Electro-Optical Kluges and Hacks

A Lab Rat's Guide to Good Measurements

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Hacks Of The Day

- Quantum detection
- A little noise theory
- Low noise front ends
  - Design tricks and circuit hacks
  - Detailed example: bootstrapped cascode TIA
- Noise Cancellers & Their Relatives
  - Motivation
  - Details
  - Other linear combinations (locking a laser to an etalon)
- High-Performance Pyroelectrics
  - Low speed wins!
- Higher speed
  - Impedance transformation: transformers, reactive networks, constant-resistance T-coils
Quantum Detection
(Optical View)

- One photon gets you one electron ($\eta \sim 1$)
- Shot noise is the intrinsic limit (*pace* squeezers)
- $N$ photons/s gives 0 dB SNR in $N/2$ Hz, max
- Signal and spurious junk are inseparable after detection

- **Etendue** ($n^2 A\Omega$) management for speed and low noise:
  - Achievable BW goes as average radiance ($W/cm^2/sr$)
  - Leakage, background, and capacitance go as the area
  - Reduce area, increase NA, consider immersion lens
  - High current density ($>10$ mA/cm$^2$) causes nonlinearity

  (And, just between you and me: small detectors are *really* hard to align)
Analytic Signals

- Circuits people use one-sided BW
- Analytic signal convention
  - Measurable quantities are real-valued
  - Analysis is easier in complex exponentials
- Analytic signal definition
  - Double signal at $f > 0$
  - Leave DC alone
  - Chop off all $f < 0$
  - A bit problematic at DC
- Causes mysterious factors of 2:
  - Mean square AC power doubled
  - 1-s boxcar has 0.5 Hz noise BW
  - $N^{1/2}$ in 1s is $(2N)^{1/2}$ in 1 Hz!
Noise Physics

- **Johnson Noise:**
  - Classical equipartition & fluctuation-dissipation theorem
  - Johnson noise PSD $P_{NJ} = kT \frac{1}{2}$ J/s/Hz when matched
    - $v_N = (4kTR)^{1/2}$, $i_N = (4kT/R)^{1/2}$ in 1 Hz (unmatched)
  - Noise temperature $T_N = T_{amb}$ (resistor), $T_N << T_{amb}$ (LNA)

- **Shot Noise:**
  - Photodetection is a Poisson process: variance = mean
  - Shot noise limit: $i_{N_{shot}} = (2eI_{dc})^{1/2} > (4kT_N/R)^{1/2}$ when:
    - Signal drops 50 mV across $R_L$ (300K)
    - Signal power $>7 \mu W$ in 50$\Omega$ (very quiet amp [35K])
  - *NB:* It's easy to make currents with no shot noise (metal resistor)
  - Pauli principle forces electrons to be highly correlated: noise power suppression is $\sim$ (mean free path)/(length of resistor)

- Technical noise (stay tuned)
Noise Definitions

- **Noise statistics are ensemble averages** or short-time averages.
  - They can be time-varying.
- **Signals at different frequencies add in power** since beat term averages to zero.
- Noise best specified as power spectral density (PSD): for reasonable bandwidths, think of this as noise in 1 Hz BW.
  - \( P_N \) is PSD, \( P_N \) is total noise power.
- **Noise Bandwidth:**
  - \( BW_N = \frac{\text{total noise power}}{\text{peak noise PSD}} \)
  - Equivalent width of power spectrum.
  - \( BW_N = \frac{1}{\text{autocorrelation width of impulse response}} \)
  - Generally wider than 3 dB BW (\( \pi/2 \) times for RC rolloff).
Quantum Detection
(Circuit View)

- **Output Current:**
  - consists of \( N \) Poissonian pulses/s regardless of QE and \( I_{\text{dark}} \)
  - Gain can't fix this (PMTs just give bigger pulses)

- All fundamental noise sources are white

- **Circuit Model:** current source shunted by \( C_d \)
  - \( C_d \sim 100 \) pF/cm\(^2\) for a good PIN device, fully depleted

