# 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)

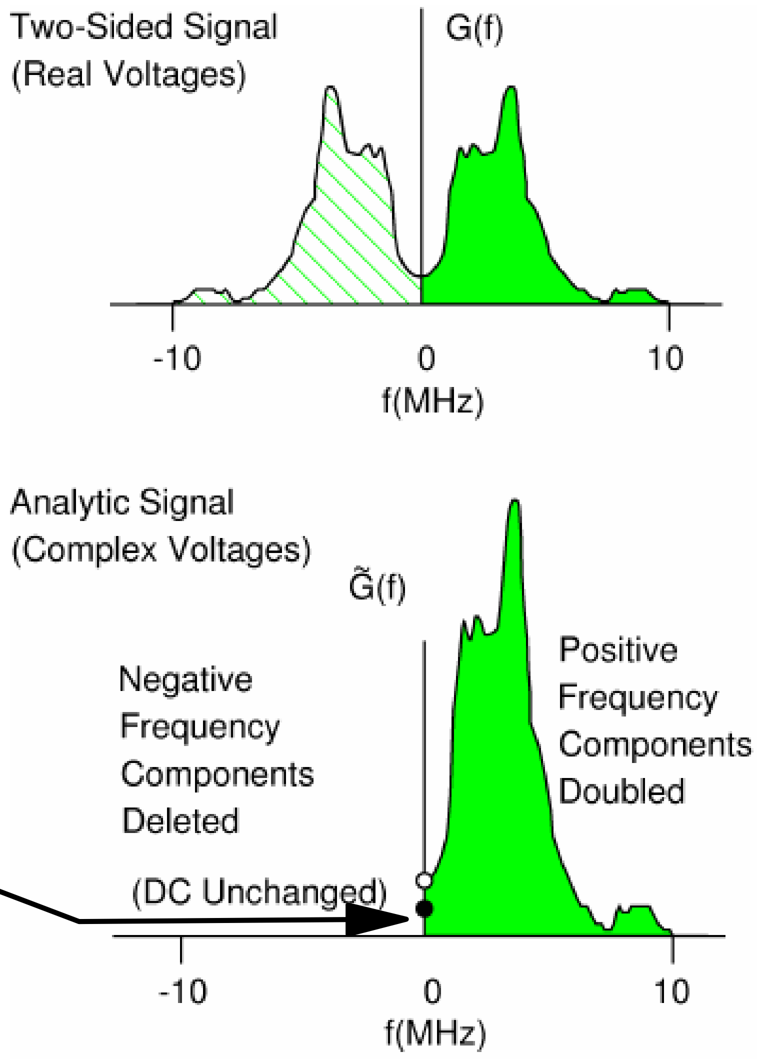
- One photon gets you one electron ($\eta \sim 1$)
- Shot noise is the intrinsic limit (*pace* squeezers)
- *N* photons/s gives 0 dB SNR in *N*/2 Hz, max
- Signal and spurious junk are inseparable after detection

- 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 $p_{NJ} = kT$ 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: $i_{Nshot} = (2eI_{dc})^{1/2} > (4kT_N/R)^{1/2}$ when:
    - Signal drops 50 mV across $R_L$ (300K)
    - Signal power >7 μW in 50Ω (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 ~ (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:
  - $BW_N$ = (total noise power)/(peak noise PSD)
  - Equivalent width of power spectrum
  - $BW_N$=1/(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 $I_{dark}$
  - Gain can't fix this (PMTs just give bigger pulses)

- All fundamental noise sources are white

- Circuit Model: current source shunted by $C_d$
  - $C_d \sim 100\ \mathrm{pF/cm}^2$ for a good PIN device, fully depleted

- Square law device:
  - $P_{opt} = hnN$, $P_{el} = (eN)^2 R_L$
  - Electrical power theoretically unlimited as $R_L$ => infinity
  - 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) ~ 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: $B >= 1$ MHz
  - Obese 1 cm$^2$ Si PIN Photodiode, $C_d = 100$ pF (fully depleted)
  - Photocurrent: $i_{phot} = 2\ \mu$A
    - Photon arrival rate $N = i_{phot}/e = 12.4$ THz

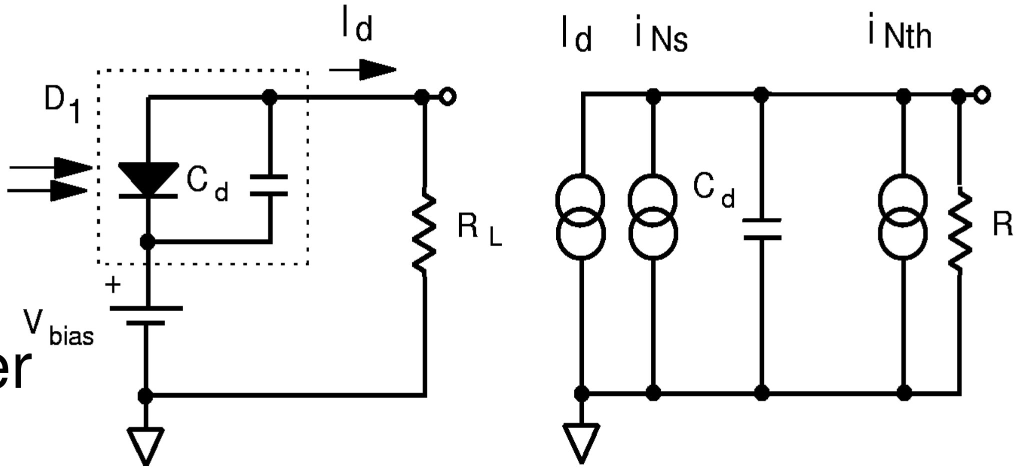
  - SNR: Within 2 dB of shot noise limit
    - Maximum SNR = $N/2B$ = 68 dB in 1 MHz

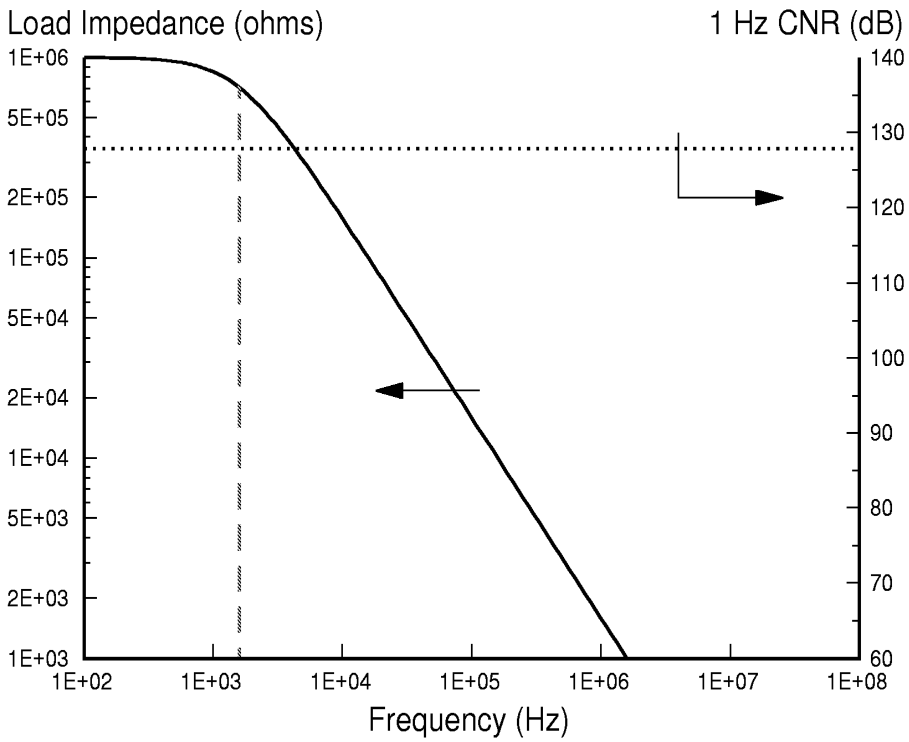
# Front End Choices

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

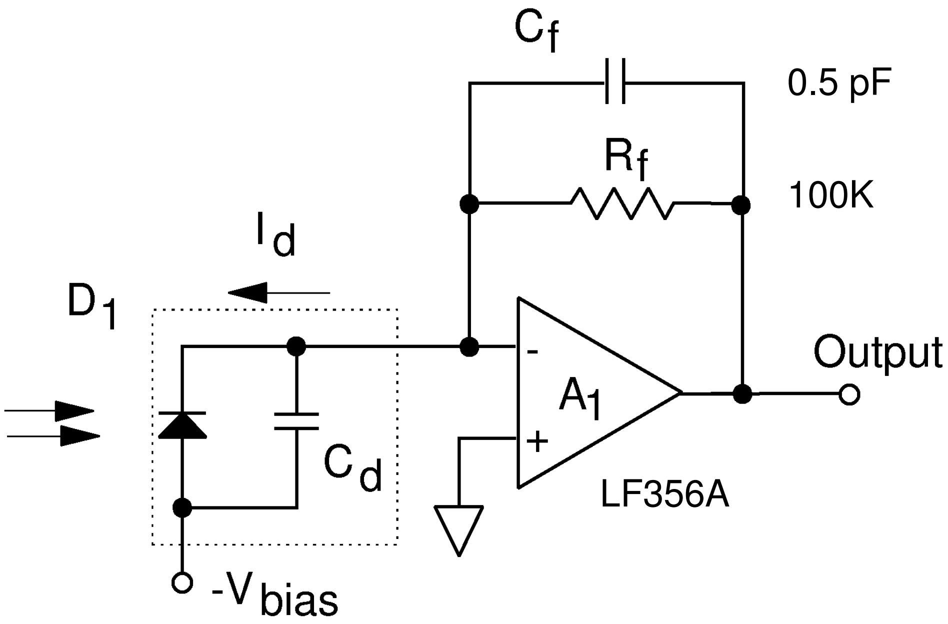
# Load Resistor

- First Try
  - $R_L$ =1 MΩ : BW = 1600 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
  - $R_{opt}$ = 100k, BW = 16 kHz

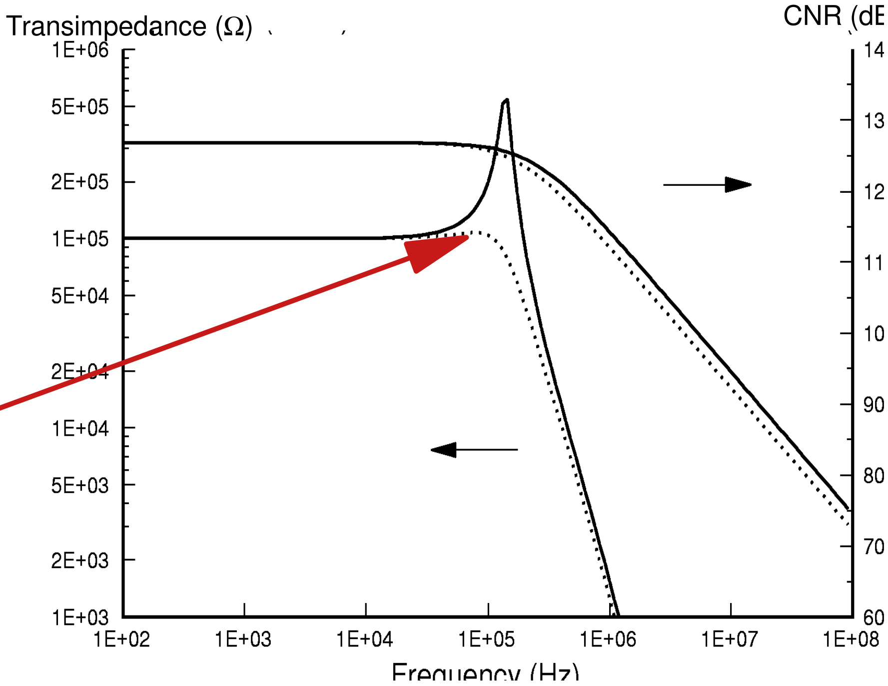




# Transimpedance Amp

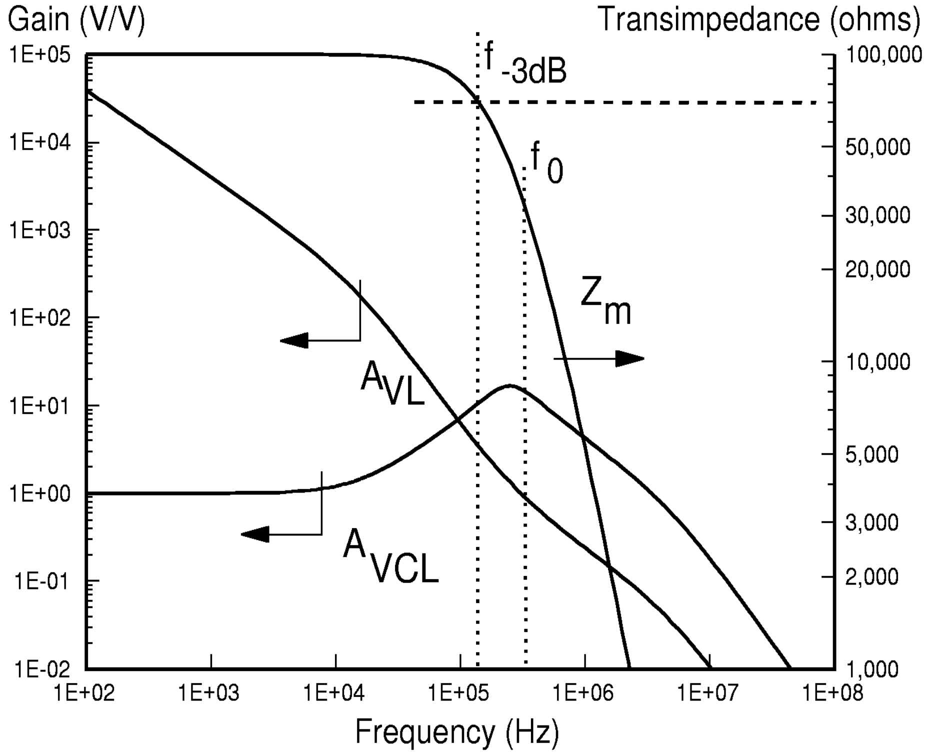


- Connect PD to virtual ground
  - Op amp wiggles output end of $R_F$ to keep input end still
- Improves BW but not SNR
  - 3 dB BW ~ $0.5(f_{RC}*GBW)^{1/2}$
- Unity gain stability unnecessary
- Big improvement but don't push it too much:
  - Noise and instability problem due to capacitive load on summing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



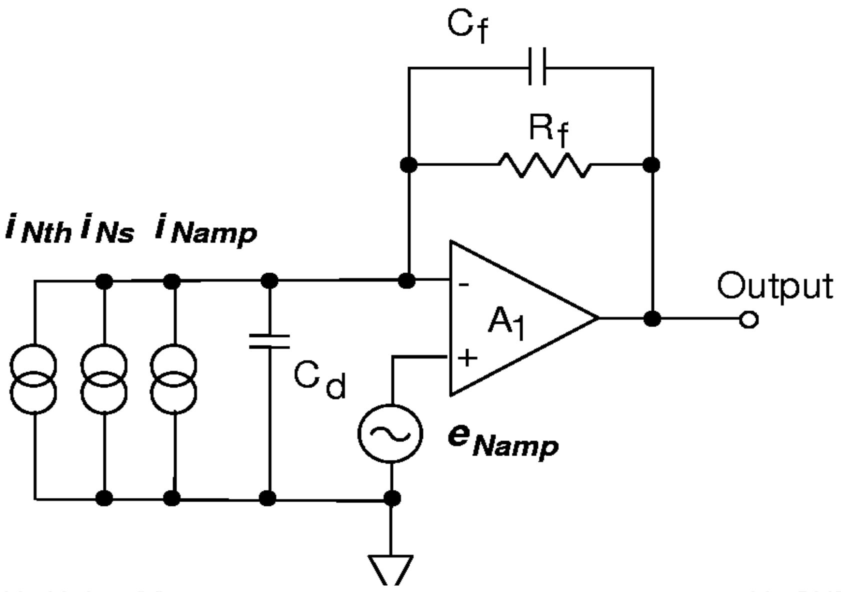
# Transimpedance Amp

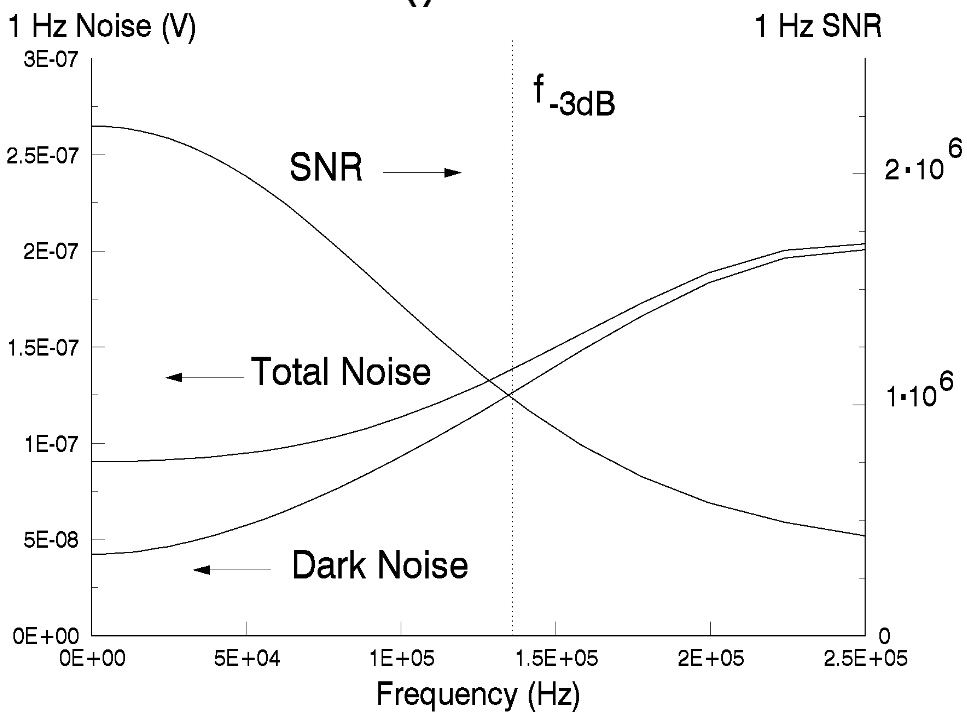
- Transimpedance BW
  - Less than closed-loop BW
  - Depends on values not ratios
  - Actual BW obtained depends on frequency compensation
- Low noise
  - Amplifier noise dominates at large $R_f$
  - Active devices can have $T_N << 300\text{K}$ ($T_N = e_N i_N / 4k$)
  - ~ 10K for good bipolar op amps
  - Even lower for FETs but needs inaccessible impedance levels



