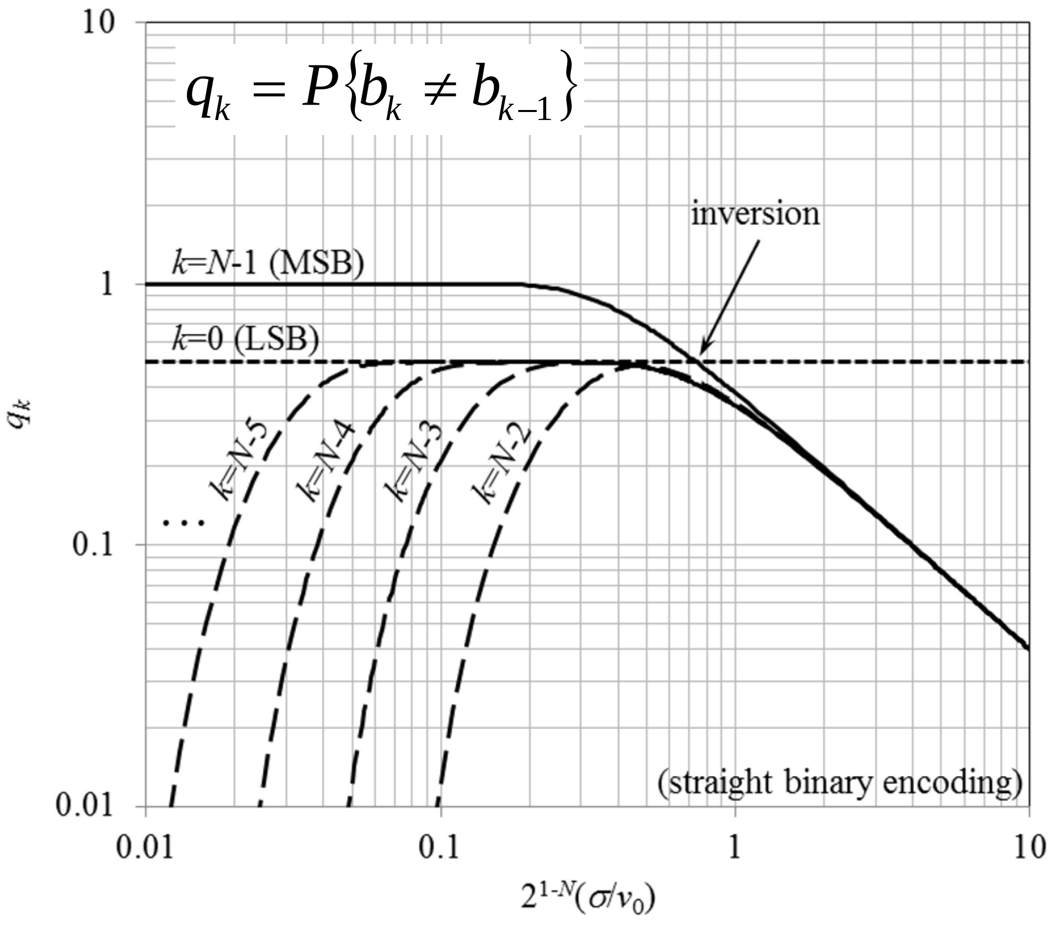
2nd Challenge: Clock Recovery

- Commercial deserializers can recover the clock from data streams that satisfy certain minimum transition density requirements.

- MAX3880 from Maxim:
  - "Tolerates >2000 Consecutive Identical Digits"
- VSC1236 from Vitesse:
  - signals Loss of Data when "transition density is less than 40%."