- **Square law device:**
  - \( P_{\text{opt}} = hN, P_{\text{el}} = (eN)^2 R_L \)
  - Electrical power theoretically unlimited as \( R_L \Rightarrow \infty \)
  - Johnson noise is always \( kT/s/Hz \): weak signals are easily swamped
Detection Regimes (Quiet Source)

- **Photon counting:**
  - $N < 10^8$ photons/s (40 pW @ 500 nm)
  - Use PMT or Geiger-mode APD (< 1 MHz)
  - Useful BW (20 dB SNR) $\sim \frac{N}{200}$

- **Shot-noise limited:**
  - $i_d R_L > 50$ mV @300K
  - Can always get there with bigger $R_L$(Si, InGaAs) but BW suffers

- **Otherwise Johnson-limited:**
  - Nice quiet photoelectrons are immersed in circuit noise
  - Circuit constants are the problem
  - Circuit hacks can be the solution
Escaping Johnson Noise

- Additive circuit noise swamps photoelectrons
  - Very wasteful--we've paid a lot for those photons!

- 3 dB SNR improvement can save:
  - Half the laser power needed
  - Half the measurement time required
  - Half the cost and 2/3 the weight of the optical system

- To escape Johnson
  - Smaller detectors, higher bias (reduces $C$)
  - Low noise amplifiers (reduces noise)
  - Electron multiplying detectors or cooled CCDs (increases signal)
  - Impedance transformation networks (increases signal)
  - Other circuit hacks
Example:
Low-Level PIN Photodiode Front End

- **Design Parameters:**
  - Bandwidth: $B \geq 1$ MHz
  - Obese 1 cm$^2$ Si PIN Photodiode, $C_d = 100$ pF (fully depleted)
  - Photocurrent: $i_{\text{phot}} = 2 \mu$A
    - Photon arrival rate $N = \frac{i_{\text{phot}}}{e} = 12.4$ THz
  - SNR: Within 2 dB of shot noise limit
    - Maximum SNR = $N / 2B = 68$ dB in 1 MHz
Front End Choices

- Load resistor
- Transimpedance amplifier
- Bootstrap + load resistor
- Cascode transimpedance amp
- Bootstrapped cascode TIA
Load Resistor

- **First Try**
  - \( R_L = 1 \text{ M}\Omega : \text{BW} = 1600 \text{ Hz} \) (ick)
- **Everything is wired in parallel:**
  - Signal and noise roll off together
  - SNR constant even though signal rolls off by 55 dB
  - Subsequent amplifier limits SNR
- **Optimization:**
  - Lower \( R \) increases BW, but SNR drops due to Johnson noise
  - Shot = Johnson when \( IR = 2kT/e \) (~50 mV@300K)
  - Optimum \( R \) drops ~ 200 mV
  - \( R_{\text{opt}} = 100\text{k}, \text{BW} = 16 \text{ kHz} \)
Transimpedance Amp

- Connect PD to virtual ground
  - Op amp wiggles output end of \( R_F \) to keep input end still
- Improves BW but not SNR
  - 3 dB BW \( \approx 0.5 (f_{RC} \cdot GBW)^{1/2} \)
- Unity gain stability unnecessary
- Big improvement but don't push it too much:
  - Noise and instability problem due to capacitive load on summing junction
  - Fast amplifiers are worst
- 0.5 pF \( C_f \) helps instability but can't fix SNR problem
Transimpedance Amp

- **Transimpedance BW**
  - Less than closed-loop BW
  - Depends on values not ratios
  - Actual BW obtained depends on frequency compensation

- **Low noise**
  - Amplifier noise dominates at large $R_f$
  - Active devices can have $T_N << 300K$ ($T_N = eN_i/N / 4k$)
  - ~10K for good bipolar op amps
  - Even lower for FETs but needs inaccessible impedance levels
DIY Op Amps

- Current noise of op amp appears in parallel with $I_{\text{phot}}$
  - Treated just like signal: no high freq SNR penalty

- Voltage noise of op amp sees full noninverting gain
  - Big noise spike at high freq, due to $C_d$ (differentiator)

- Reducing $e_{Namp}$ means running the input stage at higher bias
  - add a BJT stage to the front
  - Increases $i_{Namp}$, but that's OK
Cascode TIA