# DIY Op Amps

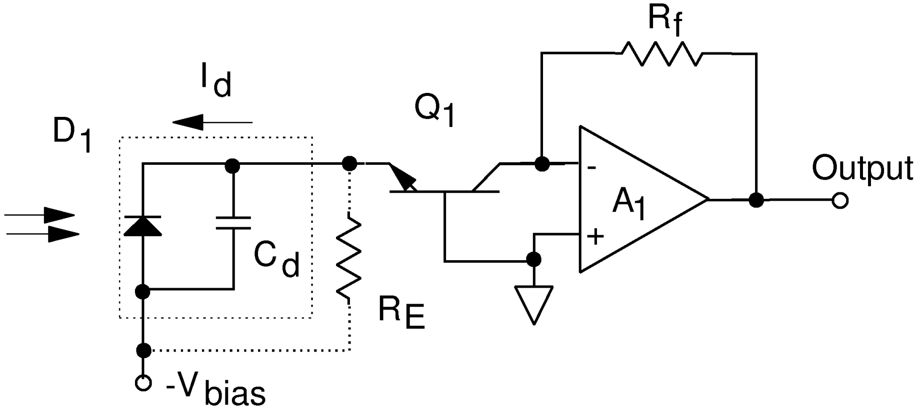
- Current noise of op amp appears in parallel with $I_{phot}$
  - Treated just like signal: no high freq SNR penalty
- Voltage noise of op amp sees *full noninverting gain*
  - Big noise spike at high freq, due to $C_d$ (differentiator)
- Reducing $e_{Namp}$ means running the input stage at higher bias
  - add a BJT stage to the front
  - Increases $i_{Namp}$ ,but that's OK

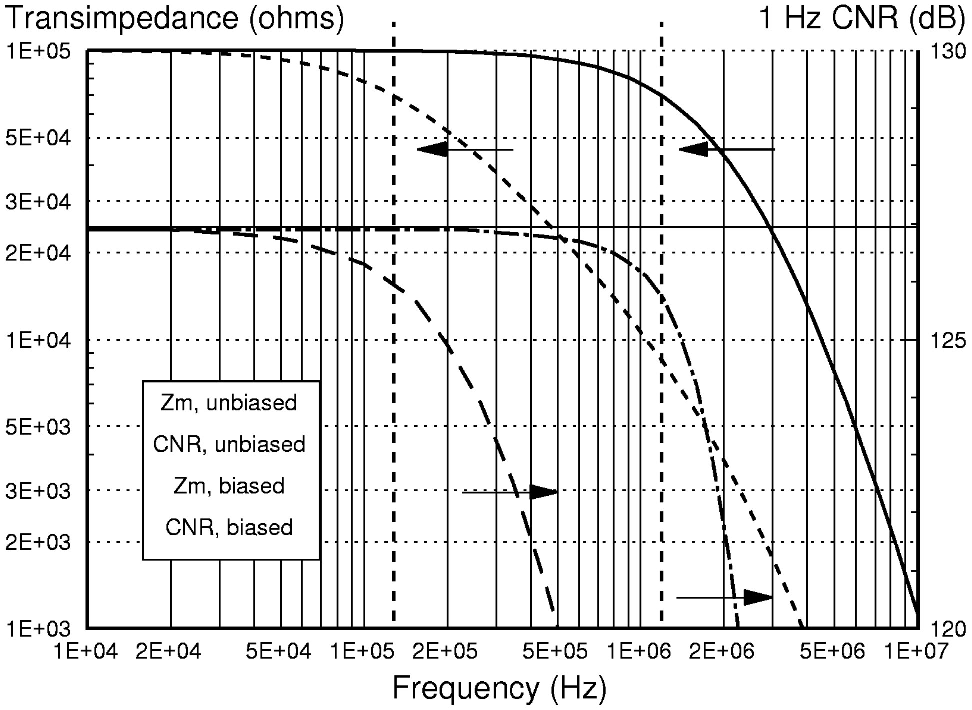




# Cascode TIA

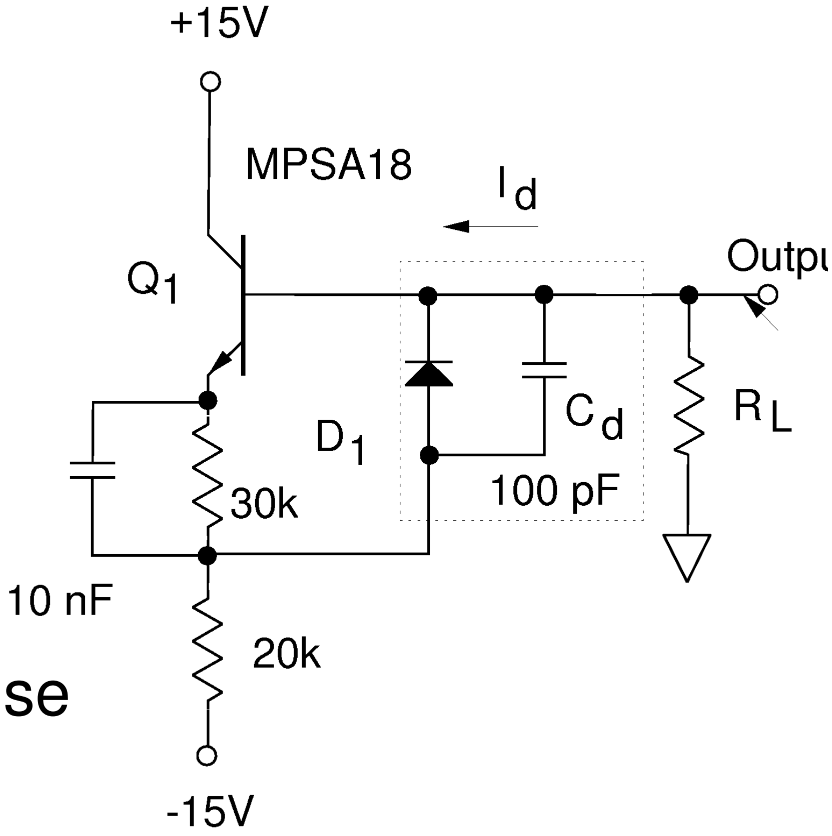
- Isolate $C_d$ from summing junction with cascode $Q_1$
  - ► BW limited by emitter impedance $r_E = 1/g_m$
  - ► BW(Hz) = 6.2 $I_C / C_d$
- Biasing cascode with sub-Poissonian $I_{\text{bias}}$ reduces $r_E$ --improves BW
  - ► Noise now limited by $R_{b'}$ and shot noise of $I_b$
  - ► Noise multiplication much reduced compared to TIA





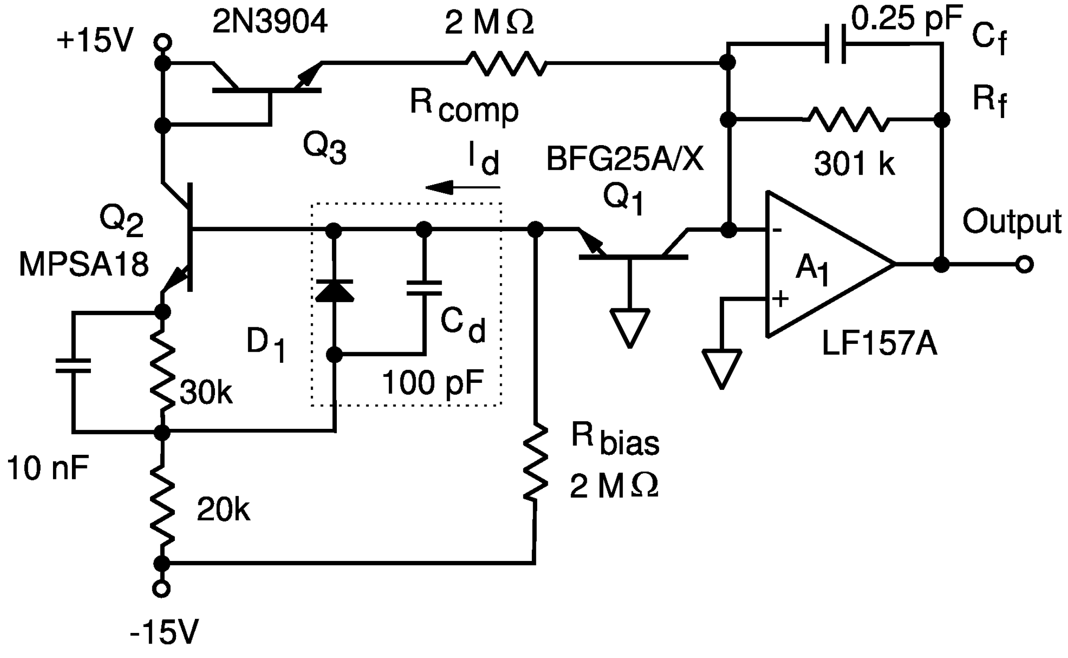
# Bootstrapping

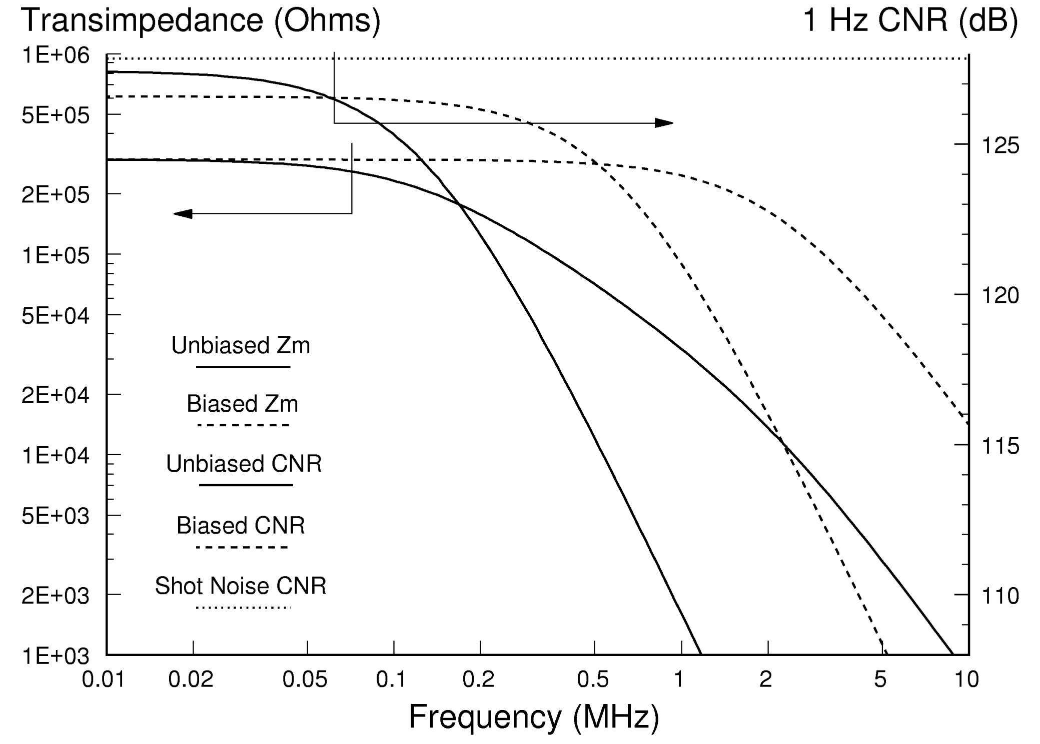
- Bootstrap transistor
  - Follower forces cold end of *D*1 to follow hot end
  - No voltage swing ->no capacitive current
- Speed set by $r_E C_d$ not $R_L C_d$
  - 50x faster than RC at $I_{dc}$=300 µA, $R_L$=100 kΩ
- Superbeta transistor
  - β ~ 1000: Very low base current noise
- Noise Voltage
  - 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

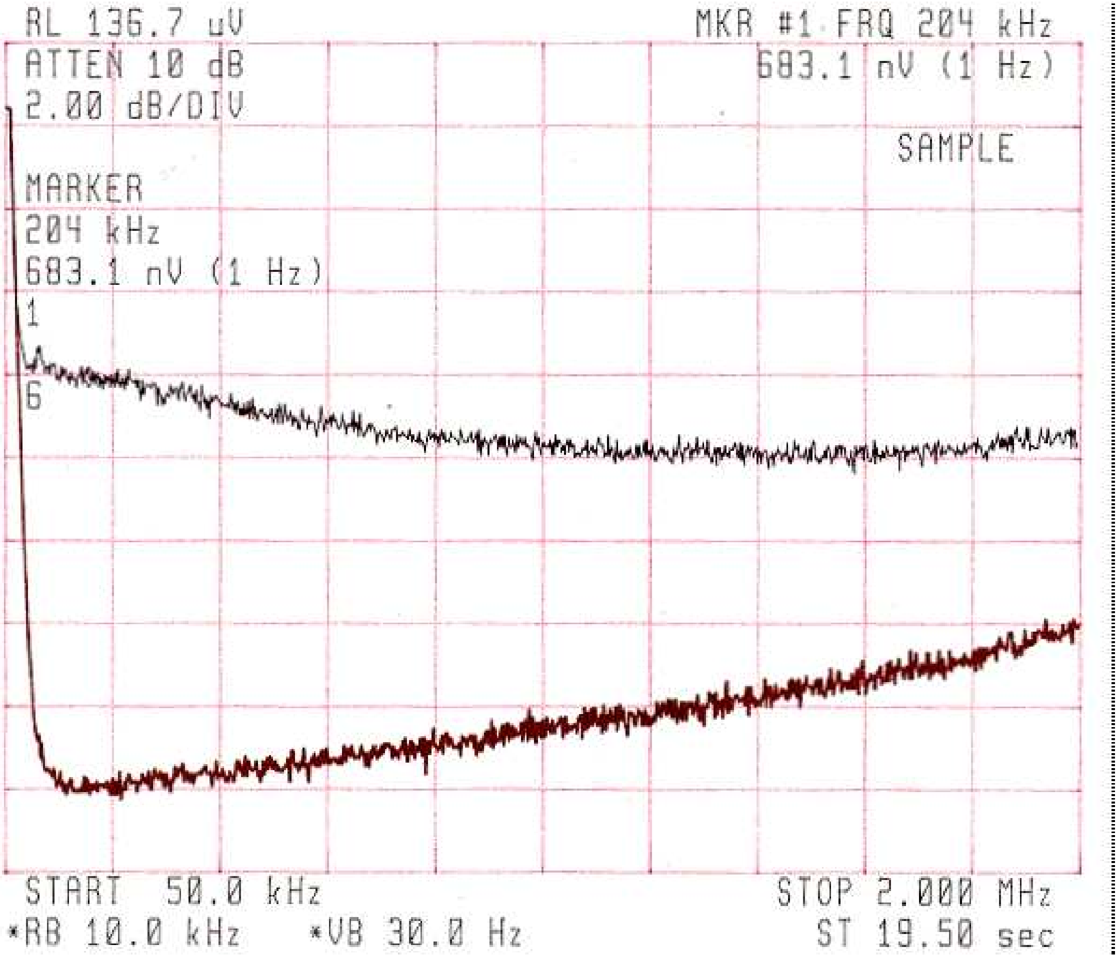
- Can't use enough $Q_1$ bias to get 1 MHz BW without being limited by $I_b$ shot noise and $R_{b'}$ Johnson noise
- Bootstrap runs at higher current: lower voltage noise
- Reduces effective $C_d$
  - ►Superbeta transistor $Q_2$ has much lower base current shot noise, so can run at higher current than $Q_1$ 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 ($p_N \sim P_{\mathrm{opt}}^2$)
  - 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

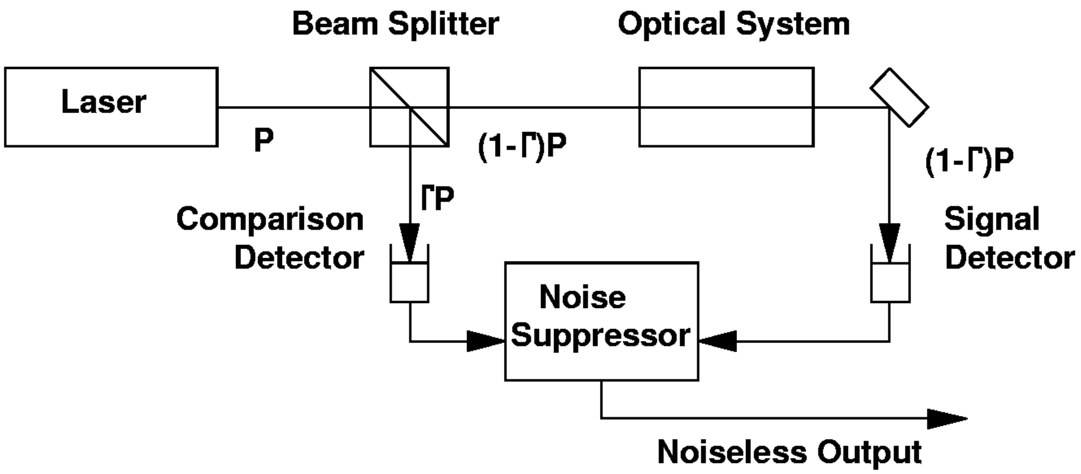
# Shot Noise

## *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

# Differential Detection Ought To Be Perfect



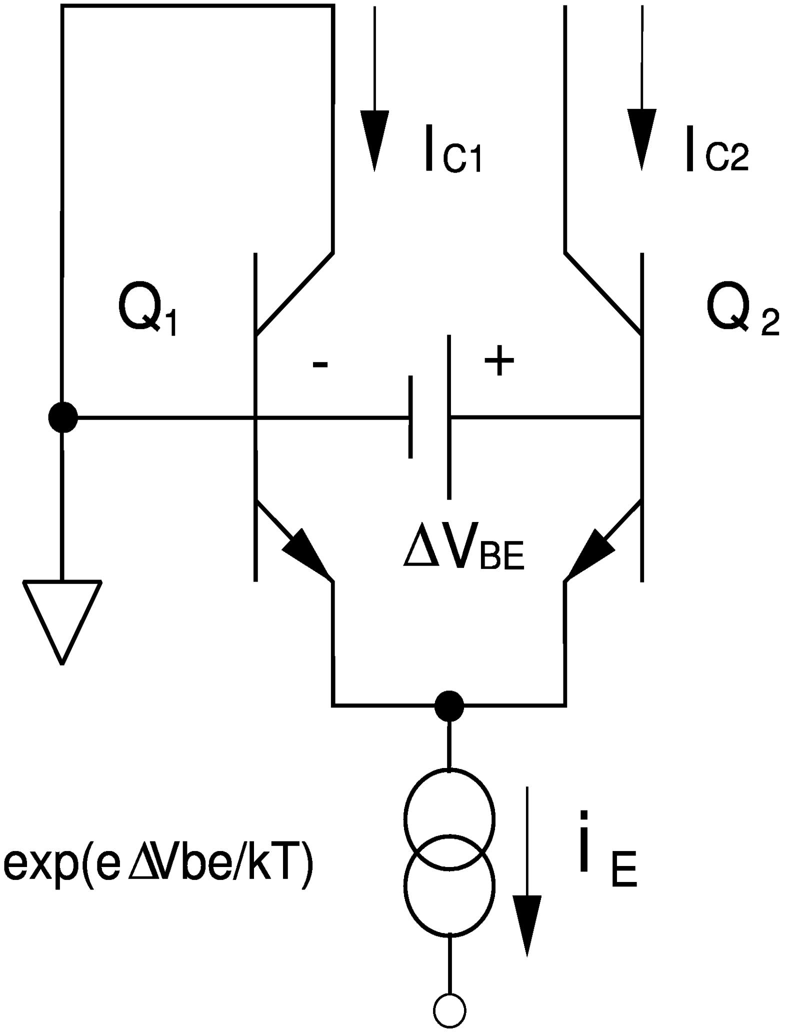
- Apart from shot noise, $I_{sig}$ and $I_{comp}$ are perfectly correlated
- Optical systems are extremely linear and wideband
- Photodiodes can also be extremely linear and pretty wideband:

  => $i_{sig}/i_{comp} == I_{sig}/I_{comp}$ (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

# BJT Differential Pair

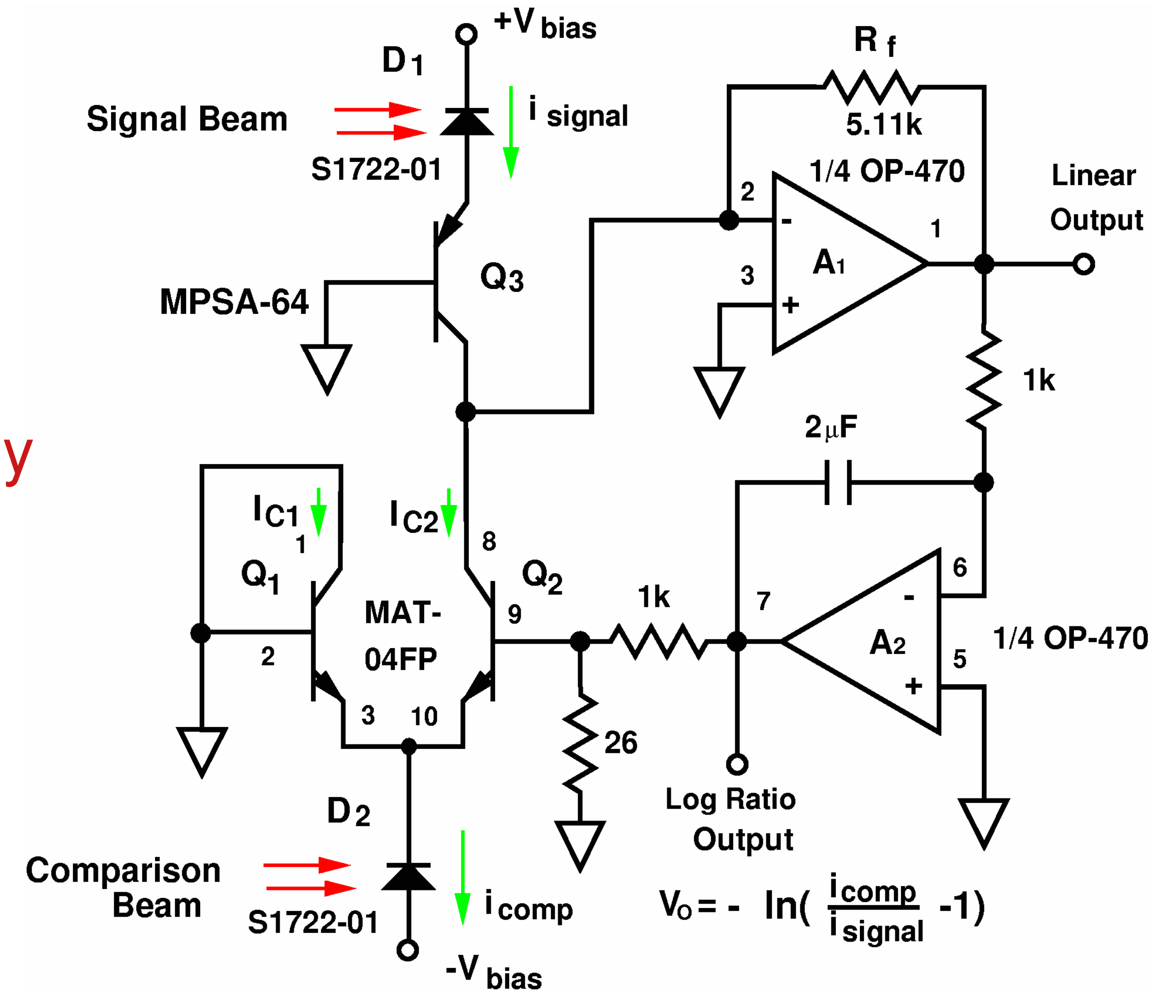
- With fixed $\Delta V_{be}$, the ratio of $I_{C2}/I_{C1}$ is constant over several decades of $I_e$.
- Linear splitting => fluctuations and DC treated alike
- ($Q_1$ is in normal bias as shown--the collector can go 200 mV *below* the base before saturation starts)
- Transistors can be fast
- Adjusting $\Delta V_{be}$ to null out the photocurrent doesn't disturb the subtraction



$$\frac{I_{C2}}{I_{C1}} = \exp(e\,\Delta V_{be}/kT)$$

# Basic Noise Canceller

- Add a diff pair to a current-differencing amplifier
- Use feedback control of $\Delta V_{be}$ to null the DC
  => 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 <==> exp(1)]



# Performance: Cancellation

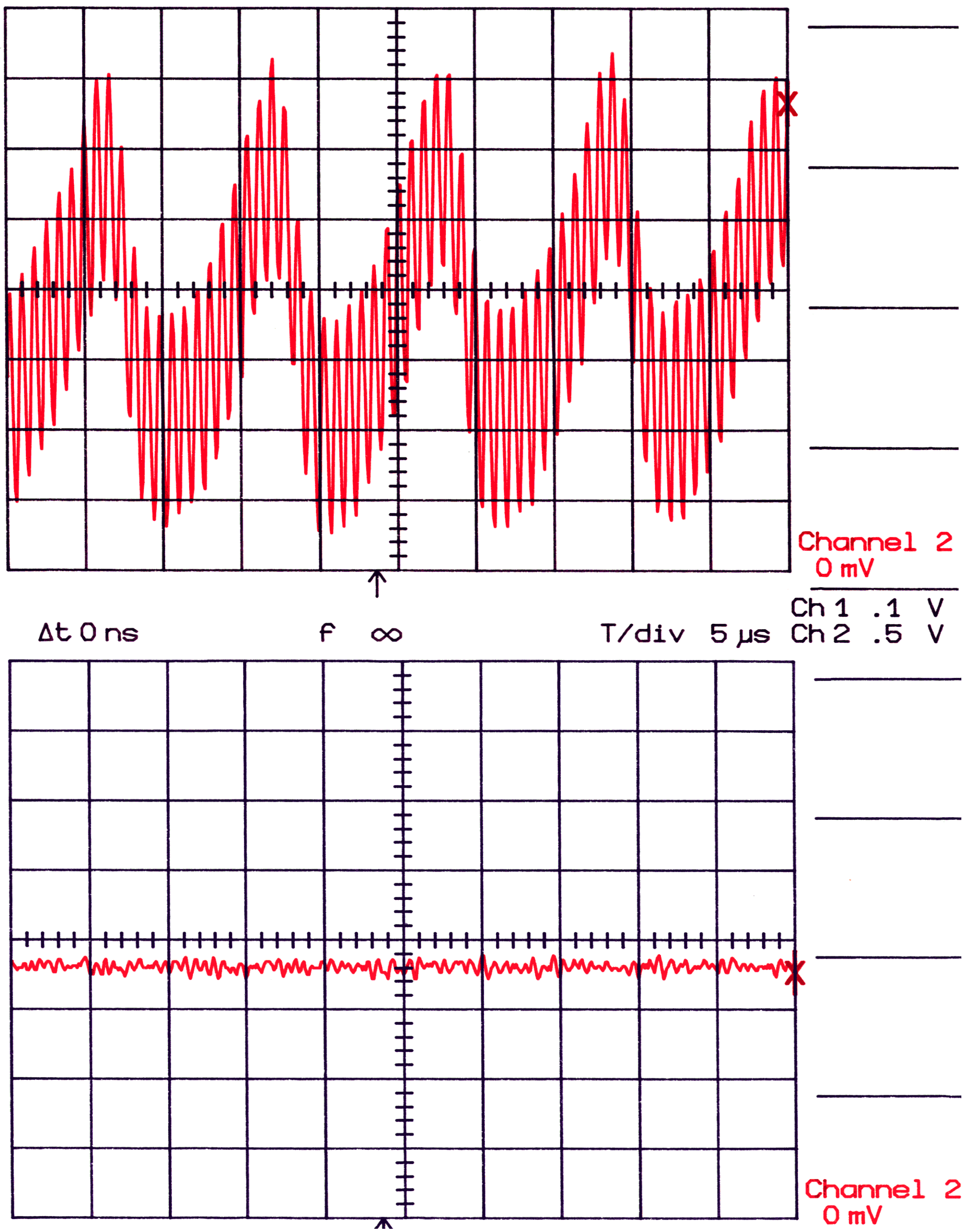
He-Ne showing a strong mode beat (oscilloscope traces)

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)

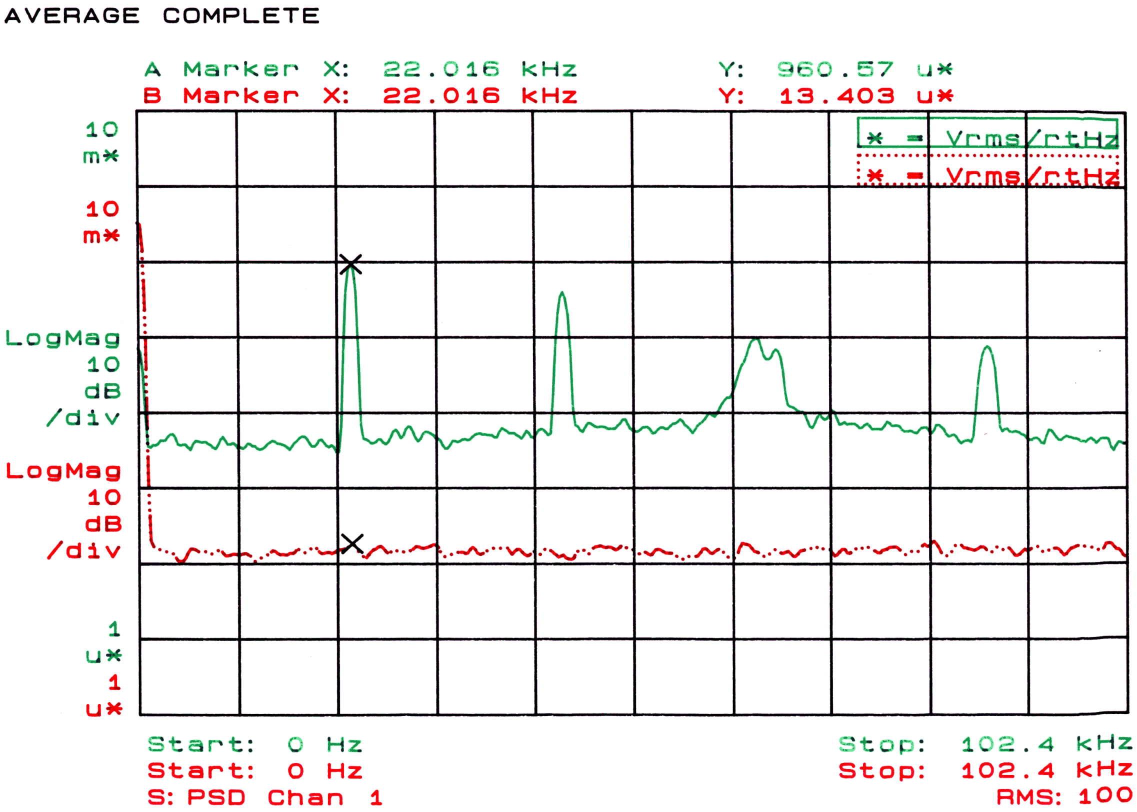
3N3904 discrete BJTs

0.75 mW $P_{sig}$, 1.5 mW $P_{comp}$

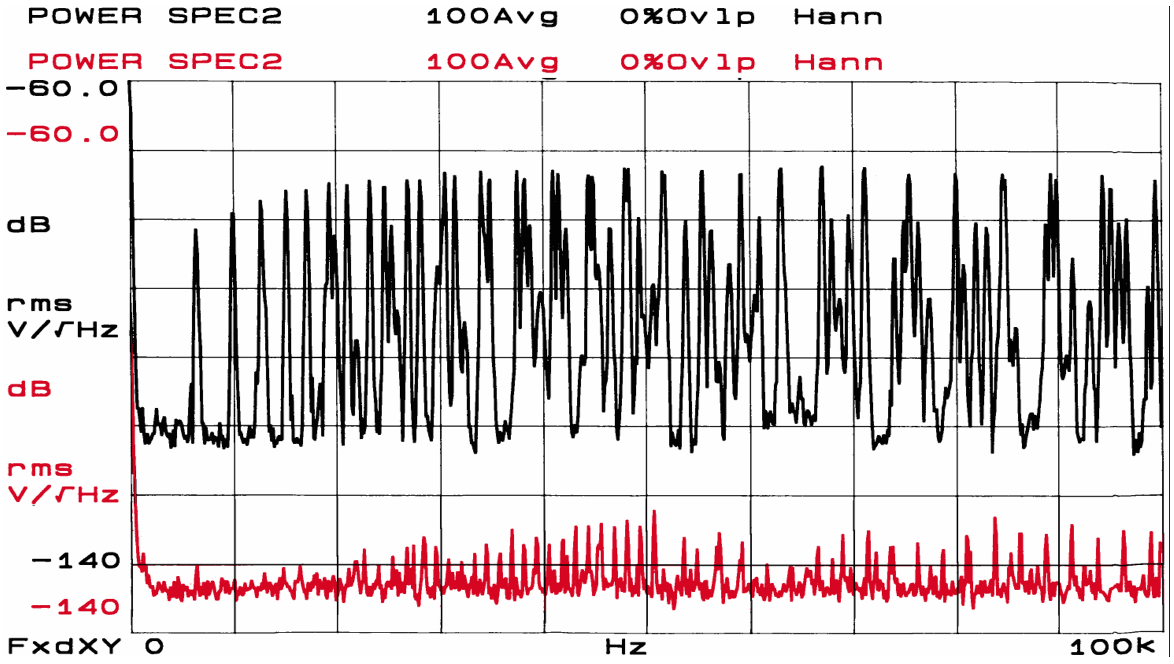


# Performance: Cancellation

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



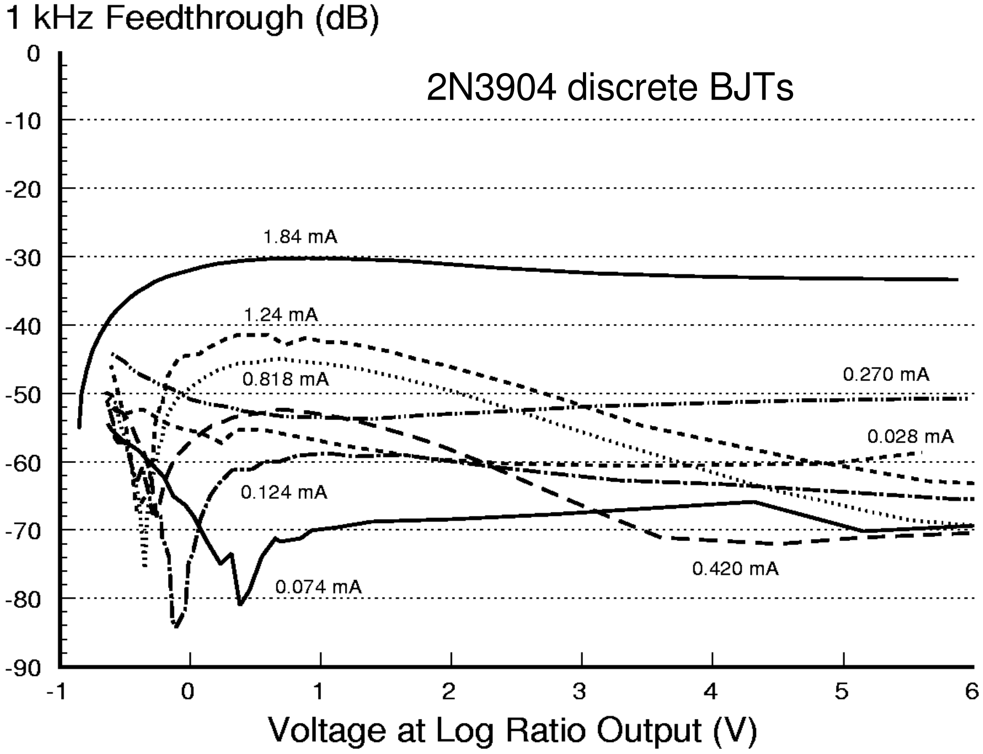
Envelopes of 100 scans, showing mode beats sweeping
Upper: TIA mode
Lower: >50 dB cancellation, even with multiple modes