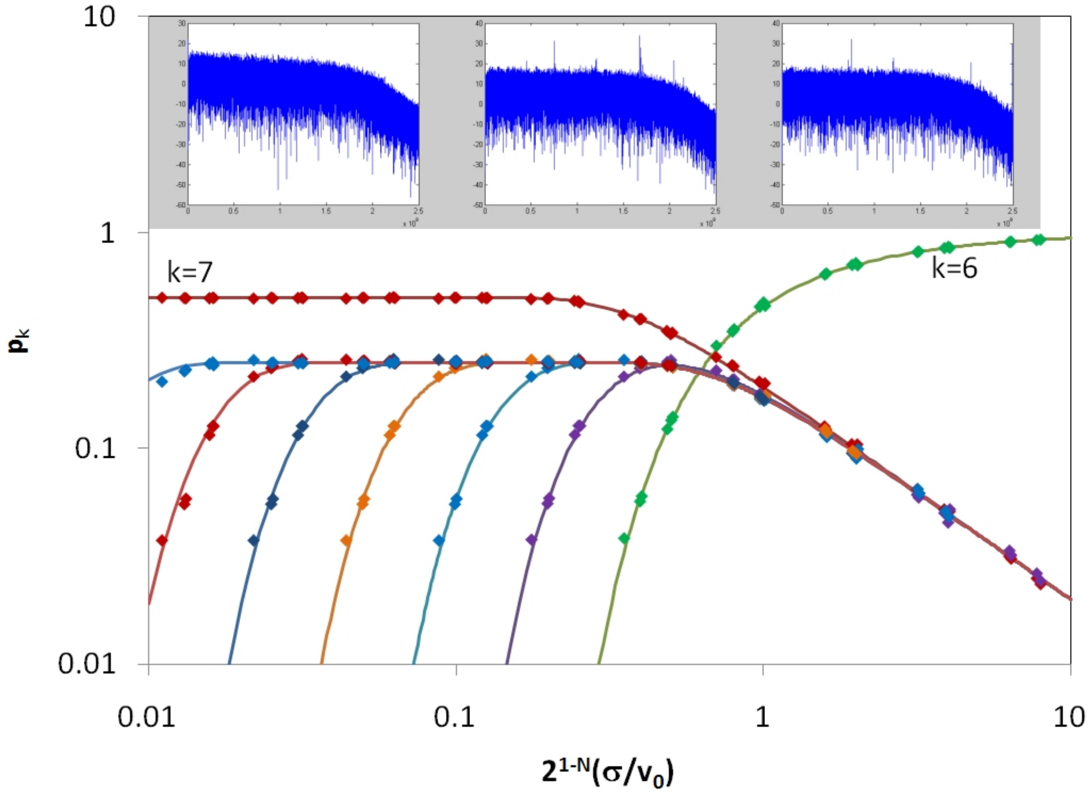


3rd Challenge: Word Alignment

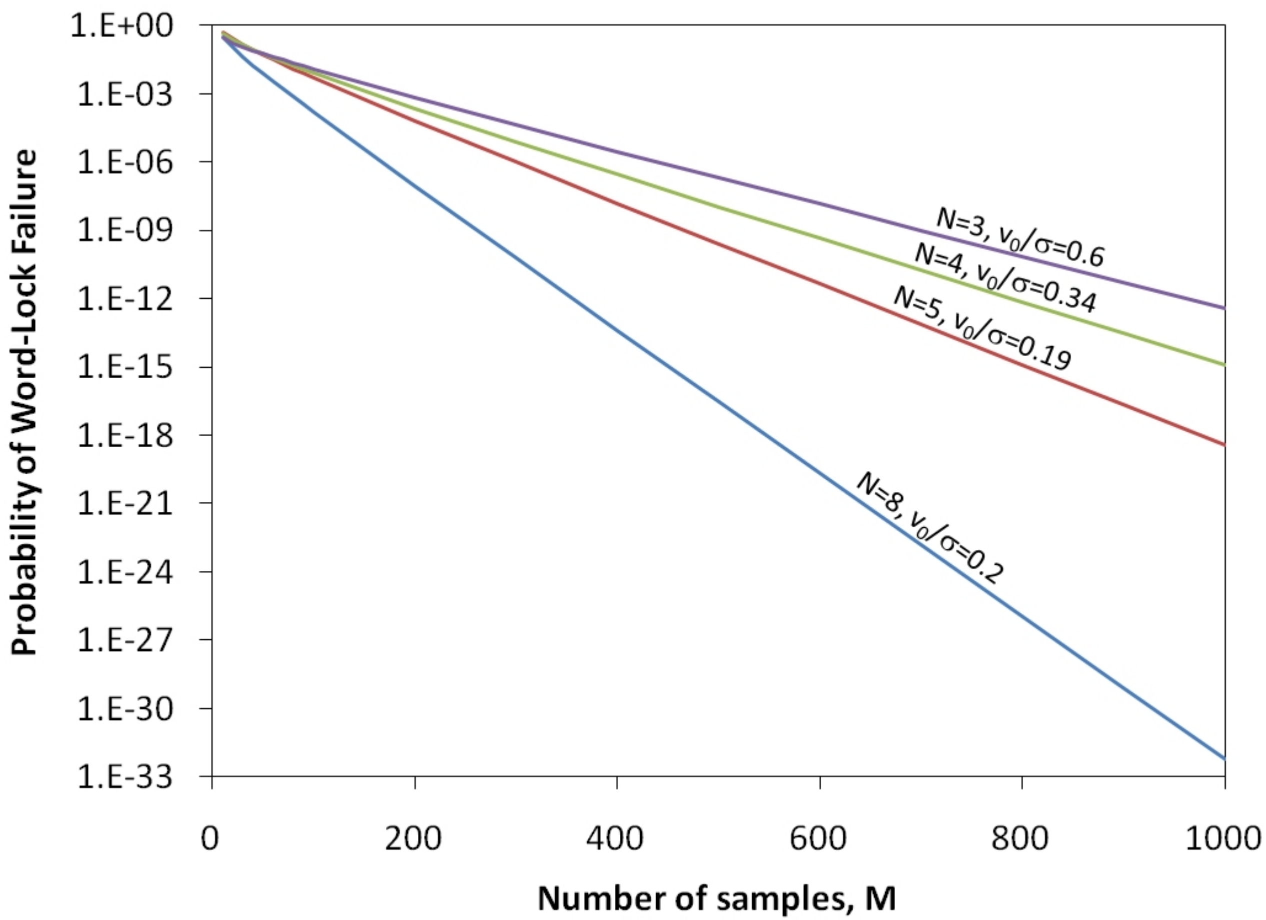


- The MSB has a predictable correlation with its neighboring bits in the most likely sample codes near the middle of the sampler range.
- This allows for the direct statistical determination of word boundaries in a serial data stream without any prior formatting.

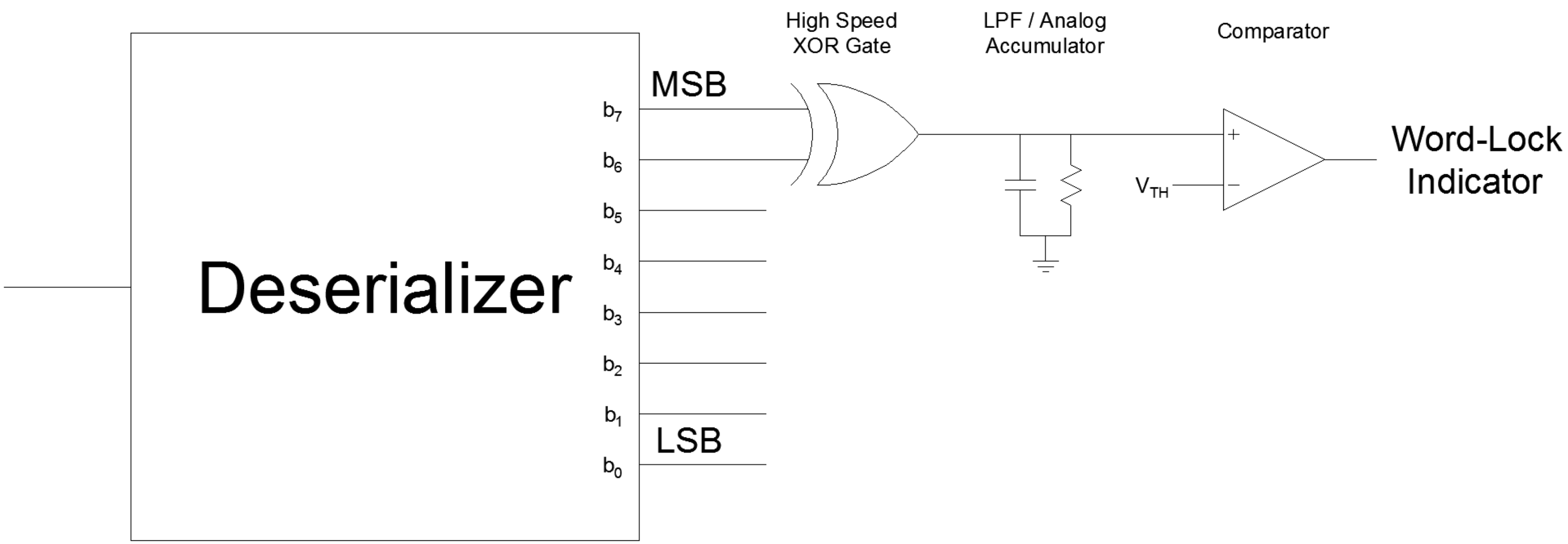
Statistics Largely Immune to Passband Shape and External Interference



Strong Statistics Provide Very Reliable Operation



For Straight Binary, a Simple XOR Gate is Sufficient



4th Challenge: Synchronization

- Without framing, differential delays on parallel fibers may cause simultaneous data streams to arrive at the backend spectrometer or correlator out of sync.
  - In this regard, it is no different from an analog fiber optic link...
- But unlike analog links, the $\Delta\tau$ must be an integer multiple of the sample period, introducing a discrete-valued phase-slope into the correlation between channels.
- In-situ calibration signals provide an easy means for monitoring these slopes/delays.
- As long as they are stable (or tracked) within a sample period, the recovered synchronicity between parallel channels will be exact.