- **Isolate $C_d$** from summing junction with cascode $Q_1$
  - BW limited by emitter impedance $r_E = 1/g_m$
  - BW(Hz) = 6.2 $I_C / C_d$

- **Biasing cascode** with sub-Poissonian $I_{bias}$ reduces $r_E$
  - Improves BW
  - Noise now limited by $R_{b'}$ and shot noise of $I_b$
  - Noise multiplication much reduced compared to TIA
Bootstrapping

- **Bootstrap transistor**
  - Follower forces cold end of $D1$ to follow hot end
  - No voltage swing
    - $\rightarrow$ no capacitive current
- **Speed set by** $r_E C_d$ not $R_L C_d$
  - 50x faster than RC at $I_{dc}=300$ $\mu$A, $R_L=100$ k$\Omega$
- **Superbeta transistor**
  - $\beta \approx 1000$: Very low base current noise
- **Noise Voltage**
  - Limited by $R_b$ and $r_E(2eI_C)^{1/2}$
  - Noise multiplication similar to TIA
- **Can be applied with other techniques**
Bootstrapped Cascode TIA

- Can't use enough $Q_1$ bias to get 1 MHz BW without being limited by $I_b$ shot noise and $R_b'$ Johnson noise
- Bootstrap runs at higher current: lower voltage noise
- Reduces effective $C_d$
  - Superbeta transistor $Q_2$ has much lower base current shot noise, so can run at higher current than $Q_1$ without ruining the SNR
  - Bootstrap can be applied along with cascode
Bootstrapped Cascode TIA

- Final performance:
  - Within 1 dB of shot noise, DC-1.3 MHz
  - 600x bandwidth improvement over naive approach
- Three turns of the crank to get 1 MHz BW with 100 pF & 2 μA
- Not much more juice available here:
  - optical fix needed next time

Bottom: Dark noise
Top: 2 μA photocurrent
Detectors With Gain

- **Electron Multiplication**: used in PMTs, APDs, & LLLCCDs
  - Gain applied to electrons before front end amplifier
  - Front end noise contribution reduced by $M$
  - Allows low load resistances => increased BW

  **HOWEVER,**...

  - Gain inherently noisy (at least 3 dB noisier than PIN)
  - Other tradeoffs depend on device (e.g. GBW of APD)

- **Shot noise doesn't improve**:
  - N photons per second gives 0 dB SNR in N/2 Hz, max
  - Gain amplifies noise along with signal
Noise Physics Again

- **Technical Noise**
  - Usually dominant in laser measurements, especially bright field
  - Dominates in large-signal limit \( (p_N \sim P_{\text{opt}}^2) \)
  - Laser RIN, demodulated FM noise, wiggle noise, below-threshold side modes, mode partition noise, coherence fluctuations microphonics, \(1/f\) noise, noisy background, phase of the moon, pink elephants,.....

- Many strategies for getting round it, such as:
  - **Reduce background**: Dark field and dim field
  - **Move to high frequency**: Heterodyne interferometers
  - **Move at least a little away from DC**: Chopping
  - **Compare beam before and after sample**: Differential detection

- NB: Lots of possibilities, because there's no 100% solution
**Shot Noise**

**Rule of One**

- One coherently added photon per second gives an ac measurement with One sigma confidence in a One hertz bandwidth.

- True for bright field or dark field:
  - Bright field == dark field, except for technical noise
    - BF: Source instability (RIN)
    - DF: Johnson noise
  - DC is actually 3 dB better for a given temporal response, except for the usual baseband suspects
Apart from shot noise, \( I_{\text{sig}} \) and \( I_{\text{comp}} \) are perfectly correlated.

Optical systems are extremely linear and wideband.

Photodiodes can also be extremely linear and pretty wideband:

\[ \frac{i_{\text{sig}}}{i_{\text{comp}}} = \frac{I_{\text{sig}}}{I_{\text{comp}}} \]  
(differential gain == average gain)

If the DC cancels, the noise cancels at all frequencies.

