

Getting Photodetection Right

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Why is photodetection so hard?

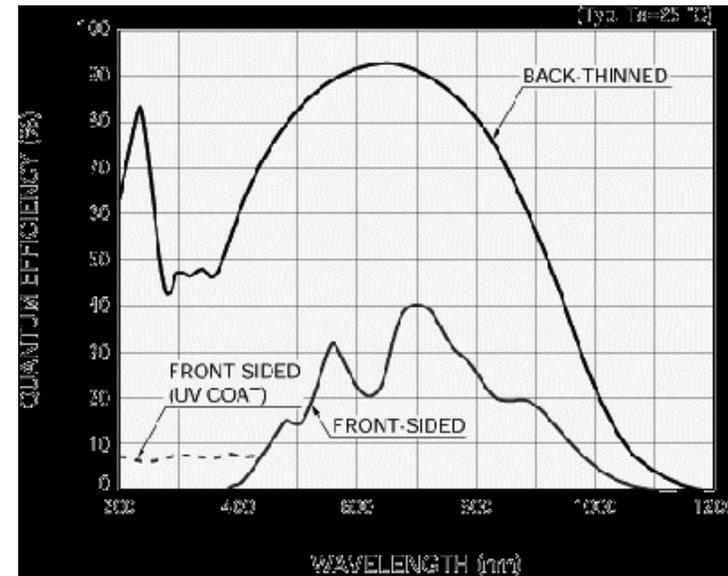
- PDs are essentially perfect transducers— $1\gamma = 1 e^-$
- Shot noise limit (1σ): 2 electrons / Hz
- 5 mW @ 633 nm: SQL = 160 dB SNR in 1 Hz

Yet:

- Telecom PDs run at ~30 dB worse than this (e.g. -38 dBm @ 120 MHz BW, 10^{-10} BER vs. -66 dBm for shot noise limit)
- Absorption spectrometers have been stuck at 10^{-5} absorption for decades (or 10^{-6} in chart space)

Why?

- Optical reason: **Stray fringes & source noise**
- Electronic reason: **Capacitance**
- Blunders: High background, **poor front end design**
- Standard quantum limit isn't quite the end anyway



(Hamamatsu S8844-0909 CCD)

Outline:

Optics and Electronics

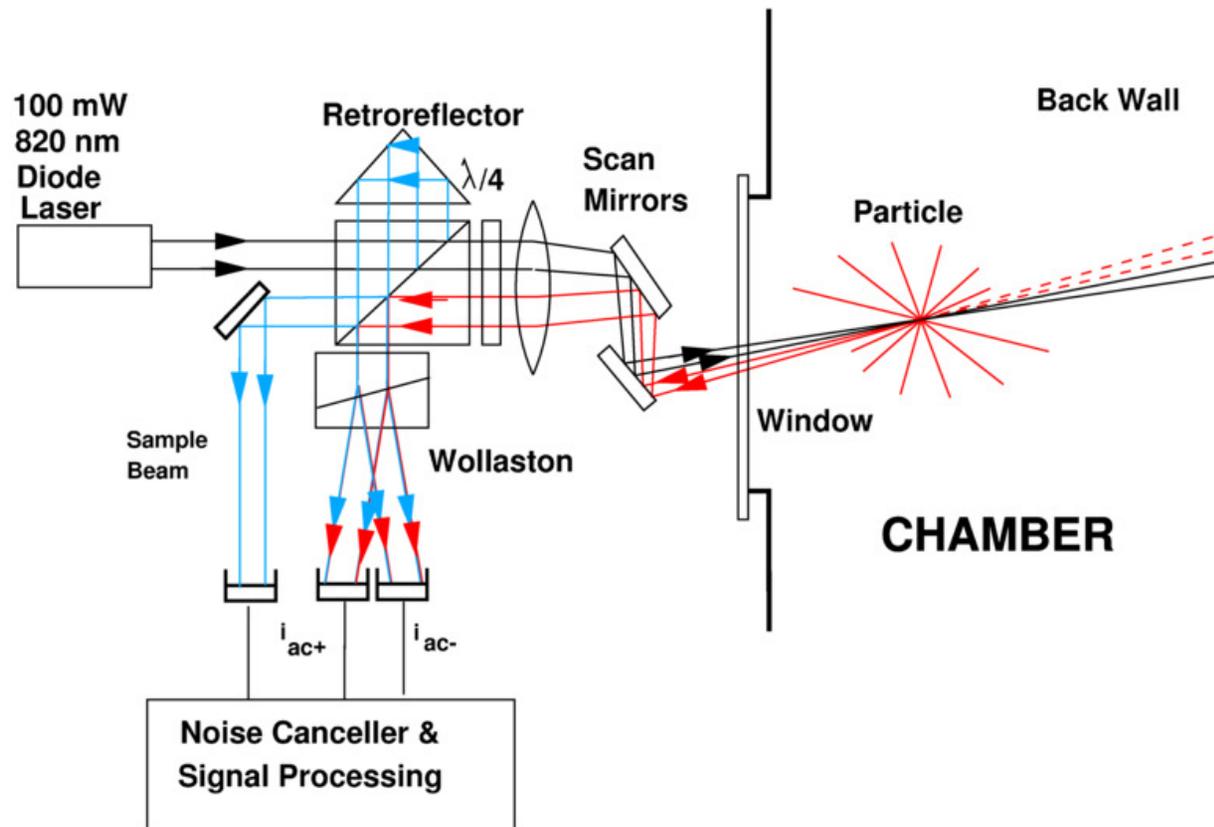
Optics

- **Lossless Interferometers**
- **Heterodyne Detection**
- **Homodyne Detection**
 - Fringe surfing
 - Doppler
- **Basic noise physics**
 - Fundamental and technical noise sources

Electronics

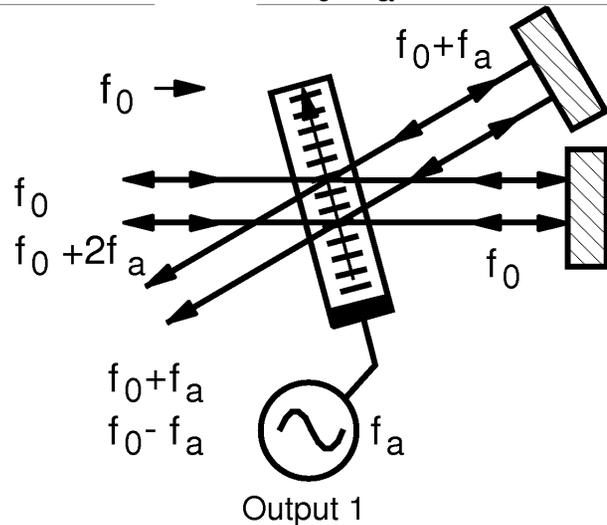
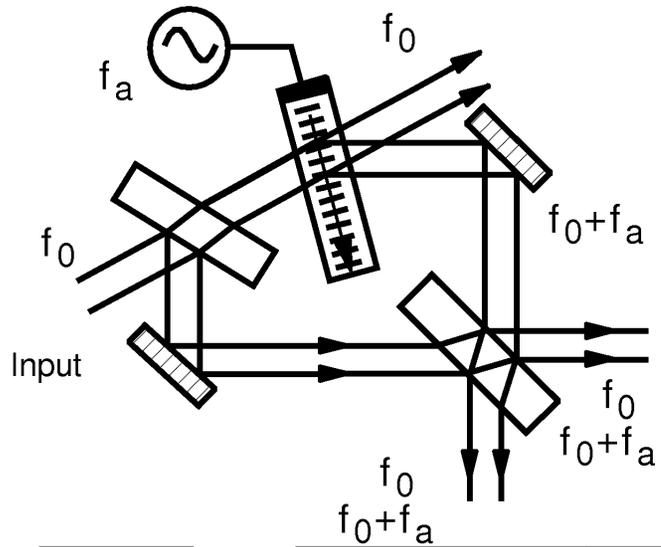
- **Laser noise cancellation**
 - Reaches SQL
 - 50-70 dB RIN reduction at low frequency, >40 dB to 10 MHz
- **Improved TIA circuitry**
 - Cascode TIA
 - 60x bandwidth improvement often possible

Lossless Interferometers



- Combine (weak) signal and (strong) LO beams: heterodyne gain, spatial and temporal filtering → sensitive & selective
- Simple idea, but often overlooked: combine orthogonally polarized beams, use a Wollaston at 45° , detect and subtract photocurrents: effectively 100% photon efficiency