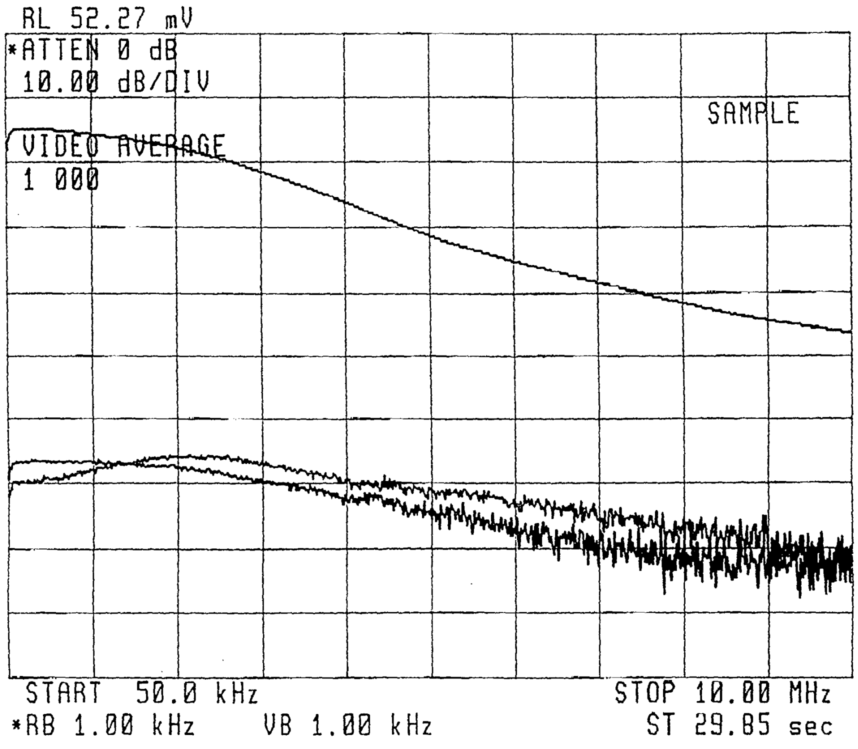


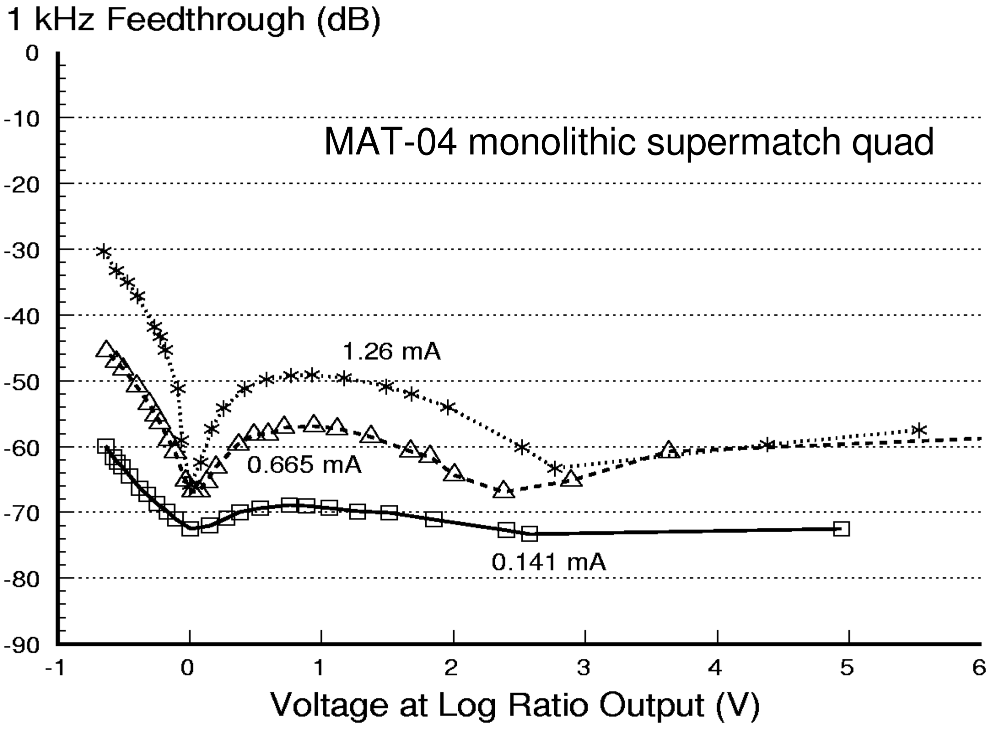
3N3904 discrete BJTs
0.75 mW $P_{sig}$, 1.5 mW $P_{comp}$

# 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

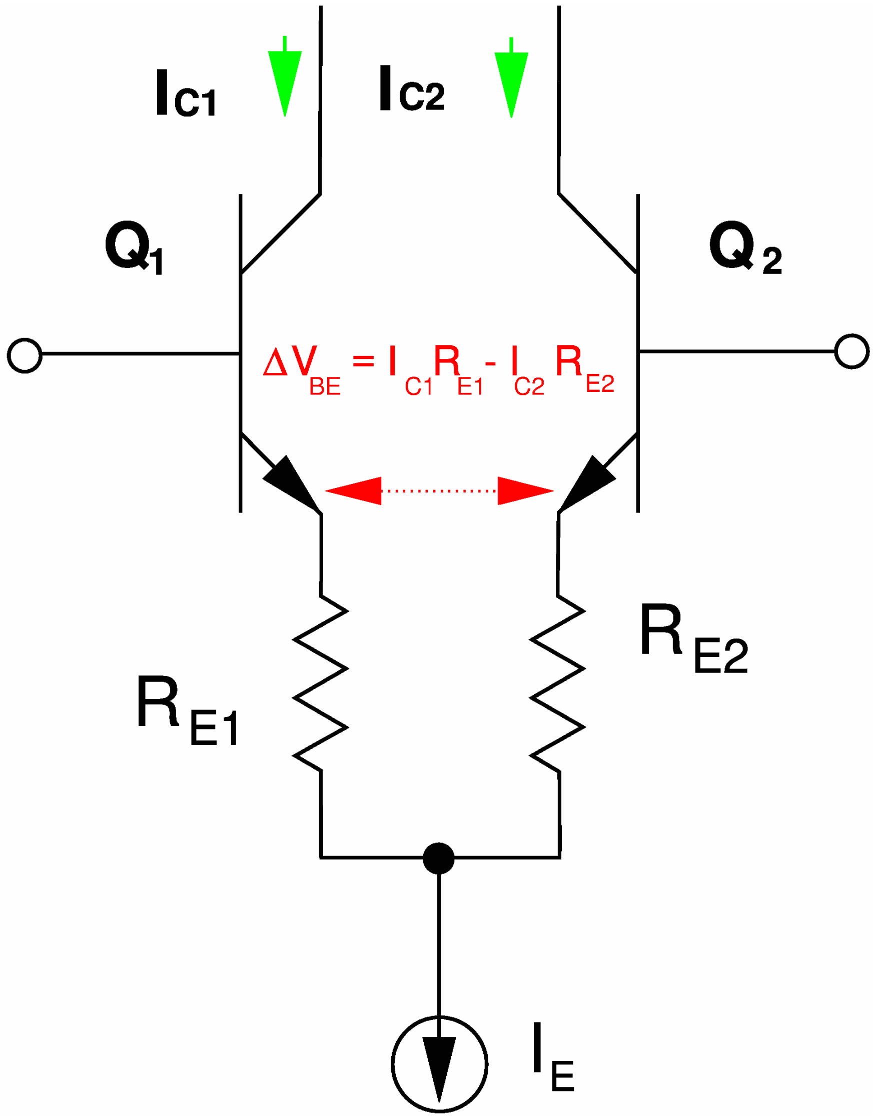




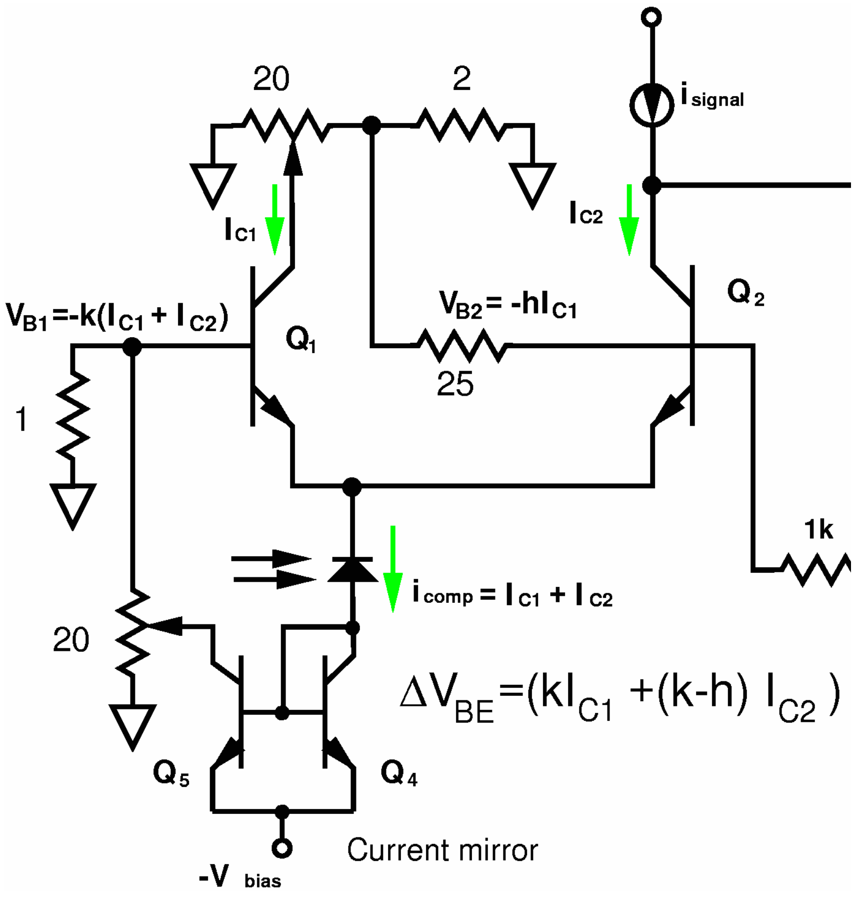


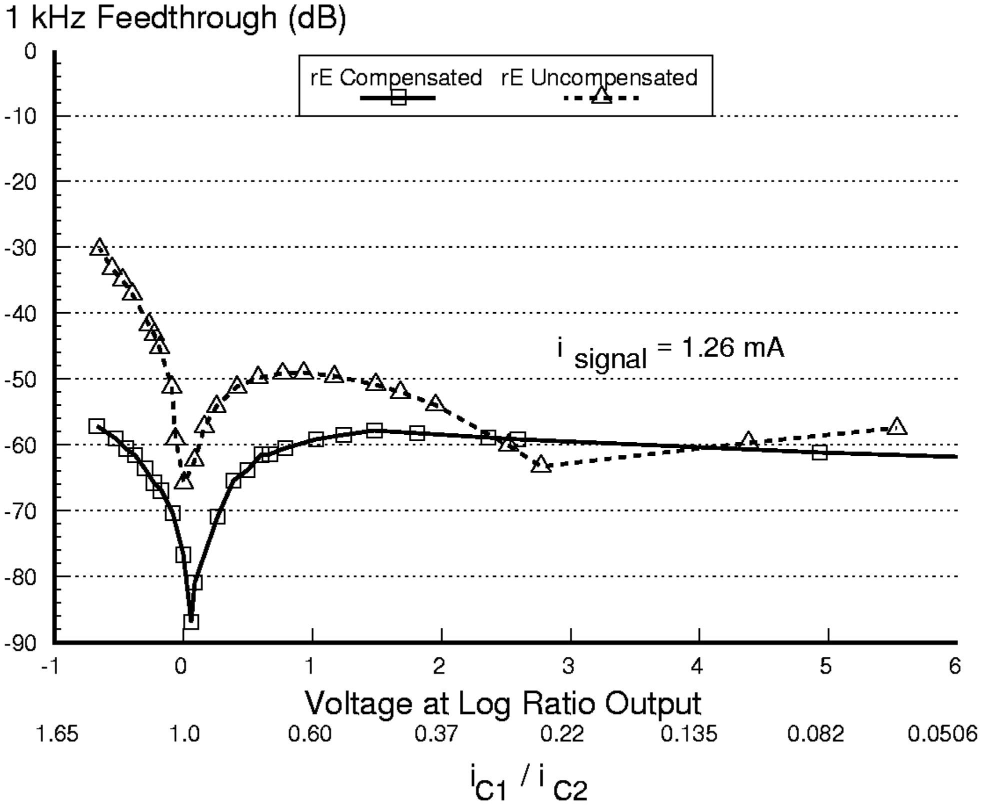
# $R_E$ Degeneration

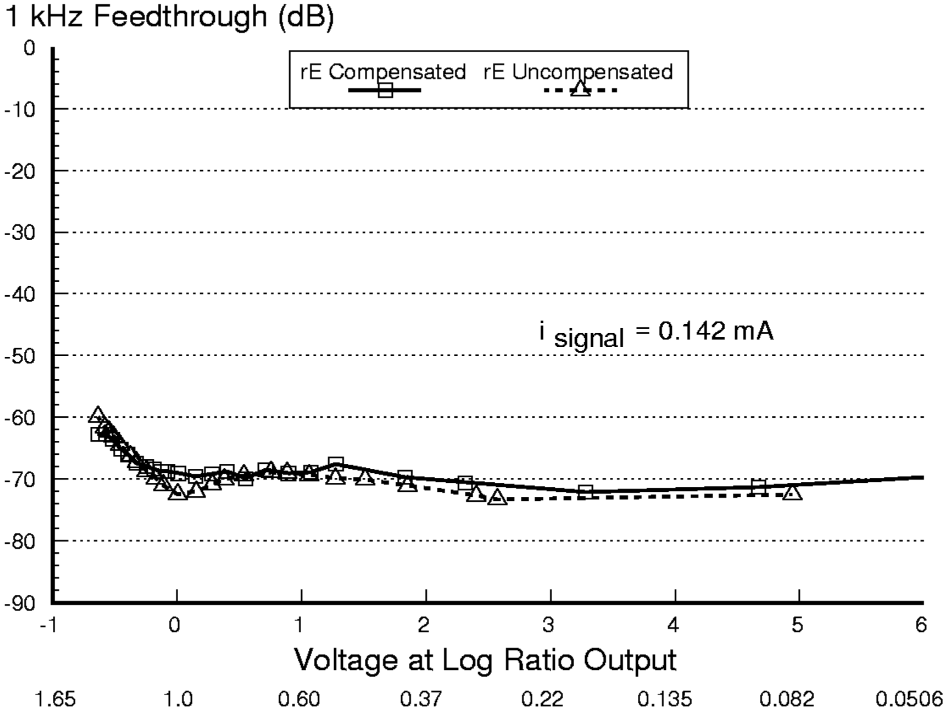
- Discretes run at different *T* => Less cancellation at high $I_c$
  - Use monolithic matching
- Main remaining limit is failure of BJTs to be exponential at high currents
  - $R_E$ produces negative feedback on emitters, tending to even out the current split
  - Apply positive FB to the bases, keeping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



# RE Compensator



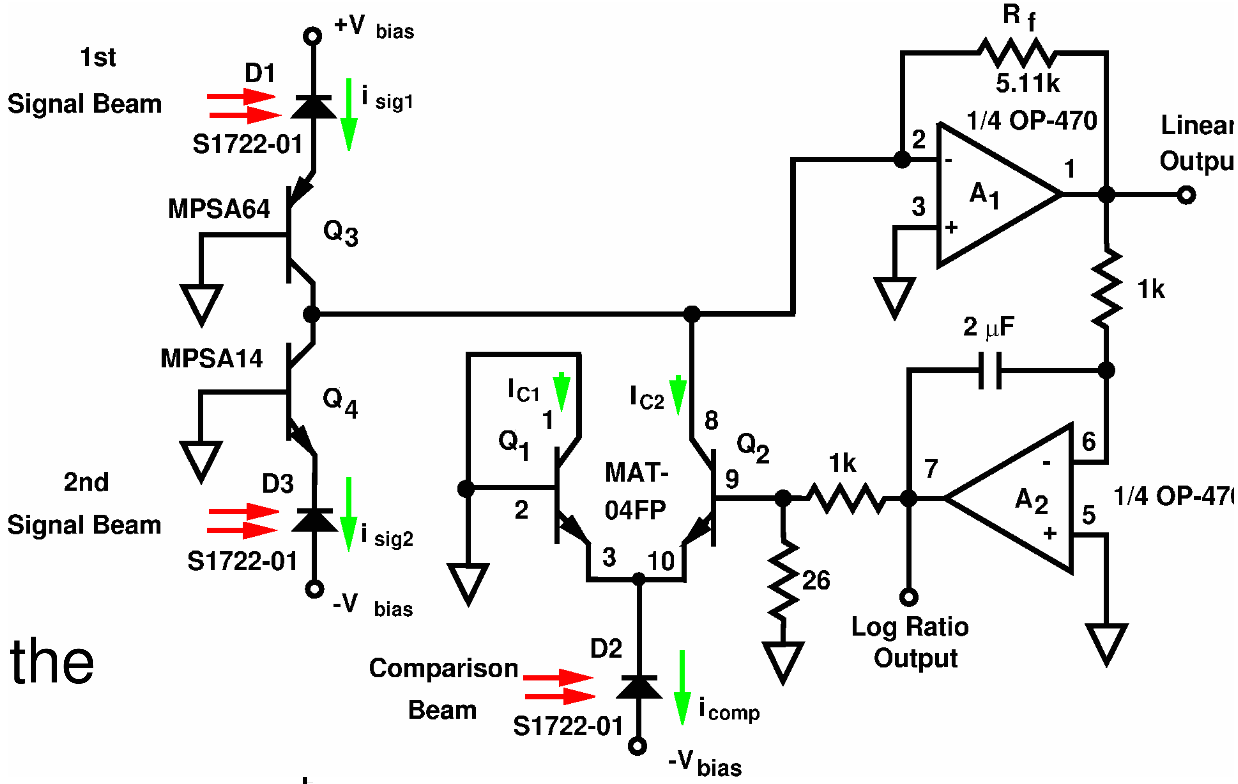


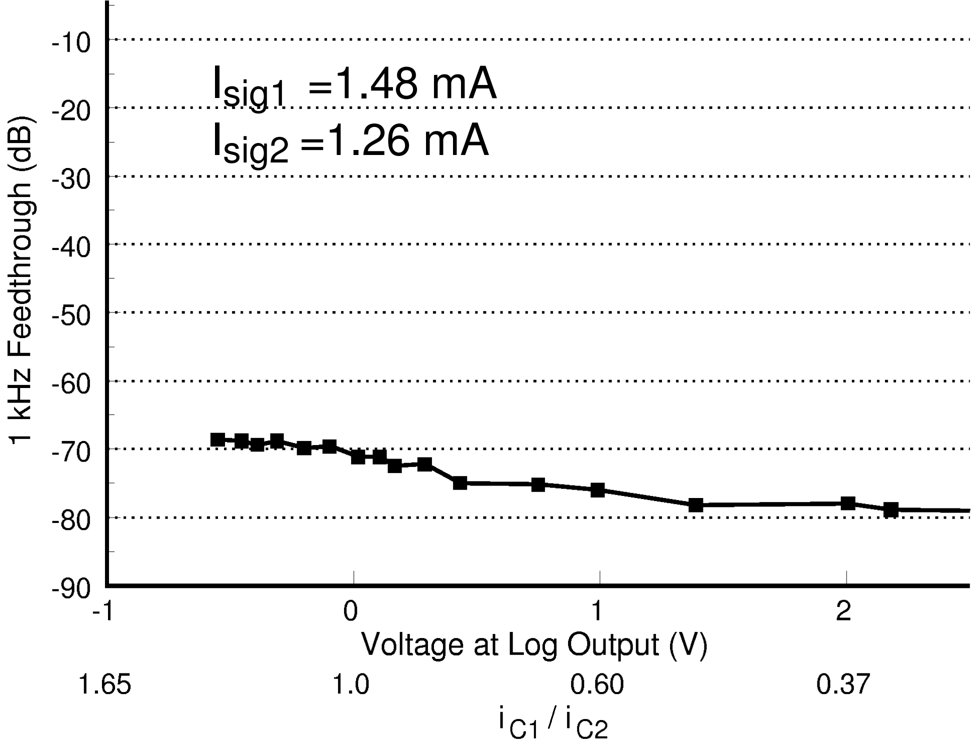


- Requires a current mirror plus a few extra resistors
- Flattens out rejection curve, 10-25 dB improvement