Problem: only works with beams of identical strength:

Need to ship a grad student with each system to keep it adjusted.
With fixed $\Delta V_{be}$, the ratio of $I_{C2}/I_{C1}$ is constant over several decades of $I_e$.

- Linear splitting $\Rightarrow$ fluctuations and DC treated alike
- ($Q_1$ is in normal bias as shown—the collector can go 200 mV below the base before saturation starts)
- Transistors can be fast
- Adjusting $\Delta V_{be}$ to null out the photocurrent doesn't disturb the subtraction
Basic Noise Canceller

- Add a diff pair to a current-differencing amplifier
- Use feedback control of $\Delta V_{be}$ to null the DC
  $\Rightarrow$ Noise cancels identically at all frequencies
- Cancellation BW independent of FB BW
- Linear highpass O/P, log ratio LP output ($\Delta V_{be}$)
- $1k:26\Omega$ divider gets rid of $kT/e$ factor in $\Delta V_{be}$
  $[2V \iff \exp(1)]$
Performance: Cancellation

He-Ne showing a strong mode beat (oscilloscope traces)

Upper: TIA mode showing beat waveforms due to 4-wave mixing (comparison beam blocked)

Lower: Cancellation to 0.5 dB above shot noise (comparison beam unblocked)

3N3904 discrete BJT
0.75 mW $P_{\text{sig}}$, 1.5 mW $P_{\text{comp}}$
Performance: Cancellation

He-Ne in quiescent period
Upper: TIA mode, showing noise and 22 kHz ripple
Lower: Cancellation to 0.5 dB above shot noise

Envelopes of 100 scans, showing mode beats sweeping
Upper: TIA mode
Lower: >50 dB cancellation, even with multiple modes

3N3904 discrete BJTs
0.75 mW $P_{\text{sig}}$, 1.5 mW $P_{\text{comp}}$
Performance: Cancellation

- 50-70 dB RIN reduction at low frequency, ~40 dB to 10 MHz
- No critical adjustments
- Cancellation at high currents limited by differential heating
**$R_E$ Degeneration**

- Discretes run at different $T$
  - $\Rightarrow$ Less cancellation at high $I_c$
    - Use monolithic matching
- Main remaining limit is failure of BJTs to be exponential at high currents
  - $R_E$ produces negative feedback on emitters, tending to even out the current split
  - Apply positive FB to the bases, keeping intrinsic $V_{BE}$ constant
RE Compensator

- Requires a current mirror plus a few extra resistors
- Flattens out rejection curve, 10-25 dB improvement
Differential Version

- Add second signal beam
- Run slightly unbalanced ($I_{\text{sig1}} > I_{\text{sig2}}$)
- Differential pair sees only the slight imbalance $I_{\text{comp}} > (I_{\text{sig1}} - I_{\text{sig2}}) \ll I_{\text{sig1}}$
- Limitations of BJTs circumvented
- 3 dB noise improvement (both signal beams contain information)
- Using log output requires more thought
- 160 dB SNR (1 Hz)

$I_{\text{sig1}} = 1.48 \text{ mA}$
$I_{\text{sig2}} = 1.26 \text{ mA}$
Differential noise canceller, diode laser, $\sim0.5$ mW/beam

$BW = 1.1\text{ MHz}$

Beam scanning around inside a chamber with a sandblasted aluminum back wall (some mode hopping)

Noise canceller leaves only shot noise

Very gaussian over $>10$ orders ($300\text{ kHz} - 8\mu\text{Hz}$)

Imputed error $\sim0.1\text{ dB}$ over full range (1-parameter fit to exact noise BW)
Multiplicative Noise

- Signal beam: 50 kHz AM
- Comparison beam vs flashlight
- Laser: Distorted 30% AM at 5 kHz
- Noise intermod suppression: \( \geq 70 \) dB
- Power returned to signal
- Peak heights are independent of power level
- Intermod suppression depends on loop gain, but:
  - The signal being ratioed has had its additive noise cancelled at all frequencies
    - Noise performance greatly improved--no additive noise!
Log-Ratio Only Version