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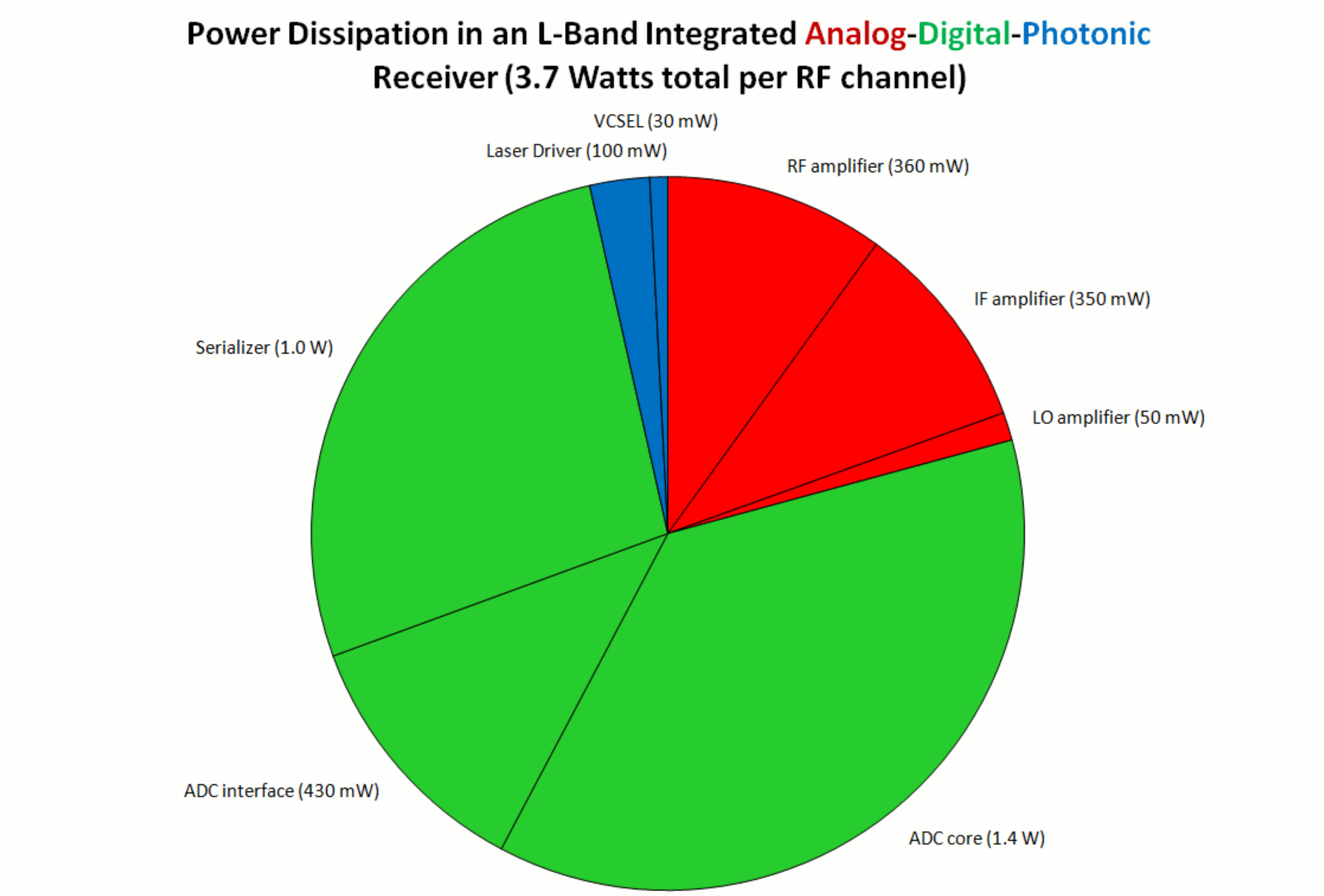
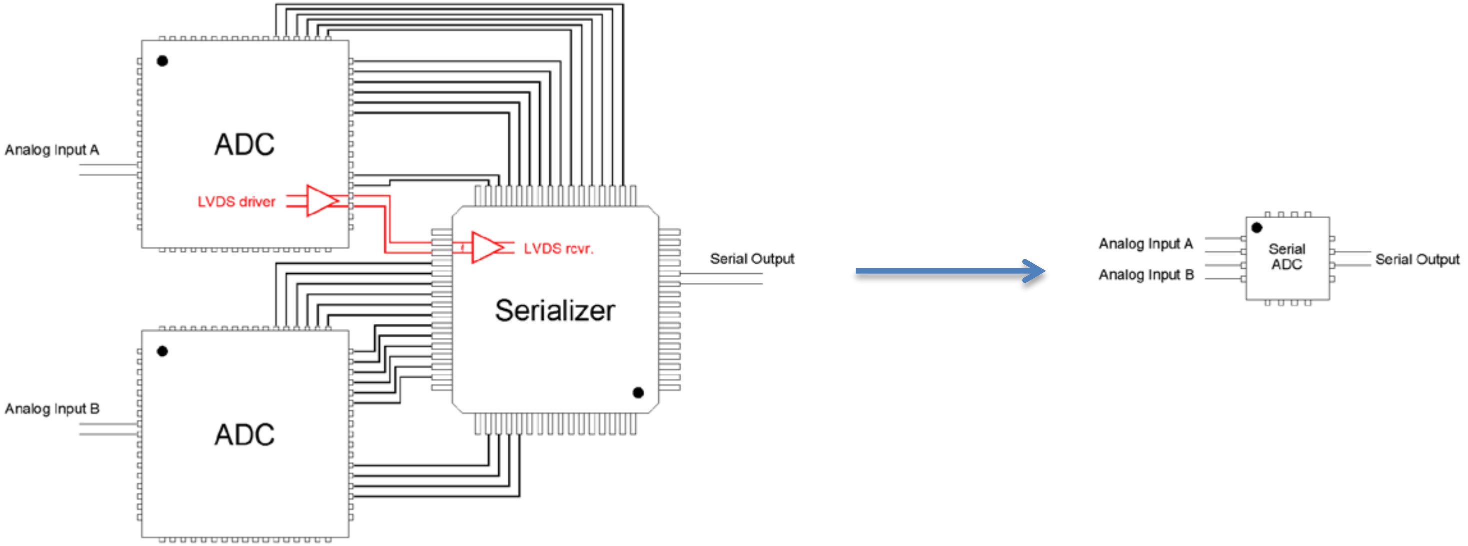
Final Challenge: Power Dissipation