# Differential Version

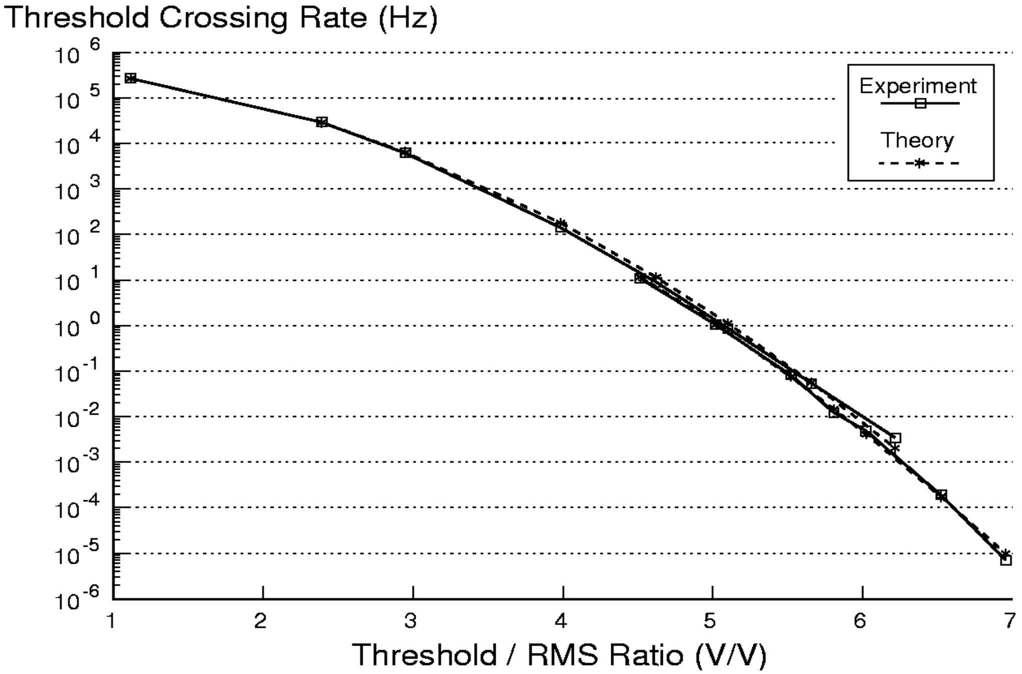
- Add second signal beam
- Run slightly unbalanced $(I_{sig1} > I_{sig2})$
- Differential pair sees only the slight imbalance
  $I_{comp} > (I_{sig1} - I_{sig2}) << I_{sig1}$
- Limitations of BJTs circumvented
- 3 dB noise improvement (both signal beams contain information)
- Using log output requires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

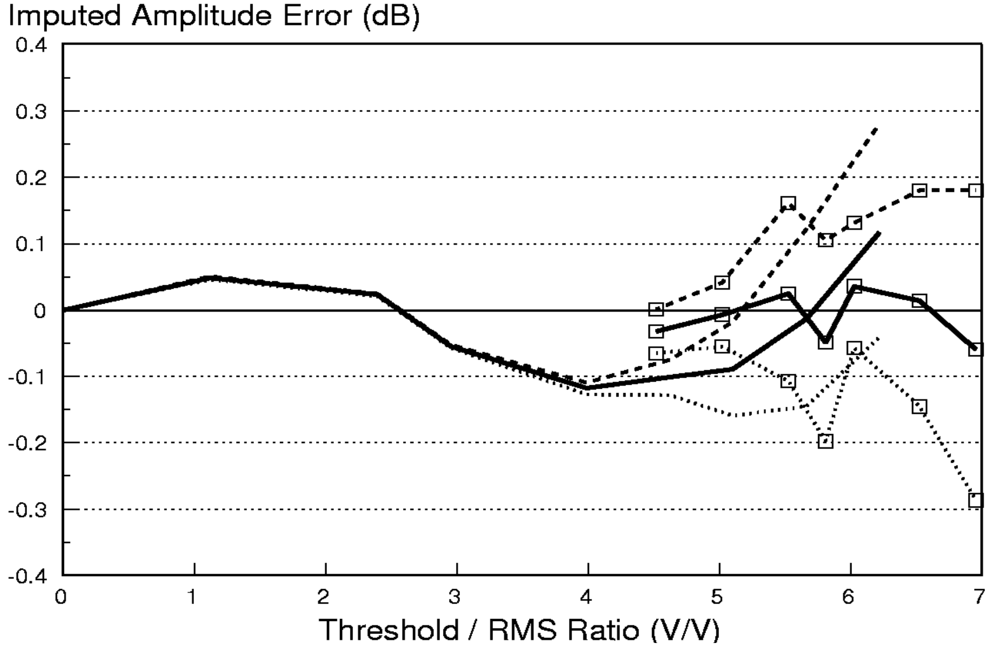




# Shot Noise
# False Alarm Rate

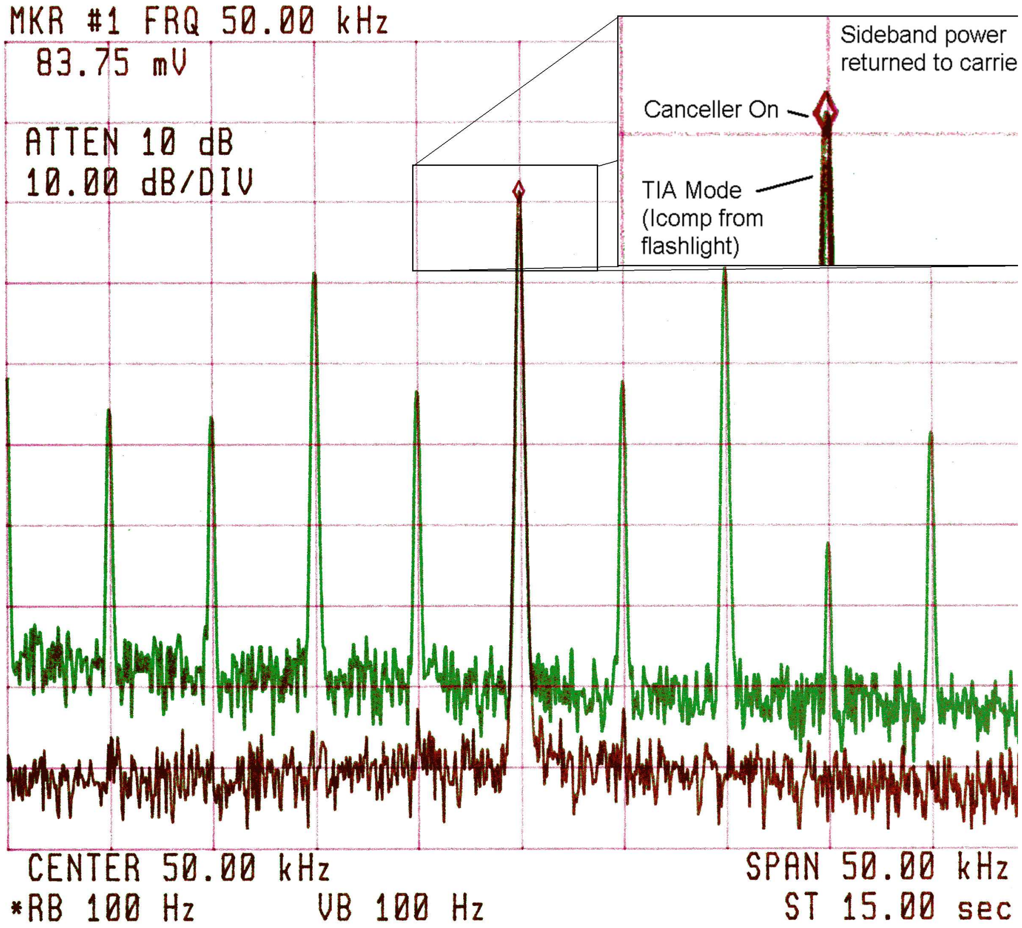
- Differential noise canceller, diode laser, ~0.5 mW/beam
- BW = 1.1 MHz
- Beam scanning around inside a chamber with a sandblasted aluminum back wall (some mode hopping)
- Noise canceller leaves only shot noise
- Very gaussian over >10 orders (300 kHz - 8 μHz)
- Imputed error ~0.1 dB over full range (1-parameter fit to exact noise BW)





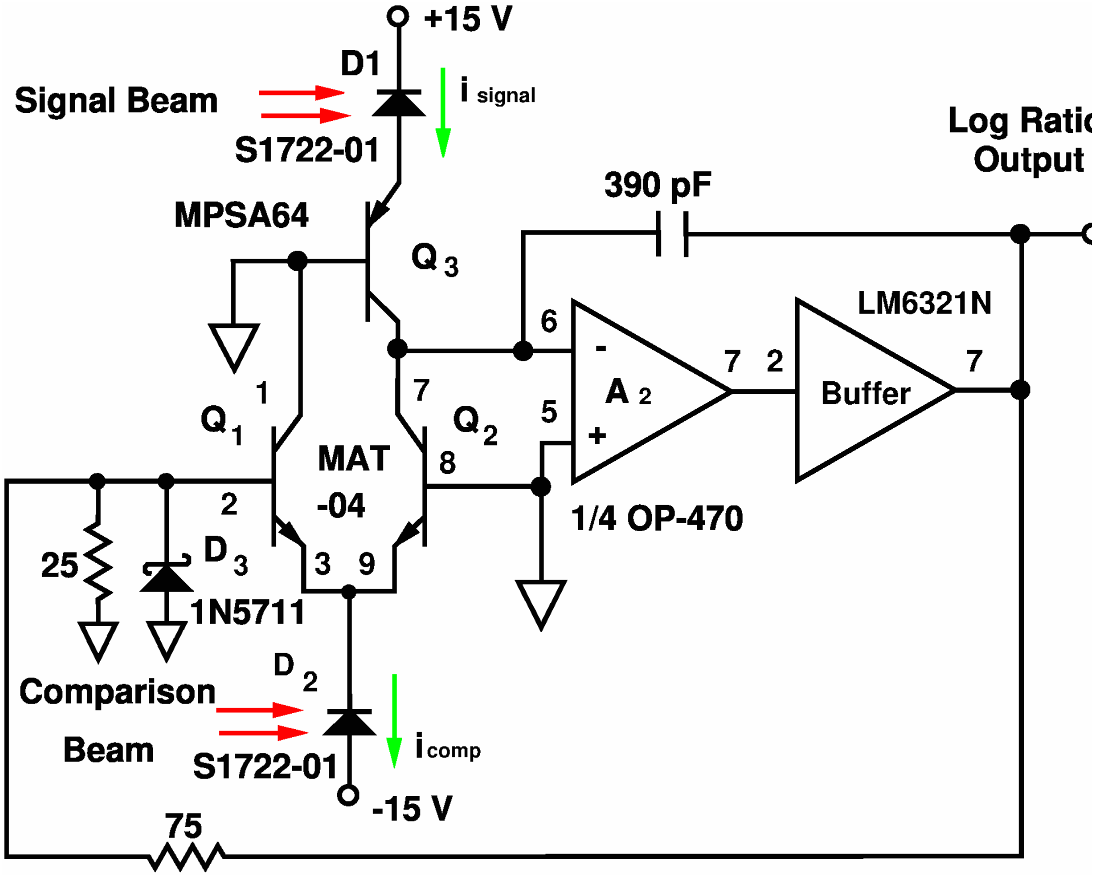
# Multiplicative Noise

- Signal beam: 50 kHz AM
- Comparison beam vs flashlight
- Laser: Distorted 30% AM at 5 kHz
- Noise intermod suppression: >= 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!



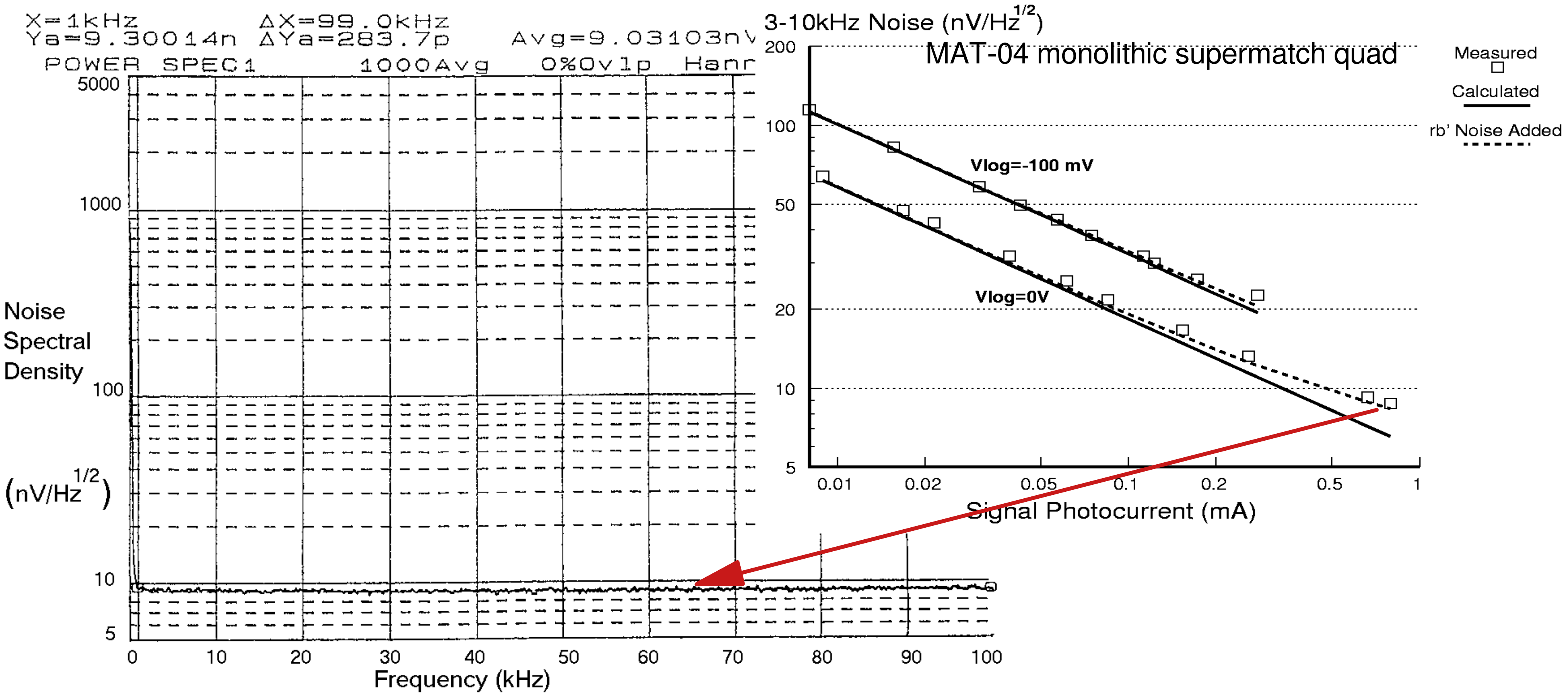
# Log-Ratio Only Version

- 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



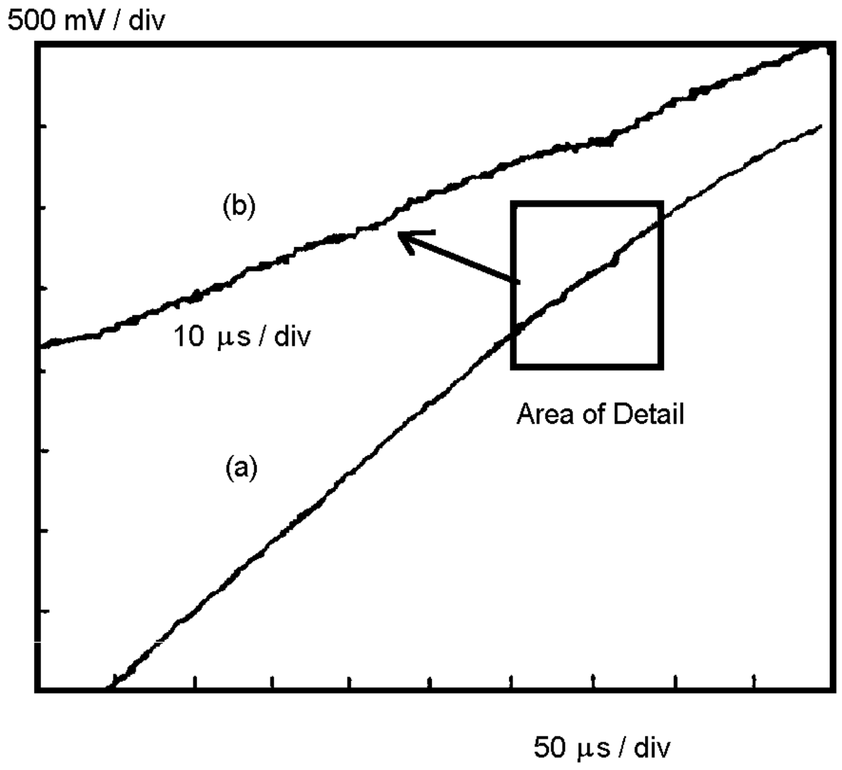
# Performance: Log Noise Floor

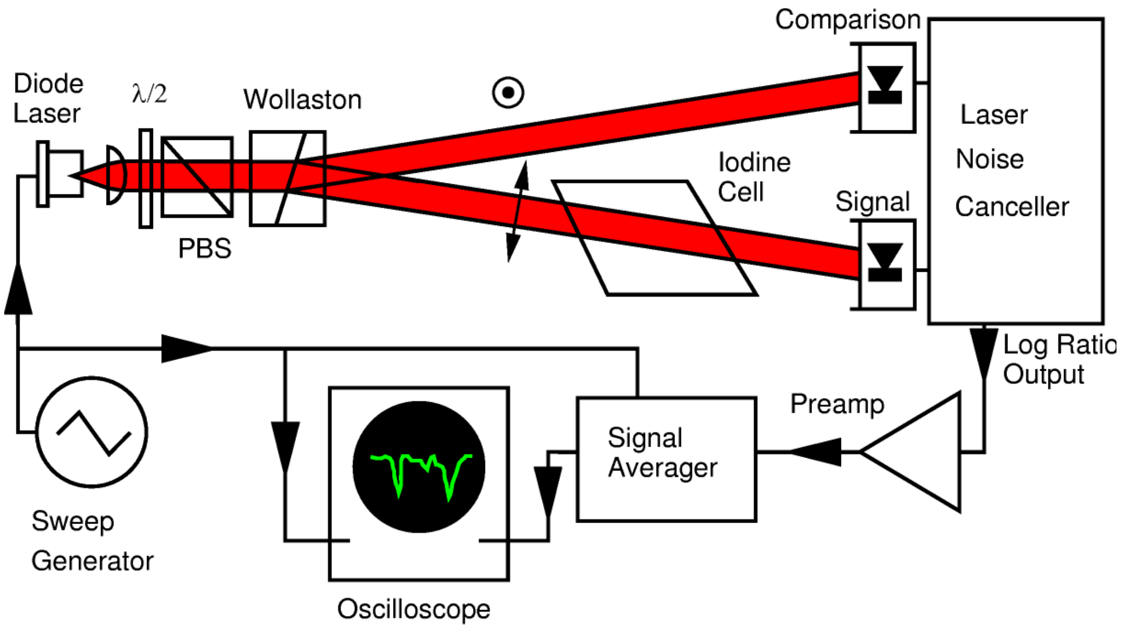
- Shot noise of $I_{sig}$ and $I_{comp}$ add in power => noise floor at least 3 dB above shot noise (but stay tuned)
- Noise floor is very flat and stable, generally within 0.5 dB of SNL except at high currents (and parallelling transistors can improve that)