- Eliminate $A_1$, swap diff pair inputs to keep FB negative
- Gives widest log BW (> 1 MHz)
- BW depends on signal levels
  - Possible parametric effects
  - Much less serious than with analogue dividers
- Noise floor 40-60 dB lower than dividers'
- Noise limited by base resistance Johnson noise at high currents
- $R_E$ compensation applicable
Performance: Log Noise Floor

- Shot noise of $I_{\text{sig}}$ and $I_{\text{comp}}$ add in power => noise floor at least 3 dB above shot noise (but stay tuned)
- Noise floor is very flat and stable, generally within 0.5 dB of SNL except at high currents (and parallelling transistors can improve that)
Log Ratio Spectroscopy

- Sensitivity ~ 1 ppm absorption
- Shot noise limited even with huge \( dP/d\omega \) (\( \Delta P \sim 30\% \) over scan range)
- Etalon fringes eliminated by subtracting pressure-broadened scan
Noise Cancellers and You

- The Good News:
  A noise canceller will cancel all correlated modulation down to the shot noise level
  - Laser RIN is substantially eliminated
  - Error in ratiometric measurements is greatly reduced

- The Bad News:
  Everything else will be left behind

- Everything depends on the correlation between signal and comparison beam remaining high
- You're going to learn things about your beams that you never wanted to know: Coherence fluctuations, spatial side modes, amplified spontaneous emission, polarization instability, vignetting, and especially etalon fringes
Applications Advice

System design

- **Etalon fringes:**
  - Keep design simple, avoid perpendicular surfaces
- **Spontaneous emission:**
  - Use an efficient polarizer right at the laser
- **Spatial decorrelation:**
  - Don't vignette anything after the beam splitter
- **Path length imbalances:**
  - Keep path lengths within ~ 10 cm of each other
- **Photodiode linearity:**
  - Keep current density lowish & reverse bias highish
  - Transistor linearity: $I_D > 1$ mA requires differential model or $R_E$ compensation
  - Keep balance somewhere near 0 V (big negative voltages hurt)
Applications Advice

System design

- **Temperature stability**
  - Etalon fringes drift like crazy (>10% transmission change/K)
    - Photodiode windows a common culprit
  - Log ratio output proportional to $T_J$
    - Temperature-stabilize $T_J$ using monolithic quad (MAT-04)
      - 1 heater, 1 thermometer, 2 for diff pair
      - $\sim 10^{-5}$ absorption stability in 1 hour

- **Care and feeding of photoelectrons:**
  - Never put photodiodes on cables--put the amplifier right there
  - Photodiode electrical shielding often required

- **Alarm conditions:**
  - Use a window comparator on the log ratio output to check for fault conditions, e.g. no light
Applications Advice

Setup & Testing

- Shot noise is easy to verify & you get the frequency response free!
  - A flashlight generates a photocurrent with exactly full shot noise
  - A dc-measuring DVM is all you need to know $i_{N\text{shot}}$
  - Source is white => Output Noise PSD == frequency response

- Check cancellation behaviour
  - Block comparison beam to turn canceller into an ordinary TIA
  - Use a flashlight to replace $I_{\text{comp}}$ in log ratio mode ($\Delta V_{\text{be}}$ constant)
  - Compare $I_{\text{comp}}$ and $I_{\text{sig}}$ to $\Delta V_{\text{be}}$ formula--do they agree?

- Wiggle and poke things
  - Tapping components with the eraser end of a pencil will tell you which ones are generating the fringes
Laser noise depends on polarization, position, and time
  - Noise is spatially variable (interference with spontaneous emission and weak spatial side modes):
    - Vignetting can destroy correlation

Etalon fringes demodulate everything
  - Mode partition noise, FM noise, weak longitudinal side modes, and coherence fluctuations turn into AM
  - Polarizing cube has 2-5% p-p fringes if perpendicular to beam
    - FSR is only 0.13 cm$^{-1}$ (fringes really demodulate everything)
  - Be paranoid about fringes

Spontaneous emission
  - Has different noise than laser light & will split differently
Coherence fluctuations
- All optical systems are interferometers

\[ I_{dc} \propto (|\psi_1|^2 + |\psi_2|^2) + 2 \text{Re}\{\psi_1 \psi_2^*\} \]