Combined ADC/Serializer Saves Power (and reduces the footprint)



Custom ADC/Serializer

- By combining the ADC and the serializer, we can replace the resistively-terminated, off-chip LVDS lines with on-chip high-impedance traces to save power.
  - In the process, reducing the pin count and package size by an order of magnitude.

- Could also save a lot of power simply by sampling at 4-bits resolution instead of 8-bits.
  - Gives wider bandwidth for the same aggregate bit rate.
  - Resolution-agnostic ADC architecture?

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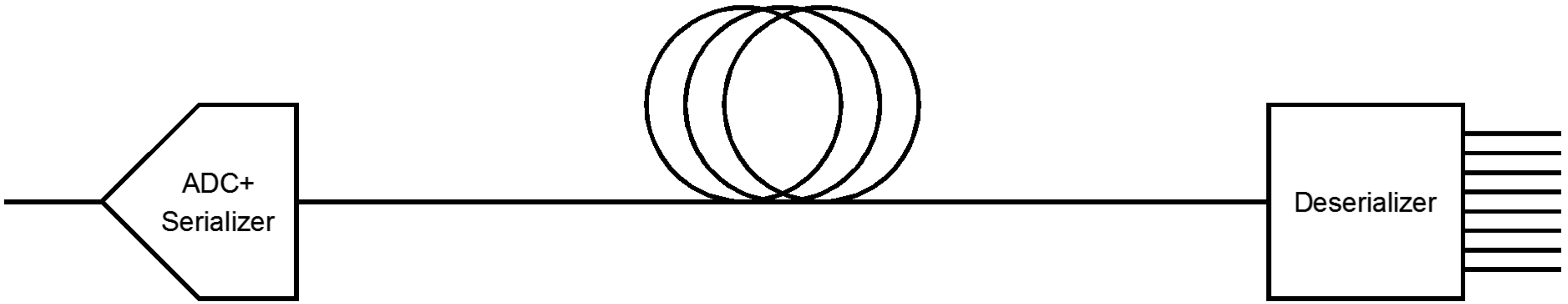
Proposed Custom Chipset for Unformatted Serial Links



- ADC+Serializer
  - High-speed
  - Low-power
  - Small footprint
  - Programmable bit-resolution
- Deserializer
  - Automatic, on-chip clock-recovery and word alignment
  - Adjustable word sequencing