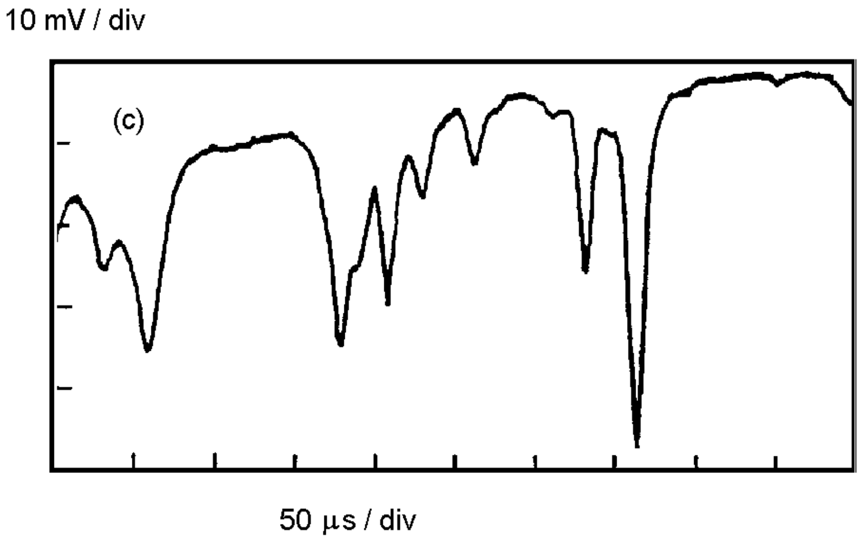


# Log Ratio Spectroscopy

- Sensitivity ~ 1 ppm absorption
- Shot noise limited even with huge $dP/d\omega$ ($\Delta P$~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
      - ~ $10^{-5}$ 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

# Measurement Physics

- 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 $\text{cm}^{-1}$ (fringes really demodulate everything)
  - Be paranoid about fringes
- Spontaneous emission
  - Has different noise than laser light & will split differently

# Measurement Physics

- Coherence fluctuations
  - All optical systems are interferometers

$$I_{dc} \propto \underset{\text{DC}}{\left(|\psi_1|^2 + |\psi_2|^2\right)} + \underset{\text{Interference}}{2\,\mathrm{Re}\left\{\psi_1\,\psi_2^*\right\}}$$

  - 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 ~$\Delta\nu$
  - 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

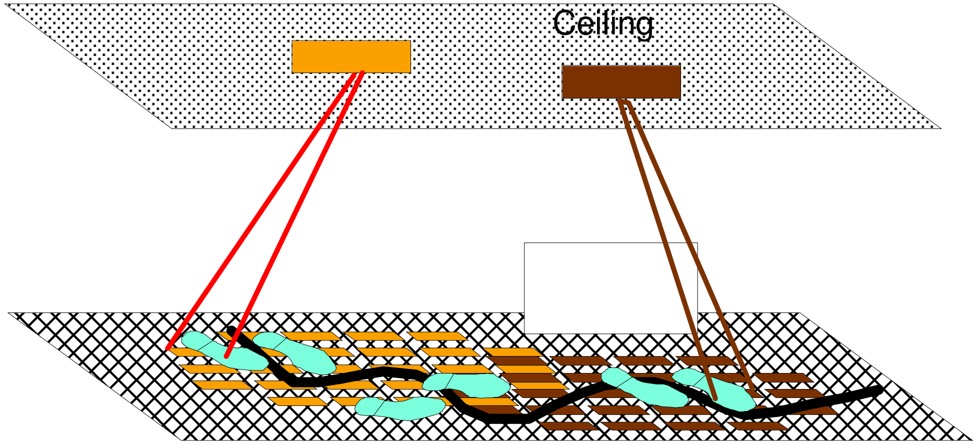
- It isn't just about detectors

- 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

# Footprints: Concept

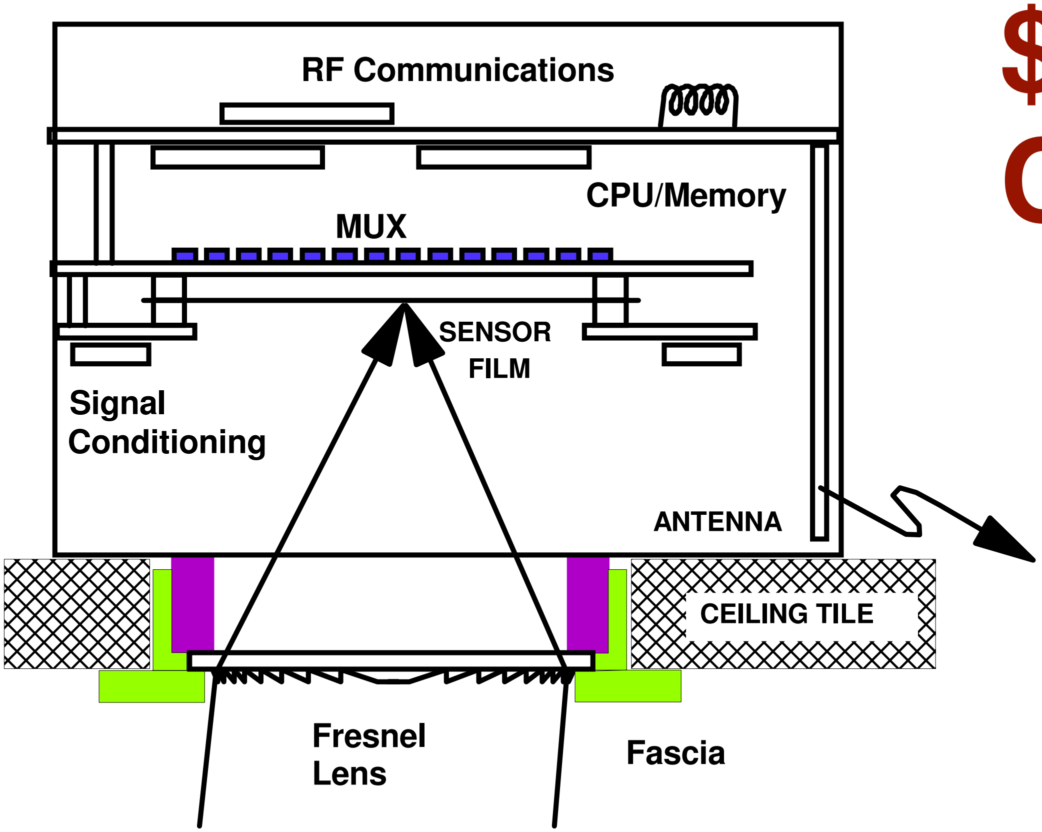


What Are My Customers Really Doing?

- 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

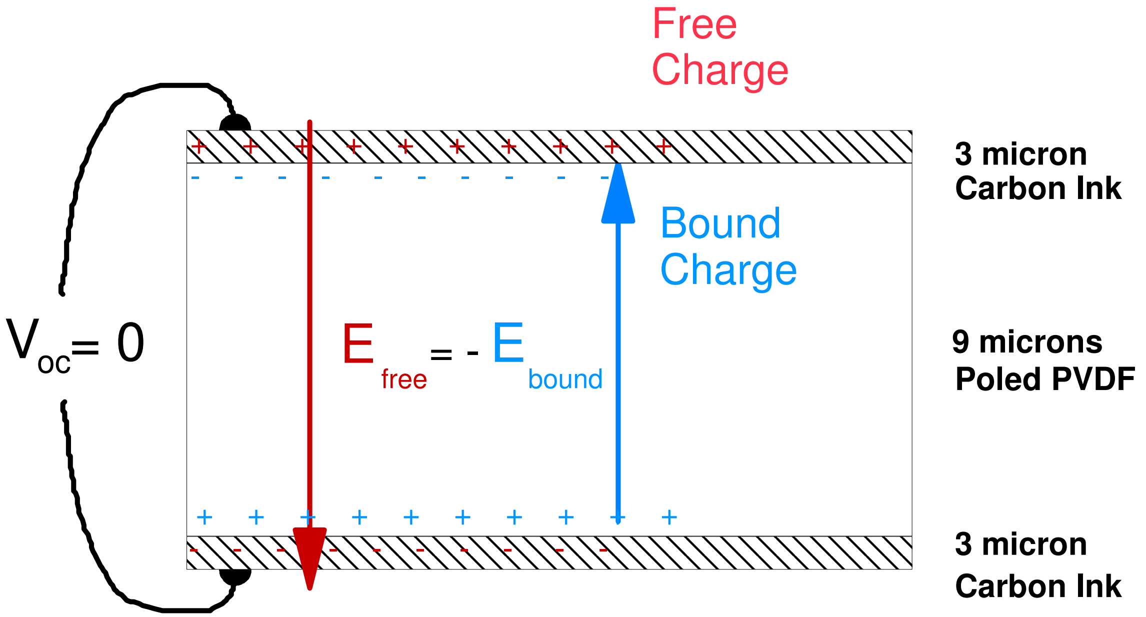


## Array of Distributed Pyroelectric Sensors

- Sensors Mounted In Ceiling

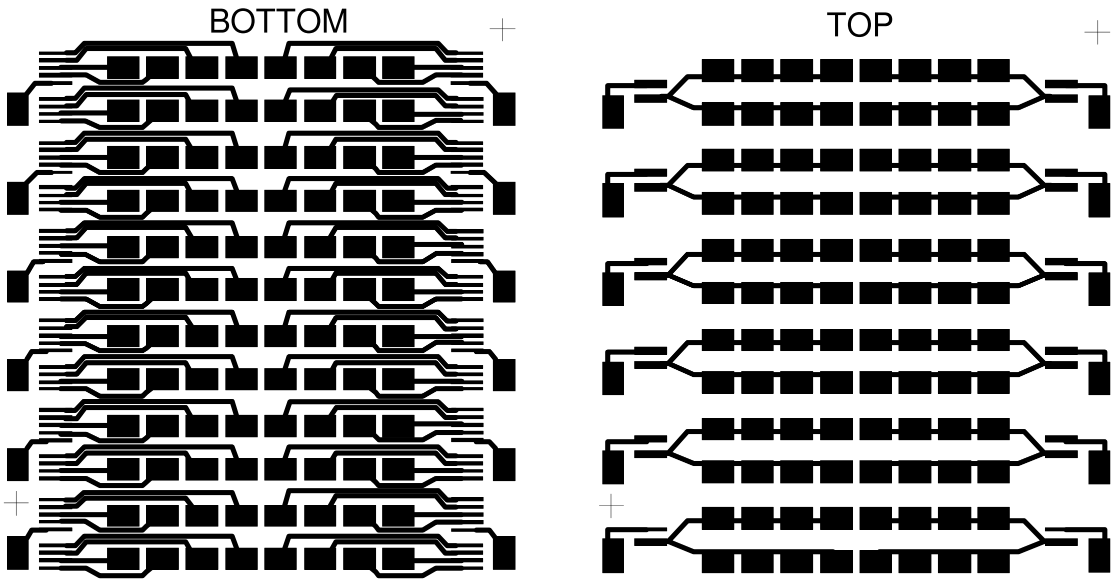
  ~ 100 pixels/sensor
- 100-1000 Sensors Per Store (100-200 sq ft each)
- Base Manufacturing Cost: $50-100

# Pyroelectric Effect



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

# Multiplexed Pyroelectric Array



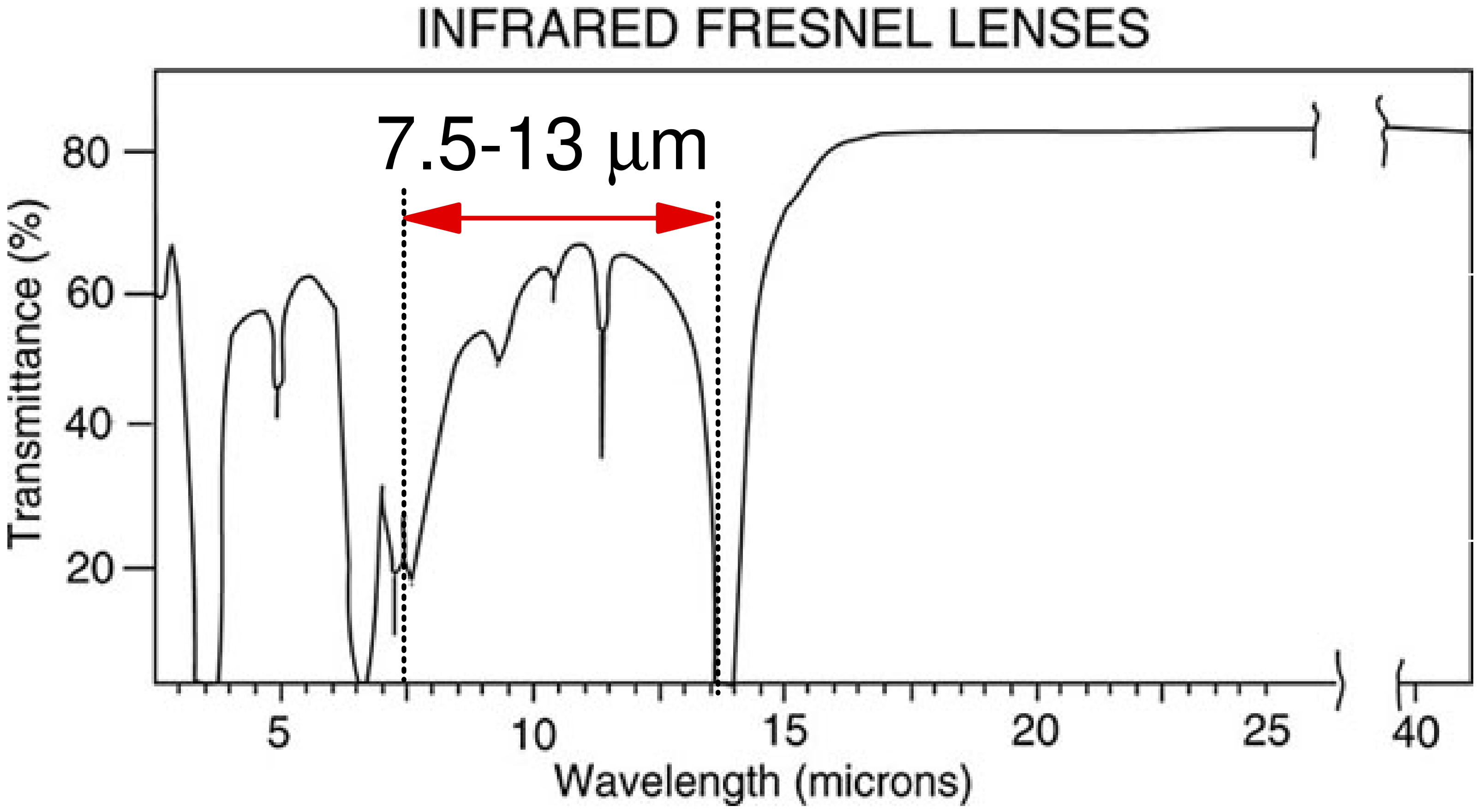
Footprints IR Sensor Photomask Rev C:  POSITIVE TONE
Phil Hobbs, June 25, 1999