- Interferometer path imbalance of 1% of coherence length => 40 dB SNR in \( \Delta \nu \), maximum (\(|\psi_1| = |\psi_2|\))
- Outside coherence length, fringes turn into *noise*
- Full interference term becomes noise in bandwidth \( \sim \Delta \nu \)
- Can easily dominate all other noise sources if \( \Delta \nu \) isn't \( >> \) BW

Time delays
- Delaying one arm reduces noise correlation due to phase shift
  - To get 40 dB cancellation, phase shift \( \omega \Delta t < 0.01 \) rad
Summary: Low Frequency Front Ends

- It isn't just about detectors

- **Good analogue design** can give huge performance gains
  - bootstrapping
  - cascode TIAs

- **Careful system design** prevents trouble:
  - Etalon fringe elimination
  - Believing your noise budget

- **Linear combinations** --used intelligently-- make hard things easier
  - Differential detection
  - Laser noise canceller
  - Cavity locking
What Are My Customers Really Doing?

- Quantitative Evaluation of Store Design
- See Where Customers Go & What They Look At
- Real-time Feedback On Store Ops
  (To make it worth instrumenting every store)

- Distribute Cheap Sensors In The Ceiling
- Extract Trajectories Automatically
$10 Pyroelectric Camera

Array of Distributed Pyroelectric Sensors
- Sensors Mounted In Ceiling
  ~ 100 pixels/sensor
- 100-1000 Sensors Per Store (100-200 sq ft each)
- Base Manufacturing Cost: $50-100
- Pyroelectric Effect

- Ferroelectric PVDF (fluorinated Saran Wrap)
- Ferroelectric Has Frozen-In $E$
  - Like Remanent $B$ In A Ferromagnet
- Polarization drops $\sim 1\% / K$
- Free Charge $q$ Flows To Zero Out $E_{\text{total}}$, so $\Delta q$ gives $\Delta T$
- Very inexpensive
- Inherently AC: Static Objects Disappear
Multiplexed Pyroelectric Array

IR FPA sensitivity, porch-light cost
- Free-Standing PVDF Film In Air
- 8 x 12 Array, 6 mm Pitch
  (Tee-shirt Lithography)
- Needs Fancy Multiplexer
Optical Design

Moulded Polyethylene Fresnel Lenses

INFRARED FRESNEL LENSES

Wavelength (microns)

Transmittance (%)

7.5-13 µm
IRstart1
OPTICAL SYSTEM LAYOUT

UNITS: MM
DES: Budd
Thermal Design

Slow is Beautiful

- Signal Power $\sim G^{-2}$
- Johnson Noise Is Flat
- (Fluctuation PSD $\sim G$)
- Bandwidth $\sim G/M_{\text{th}}$
- Johnson-Limited SNR $\sim 1/G$

$\Rightarrow$ Insulate the Sensor & Filter Data To Recover BW

$$G_{\text{Total}} = G_{\text{Rad}} + G_{\text{Cond}} + G_{\text{Air}}$$

$$\Delta T = \frac{\varepsilon I}{G_{\text{Total}}}$$

$$\frac{dT}{dt} = \frac{\varepsilon I - G_{\text{Total}} \Delta T}{dM_{\text{th}} / dA}$$
Thermodynamic Efficiency

- Sensitivity proportional to surface emissivity
- Carbon ink is shiny at 10 µm
- "Swiss-cheese" ink blanket halves the thermal mass
- Tuned metal coating increases $\Delta T$
- Ink lattice on tuned metal should give ~ 20 dB more signal
Sensor Design: Multiplexer

- $\Delta T_{\text{pixel}} \sim 8 \text{ K} \ (\text{Human Crossing the Floor})$
- $\Delta q/\Delta T_{\text{pixel}} = (3 \text{V/K})(160 \text{ pF}) \sim 500 \text{ pC/K}$
- $\text{BUT: } \Delta T_{\text{pixel}} / \Delta T_{\text{IFOV}} \sim 0.002, \tau \sim 2 \text{ s} \ (10 \text{ Frames})$
  - Total Signal Available $\sim 0.1 \text{ pC/pixel/frame}$

- Multiplexer Leakage $\leq 5 \text{ pA}$
- Charge Injection $< 0.5 \text{ pC}$
- Nothing like it is available commercially
Diode Switches

- Nanoamp Leakage
- Control And Data Paths Not Separate
- Unidirectional And Nonlinear: Bias Required

\[ I_F = I_S \left( \exp \left( \frac{eV_F}{kT} \right) - 1 \right) \]

\[ R_0 = \left. \frac{\partial V_F}{\partial I_F} \right|_{V_F=0} = \frac{kT}{e I_S} \]

- 1 mA \( I_F \): Si diode \( \sim 0.65 \) V, LED \( \sim 1.6 \) V
  
  => \( I_S \) for a LED Should Be \( 10^{-16} \) That of Si

- \$0.05 LED has \( |I_F| < 100 \) fA, -5 V < \( V_F < +0.5 \) V
Biasing Hack

- Need 1-5 pA Bias Per Pixel, CPU Adjustable
- $10^{12} \ \Omega$ Resistors Don't Come in SMT
- Use Photocurrent Instead

- LED Is a Photodiode Too
- Use Diffused Light From CPU-Throttled LEDS
- 1 mA LED Drive => 1 pA Bias
- Switch + Adjustable Bias = 1 LED @ $0.05$/Pixel
Footprints Data

(Raw data, 1 sq ft pixels, 28 µm metallized PVDF)

(Pseudo-integral, 1 sq ft pixels, 4 µm carbon ink on 9 µm PVDF)
Footprints Data

(Pseudo-integral, 1 sq ft pixels, 4 µm carbon ink on 9 µm PVDF)
More if time permits....
Going Faster: RF Techniques

- TC reduction goes only so far
  - Impedance Transformation
  - Reactive networks
  - Transmission-line transformers
  - Constant-resistance T-coils

- Low-noise RF amps
  - 35K noise temperature: 9 dB improvement vs 300K
  - Driving 50Ω
Noise Figure & Noise Temperature

- Ways of quoting low noise levels

- Noise Figure
  - NF = 10 log[(SNR before)/(SNR after)] (300K source)
  - 3 dB is garden-variety
  - < 0.4 dB is the state-of-the-art @ 1-2 GHz (Miteq)

- Noise Temperature
  - Very low NFs awkward to use
  - $T_N = P_N / (kB)$
  - $T_N = 300K(10^{\frac{NF}{10}} - 1)$
  - 3 dB NF = 300K $T_N$, 0.5 dB NF = 35K $T_N$, LT1028 = 15K (@1kHz)
  - $T_N \ll T_{ambient}$! (F-D theorem doesn't apply to active circuits--or refrigerators for that matter)
Impedance Transformation

- **PD is a current source**
  - Signal power proportional to $\text{Re}\{Z_L\}$
  - Increasing $Z_L$ at the diode can improve SNR
  - Want all-reactive networks
    - Resistors in the matching network dissipate power uselessly and add a 300 K noise source to a ~ 40 K system

- *Not* an impedance matching problem for $\lambda < 1.8 \ \mu\text{m}$!
  - Available power not fixed for Si, InGaAs PDs
  - Source impedance poorly defined
  - IR diodes, e.g. InAs, InSb, HgCdTe have low shunt resistances:
    - Available power is fixed, so impedance matching is relevant
Impedance Transformation

- Low Noise Amps
  - PD is a nearly-pure reactance => almost noiseless
  - 35K amp is 9 dB quieter than 300K amp for reactive source
  - BJT emitter ideally has $T_N = T_{amb}/2$,
    - ideal BJT base has $T_N = T_{amb}/(2\beta)$--same noise voltage, $\beta$ times higher impedance
  - Connect PD straight into MMIC with no resistor or capacitor--fix frequency funnies afterwards, at higher signal levels

- Transformers
  - Quiet RF amps are all around 50 Ω (amps are typically 2:1 VSWR, so it might be 100Ω or 25Ω)
  - $N:1$ turns ratio gives $N^2$ impedance change
  - Transform 50 Ω up for Si PD, or down for, e.g., InAs
Bode Limit