## 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

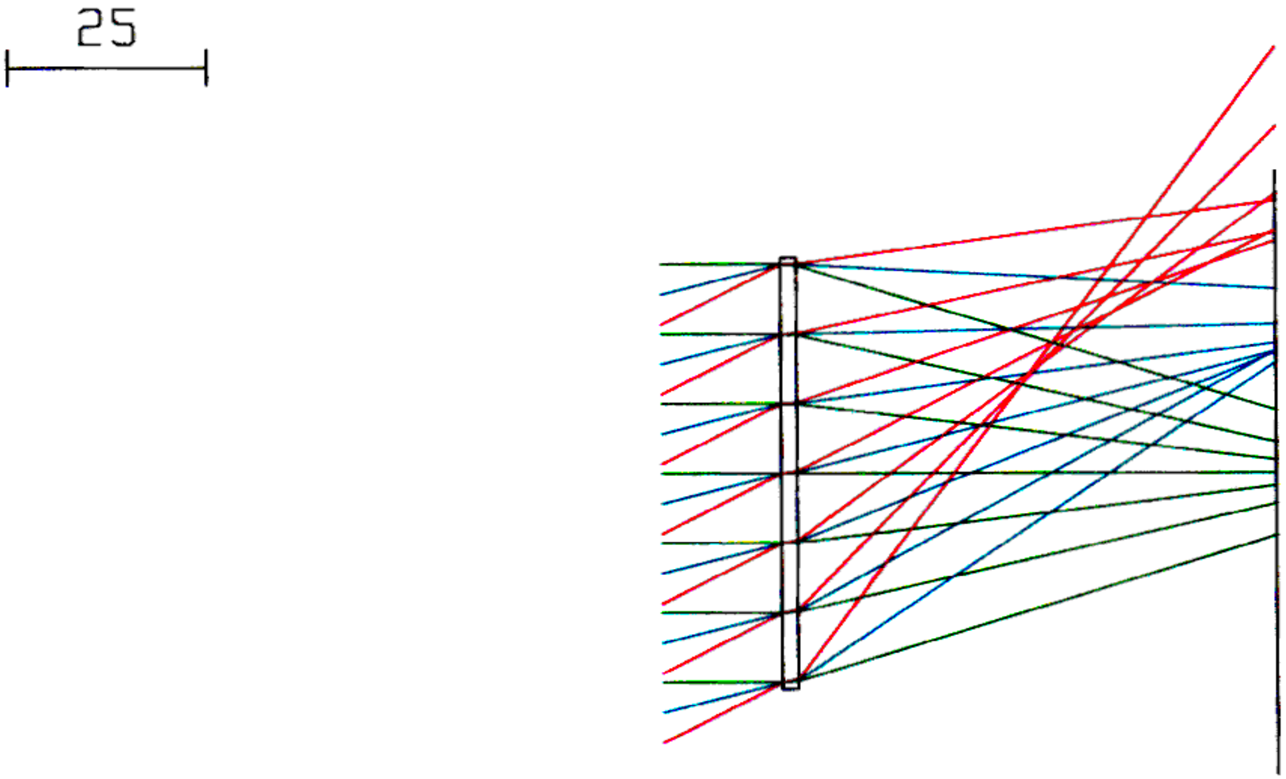
# Optical Design

## Moulded Polyethylene Fresnel Lenses



IRstart1
OPTICAL SYSTEM LAYOUT

UNITS: MM
DES: Budd

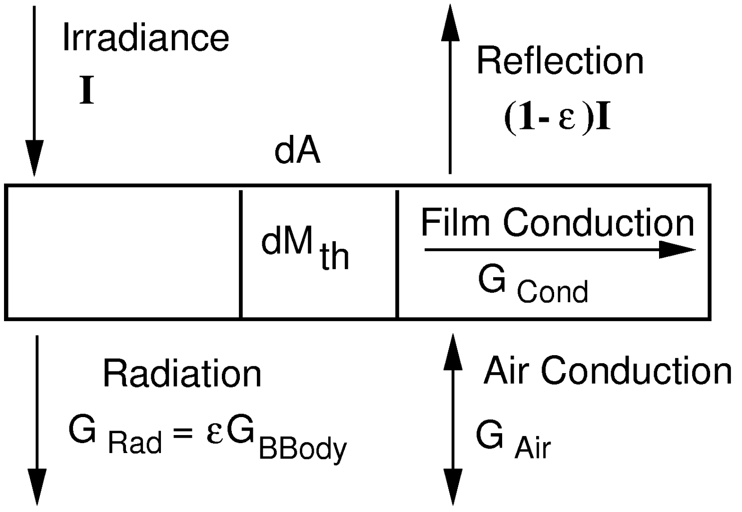


# Thermal Design

Slow is Beautiful

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

=> Insulate the Sensor & Filter Data To Recover BW



Irradiance $\mathbf{I}$

Reflection $(1-\varepsilon)\mathbf{I}$

dA

$dM_{th}$

Film Conduction $G_{Cond}$

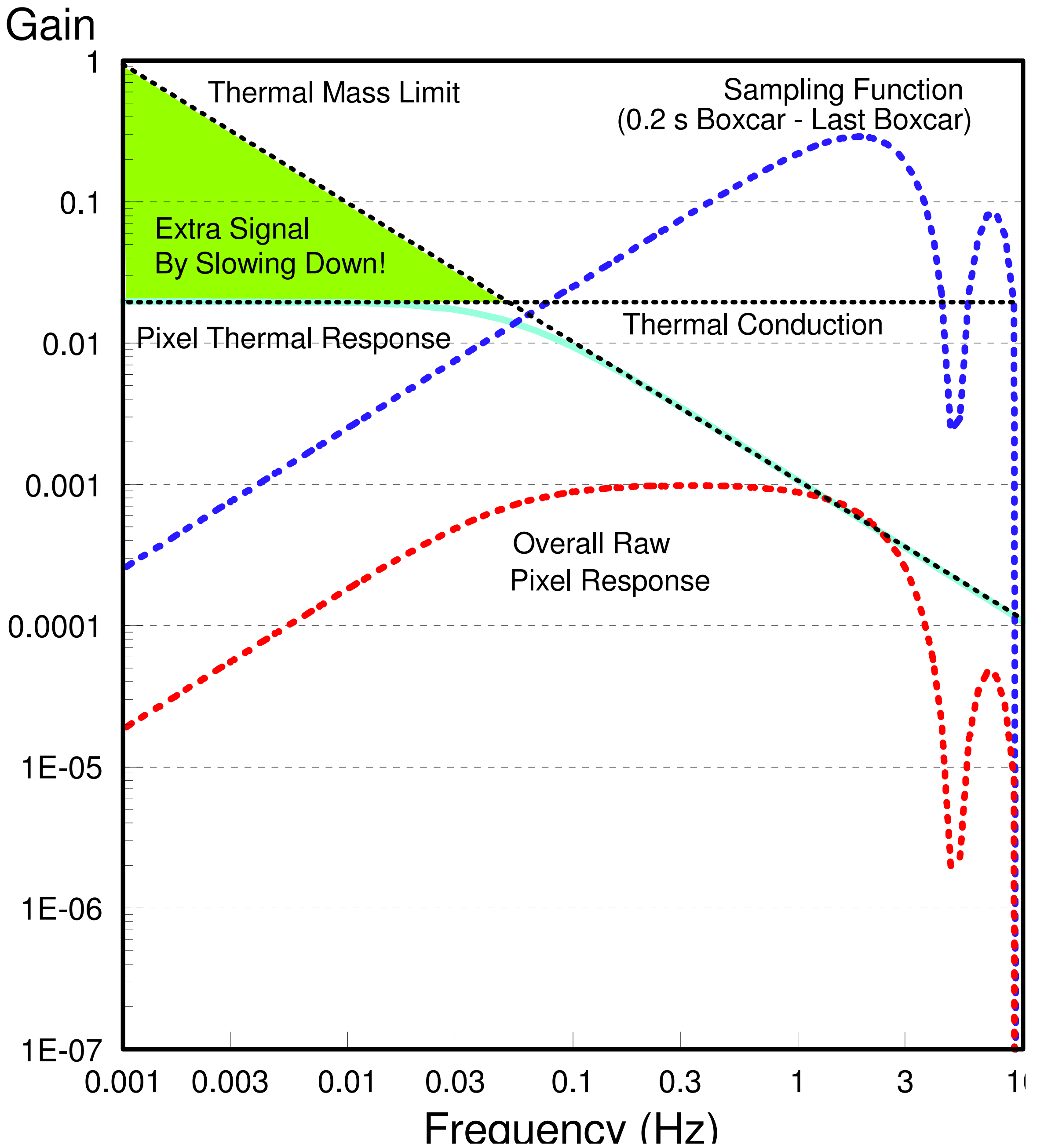
Radiation $G_{Rad} = \varepsilon G_{BBody}$

Air Conduction $G_{Air}$

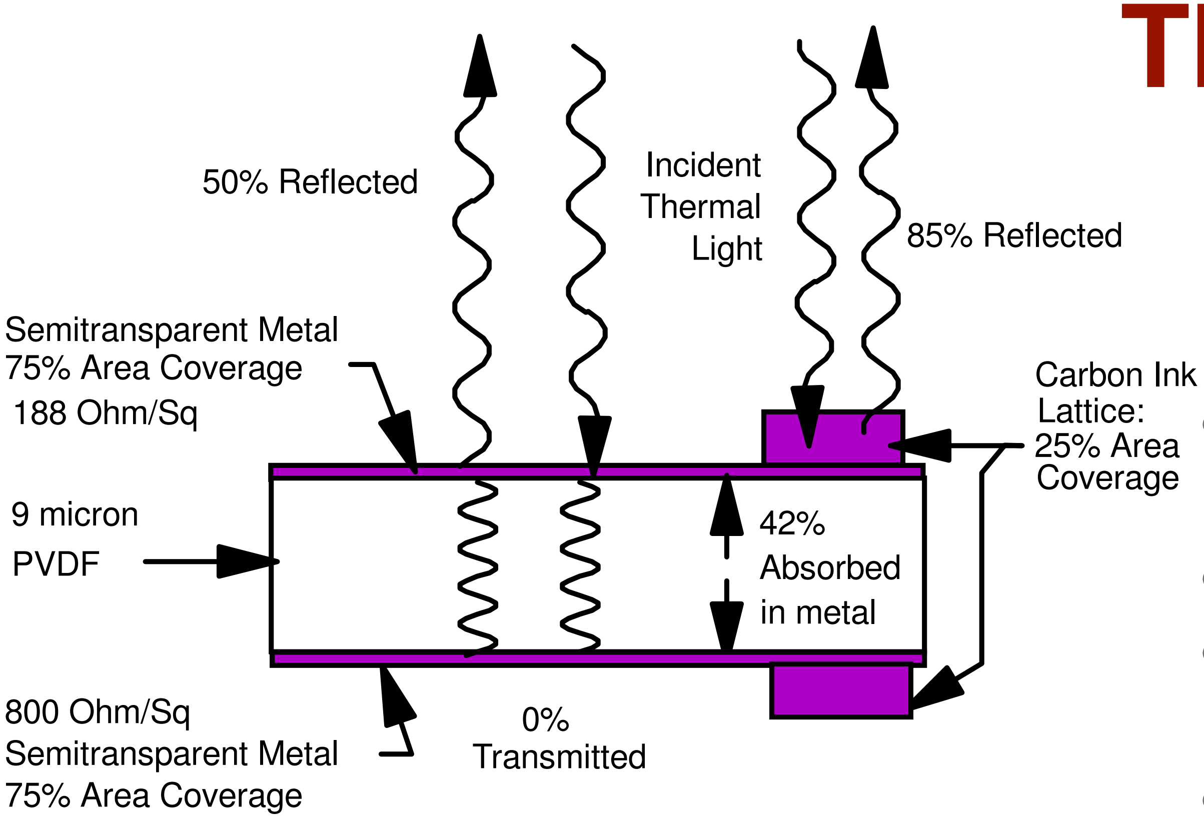
$G_{Total} = G_{Rad} + G_{Cond} + G_{Air}$

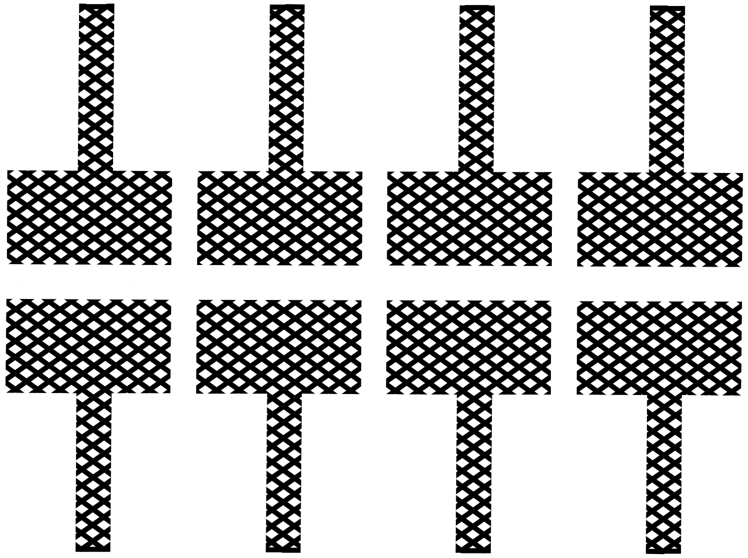
$\Delta \mathbf{T} = \varepsilon \mathbf{I}/\mathbf{G}_{Total}$

$dT/dt = (\varepsilon I - G_{Total}\Delta T)/(dM_{th}/dA)$



# Thermodynamic Efficiency





- Sensitivity proportional to surface emissivity
- Carbon ink is shiny at 10 $\mu$m
- "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

- $\Delta T_{\text{pixel}}$ ~ 8 K (Human Crossing the Floor)
- $\Delta q/\Delta T_{\text{pixel}}$ = (3V/K)(160 pF) ~ 500 pC/K

  BUT: $\Delta T_{\text{pixel}} / \Delta T_{\text{IFOV}}$ ~ 0.002, $\tau$ ~ 2 s (10 Frames)

  Total Signal Available ~ 0.1 pC/pixel/frame

- Multiplexer Leakage <= 5 pA
- Charge Injection < 0.5 pC
- Nothing like it is available commercially

# Diode Switches

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

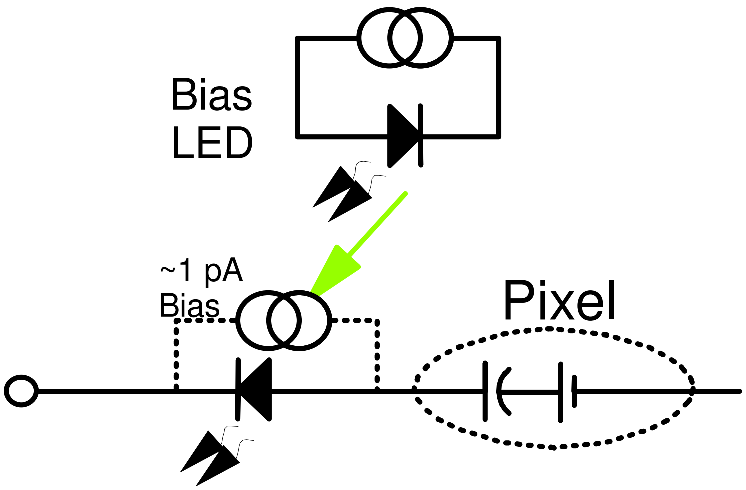
$$I_F = I_S\left(\exp\left(\frac{eV_f}{kT}\right) - 1\right) \qquad R_0 = \left.\frac{\partial V_F}{\partial I_F}\right|_{V_F = 0} = \frac{kT}{eI_S}$$

- 1 mA $I_F$: Si diode ~ 0.65 V, LED ~ 1.6 V

  => $I_S$ for a LED Should Be $10^{-16}$ That of Si
- \$0.05 LED has $|I_F| < 100$ fA, $-5\text{ V} < V_F < +0.5\text{ V}$

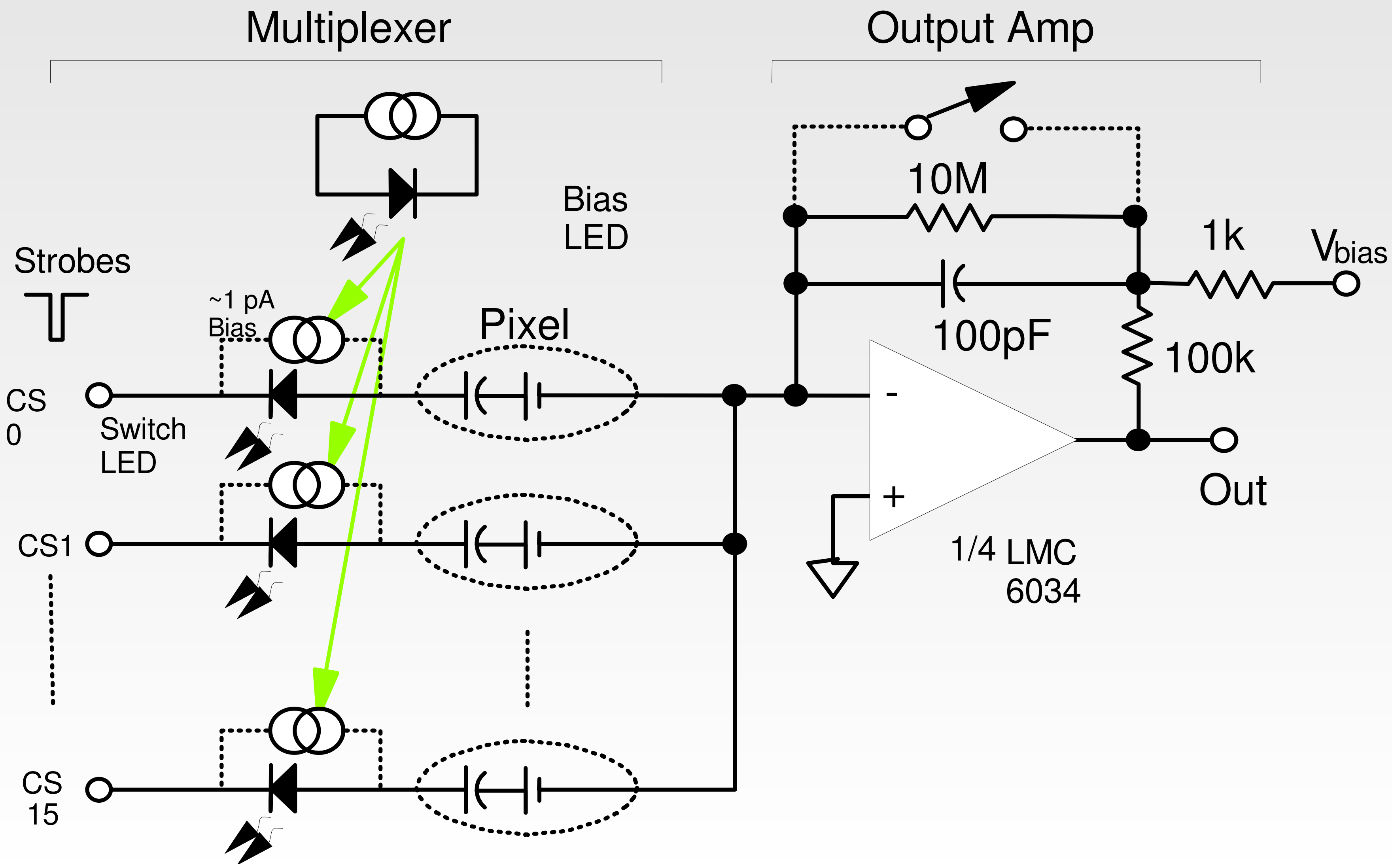
# Biasing Hack

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

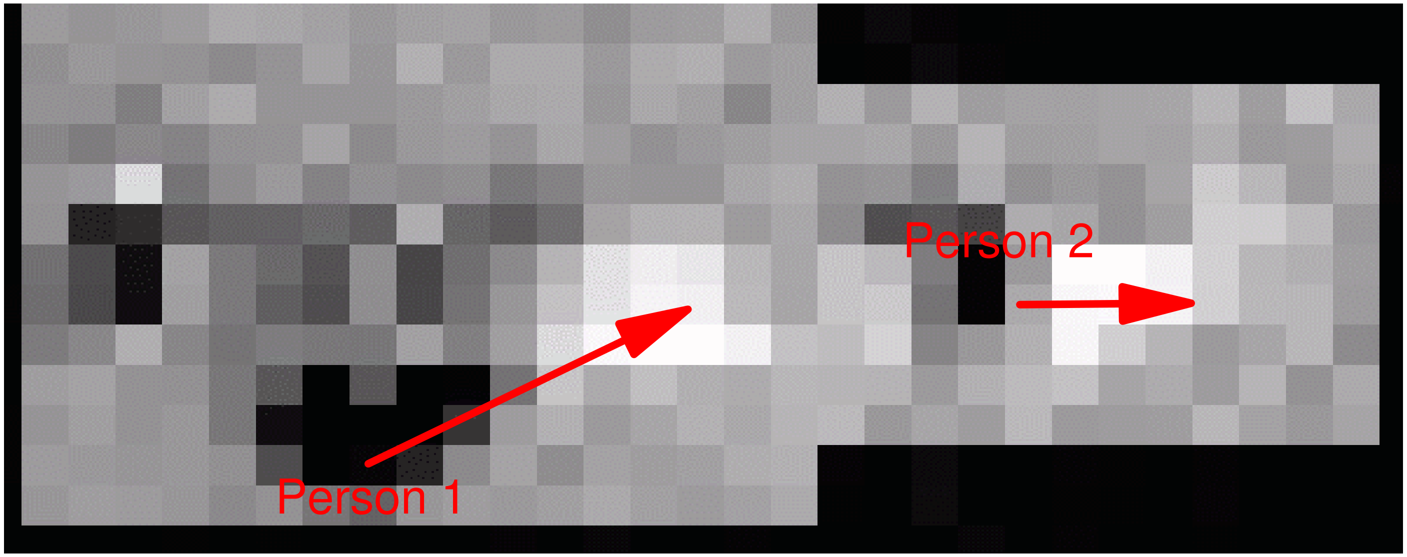


- LED Is a Photodiode Too
- Use Diffused Light From CPU-Throttled LEDS
- 1 mA LED Drive => 1 pA Bias
- Switch + Adjustable Bias = 1 LED @ $0.05/Pixel