- How wide can we go?
  - Bode theorem specifies tradeoff between BW and insertion gain $\Gamma$

$$\int_0^\infty \ln\left(\frac{1}{|\Gamma|^2}\right) d\omega \leq \frac{2 \pi}{RC}$$

- $|\Gamma|^2$ is the return loss (fraction of power reflected from the load)
- RC has 1.03 dB average passband loss (to 3 dB points)
- Choose $|\Gamma|^2 = 0.21$ (79% efficiency, or 1.03 dB signal loss)
  - BW increases 4x vs RC, for no net signal loss whatsoever
- 3 elements will usually get within 0.5 dB of this limit
- Increasing mismatch gains bandwidth almost reciprocally
  - $|\Gamma|^2 = 0.5$ gives 9x BW @ 3 dB loss
L-Network or Series Peaking

- **Simplest Reactive Network**

  - Moves RC bandwidth from DC to $f_0$ (same BW, settling time doubled)
    - $Q = \frac{X}{R}$ [at resonance, $Q = \frac{1}{\left(\omega_0RC\right)}$ (ratio of $f_0$ to $f_{RC}$)]
    - Bandwidth $BW_{3dB} = \frac{\omega_0}{Q}$
  - Transforms load impedance by a factor of $Q^2 + 1$
    - $50 \ \Omega, \ Q = 10 \Rightarrow$ effective $RL = 5k\Omega$ (pure resistance at $\omega_0$)
    - Can also be used at baseband for a $1.4x$ BW increase
Constant-Resistance T-Coil

**Tektronix Vertical Amplifier Secret**

- Doesn't waste current in $R$ while there's $C$ to charge
- 2.8x BW increase (at 3 dB points)
- No overshoot or ringing
- Design equations available

- Best simple network for baseband use (lowpass characteristic)
- Disadvantage: Load resistor and output are different nodes
  - Harder to get $T_N < 300K$ (may have to put active device in for $R$)
Example: 5 pF PD, DC-50 MHz

- **Direct connection to 50 Ω**
  - BW = \( \frac{1}{2\pi(5pF)(50Ω)} \) = 640 MHz
  - Shot noise limit: \( I_{\text{phot}} \geq 1 \text{ mA} \) (300K), 370 µA (35K)
  - *Wasteful*

- **3:1 Turns Ratio Transformer (450Ω)**
  - BW = \( \frac{1}{2\pi(5pF)(450Ω)} \) = 70MHz
  - Shot noise limit: \( I_{\text{phot}} \geq 115 \text{ µA} \) (300K), 13 µA (35K)
  - (DC current x AC resistance > 50 mV (300K), > 6 mV (35K))
  - *9 dB SNR improvement (Johnson limit)*
Example: 5 pF PD, DC-50 MHz

- **Constant-Resistance T-Coil:**
  - 2.8x BW increase, resistive load
  - Can be used with 6:1 transformer
  - $R_L = 1800\,\Omega$
  - SN Limit: 29 $\mu$A (300K), 3.4 $\mu$A (35K)
  - Best step response
  - 15 dB SNR improvement

- **Bode Limit:**
  - 4x BW increase, resistive load
  - $R_L = 2550\,\Omega$
  - SN Limit: 20 $\mu$A (300K), 2.4 $\mu$A (35K)
  - 17 dB SNR improvement
  - Beyond there, you have to trade off SNR or reduce $C_d$
Example: 5 pF PD, 250+-5 MHz

- Put passband anywhere you like
  - Simple 81 nH series $L$, 5 $\Omega$ load
  - $R_L=3130$ $\Omega$ (Q=25--no higher)
  - Use e.g. a cascode or 1:3 xfrmr
  - Can tune by changing $V_{\text{bias}}$
  - SN Limit: 16 $\mu$A (300K), 2 $\mu$A (35K)
  - 17 dB SNR improvement vs 50 $\Omega$

- Bode Limit:
  - 4x BW increase, resistive load
  - $R_L=12.8$ k$\Omega$
  - SN Limit: 4 $\mu$A (300K), 0.5 $\mu$A (35K)
  - 24 dB SNR improvement vs 50 $\Omega$