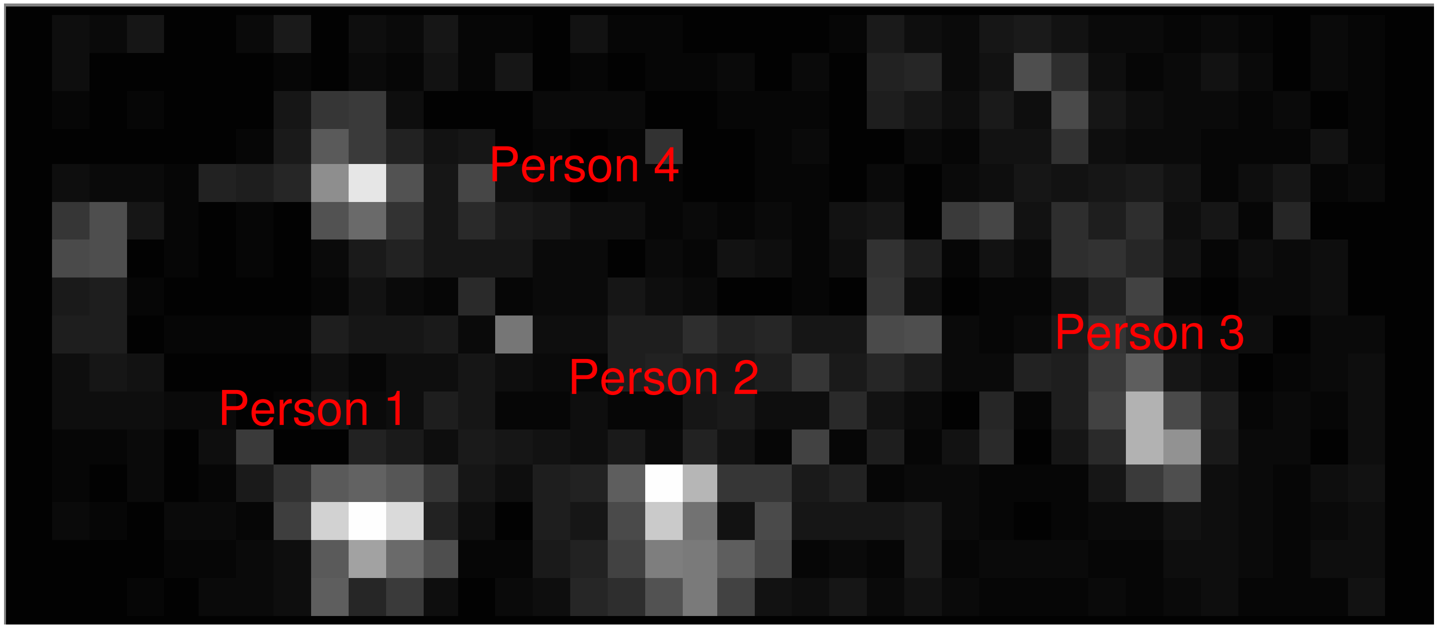
# LED Mux Schematic



# Footprints Data

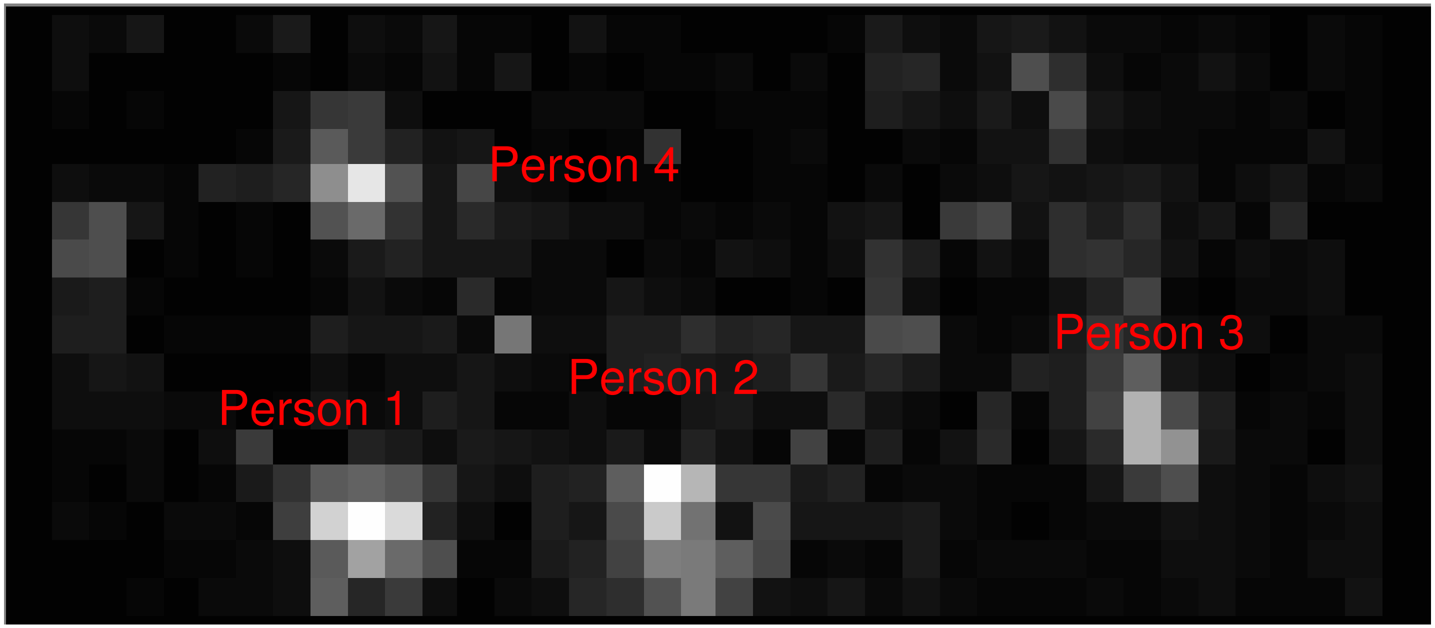


(Raw data,
1 sq ft pixels,
28 μm metallized
PVDF)



(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
  - $T_N = P_N / (kB)$
  - $T_N = 300K(10^{NF/10} - 1)$
  - 3 dB NF = 300K $T_N$, 0.5 dB NF = 35K $T_N$, LT1028 = 15K (@1kHz)
  - $T_N << T_{ambient}$! (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 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 $\lambda < 1.8$ µm!
  - 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 $T_N = T_{\text{amb}} / 2$,
    - ideal BJT base has $T_N = T_{\text{amb}} / (2\beta)$--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

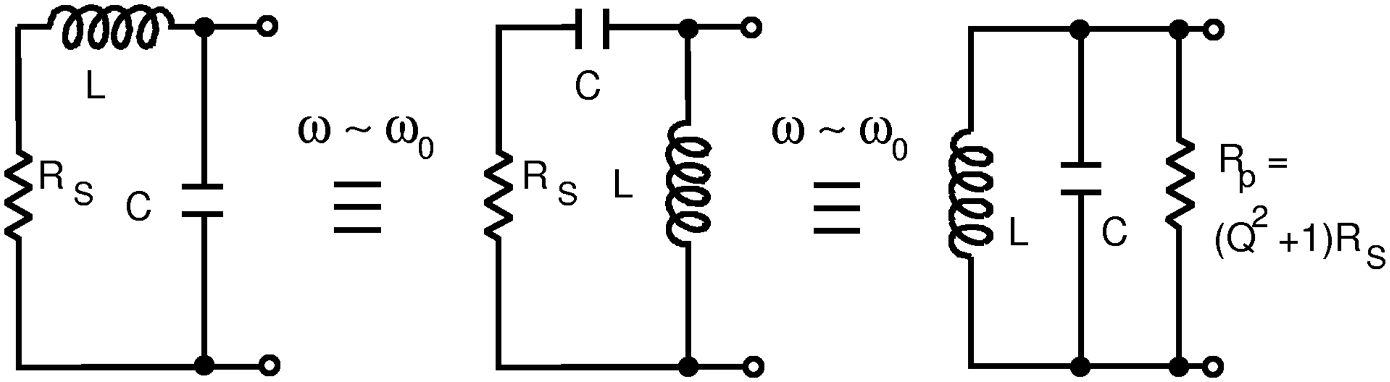
- How wide can we go?
  - Bode theorem specifies tradeoff between BW and insertion gain $\Gamma$

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

- $|\Gamma|^2$ 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



Lowpass
L Network

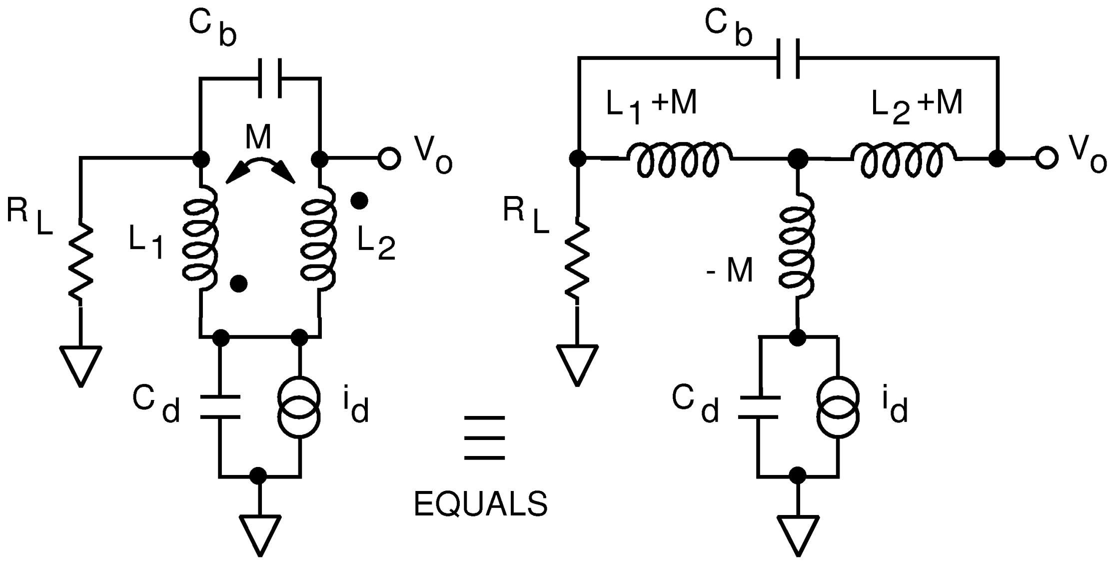
Highpass
L Network

Tank Circuit

- Moves RC bandwidth from DC to $f_0$ (same BW, settling time doubled)
  - $Q = X/R$ [at resonance, $Q = 1/(\omega_0 RC)$ (ratio of $f_0$ to $f_{RC}$)
  - Bandwidth $BW_{3dB} = \omega_0/Q$
- Transforms load impedance by a factor of $Q^2+1$
  - 50 Ω , $Q = 10$ => effective RL = 5kΩ (pure resistance at $\omega_0$)
  - Can also be used at baseband for a 1.4x BW increase

# Constant-Resistance T-Coil

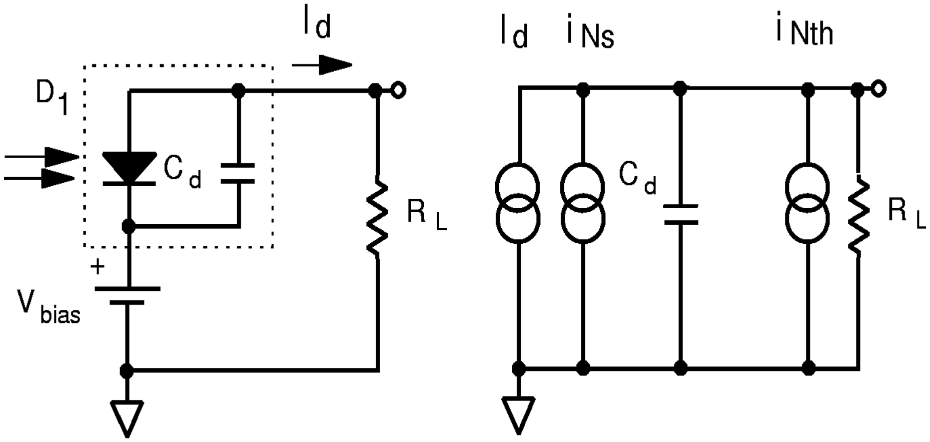
- Tektronix Vertical Amplifier Secret



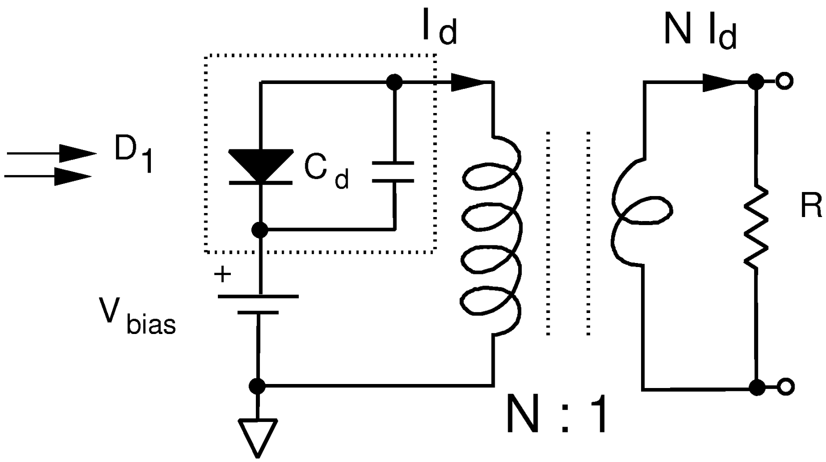
  Doesn't waste current in $R$ while there's $C$ to charge
  - 2.8x BW increase (at 3 dB points)
  - No overshoot or ringing
  - Design equations available
- Best simple network for baseband use (lowpass characteristic)
- Disadvantage: Load resistor and output are different nodes
  - Harder to get $T_N <$ 300K (may have to put active device in for $R$)

# Example: 5 pF PD, DC-50 MHz

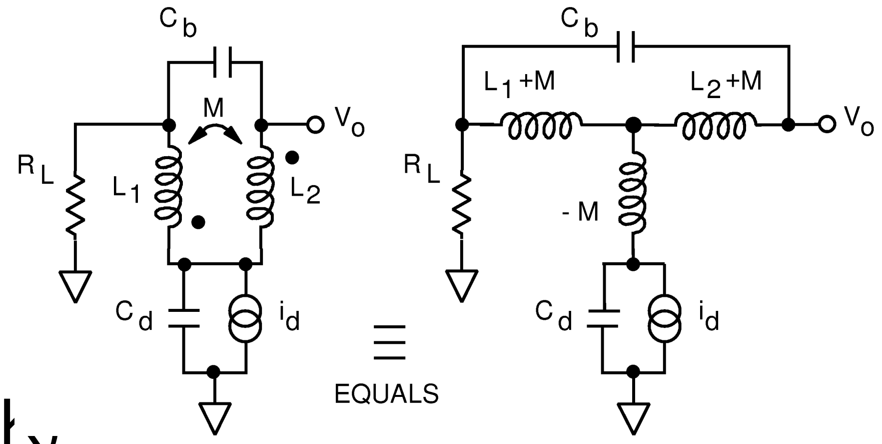
- Direct connection to 50 Ω
  - BW = 1/[2p(5pF)(50Ω)]=640 MHz
  - Shot noise limit: Iphot >= 1 mA (300K), 370 µA (35K)
  - *Wasteful*



- 3:1 Turns Ratio Transformer (450Ω)
  - BW = 1/[2π(5pF)(450Ω)] = 70MHz
  - Shot noise limit: $I_{phot}$ >= 115 µA (300K), 13 µA (35K)
  - (DC current x AC resistance > 50 mV (300K), > 6 mV (35K))
  - *9 dB SNR improvement (Johnson limit)*



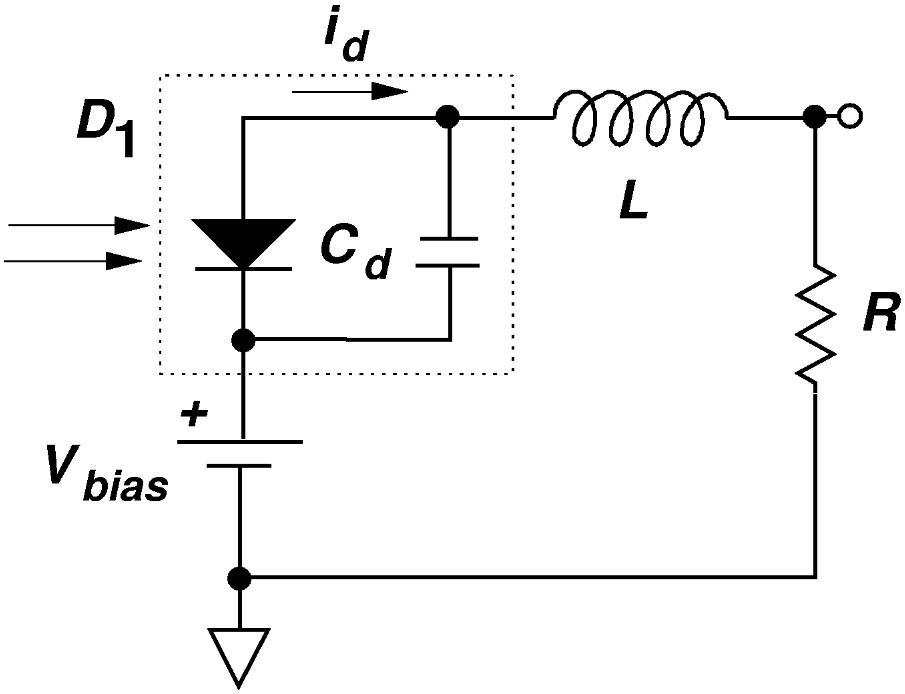
# Example: 5 pF PD, DC-50 MHz



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

- Bode Limit:
  - 4x BW increase, resistive load
  - $R_L = 2550\ \Omega$
  - SN Limit: 20 µA (300K), 2.4 µA (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 Ω load
  - $R_L$=3130 Ω (Q=25--no higher)
  - Use e.g. a cascode or 1:3 xfrmr
  - Can tune by changing $V_{\text{bias}}$
  - SN Limit: 16 μA (300K), 2 μA (35K
  - 17 dB SNR improvement vs 50 Ω
- Bode Limit:
  - 4x BW increase, resistive load
  - $R_L$=12.8 kΩ
  - SN Limit: 4 μA (300K), 0.5 μA (35K)
  - 24 dB SNR improvement vs 50 Ω