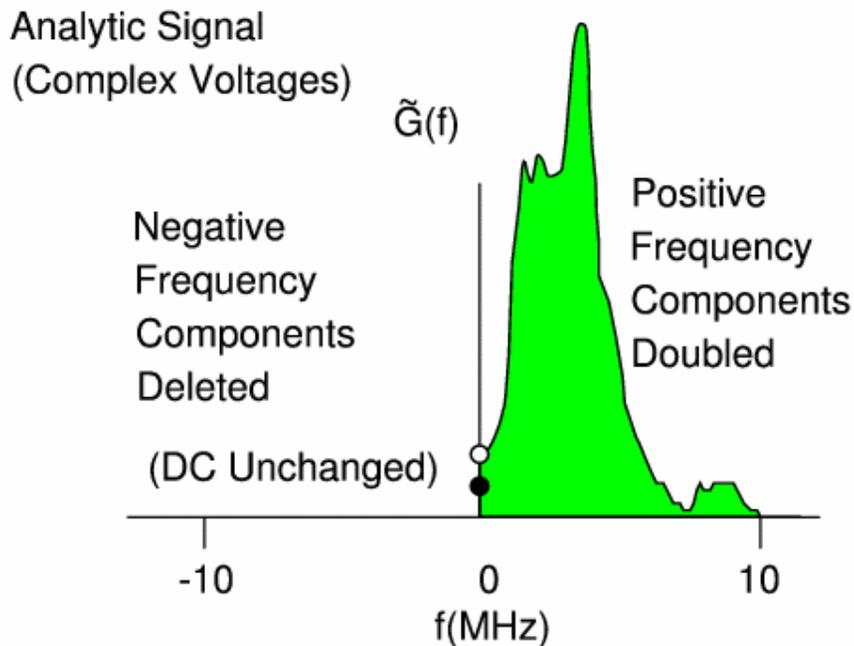
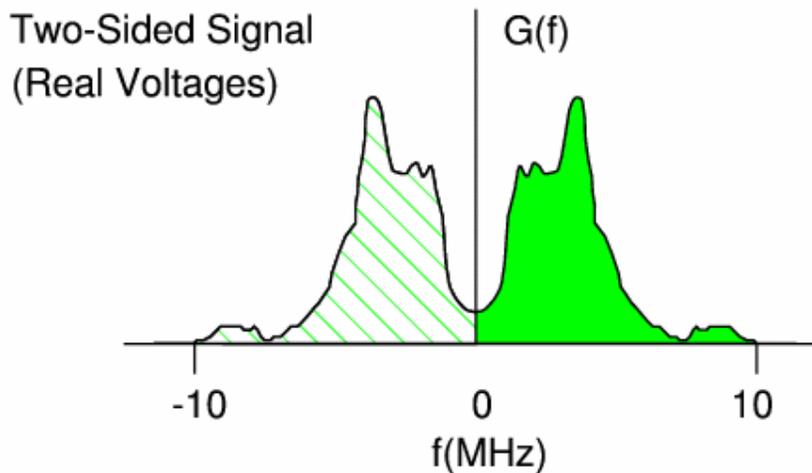
Heterodyne Detection



$$I_{dc} \propto \underbrace{(|\psi_1|^2 + |\psi_2|^2)}_{\text{DC}} + \underbrace{2\text{Re}\{\psi_1 \psi_2^*\}}_{\text{Interference}}$$

- Heterodyne adds LO beam at some frequency offset, detects envelope
- SQL signal-to-noise equals that of the *weaker* beam
- Allows shot noise limited measurements for all signal levels
- Handles Doppler very well (\pm velocity distinguished)
- Preserves both phases
- 3 dB SNR penalty due to image frequency noise

Analytic Signal Basis



- Observables are real-valued
→ spectrum $G(f)$ is Hermitian
- Carrying along CC is twice the work (4x the blunders)
- Use exponential notation for simple sines, but what about more general signals?
- Analytic signal idea: form $g + iH(g)$ to cancel out negative frequencies
- 2x power, 0.5x BW explains mysterious factors of 2:
 - thermal noise = kT/Hz
 - shot noise = $(2eI)^{1/2}$

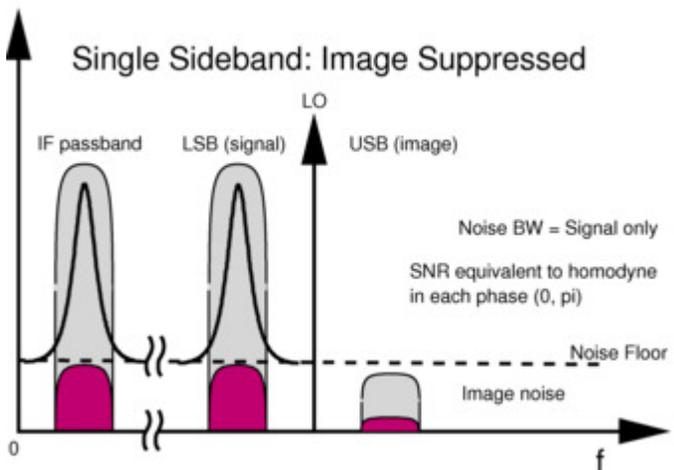
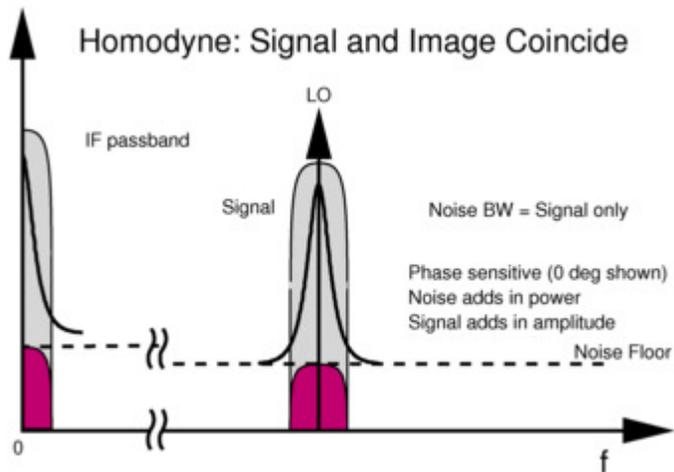
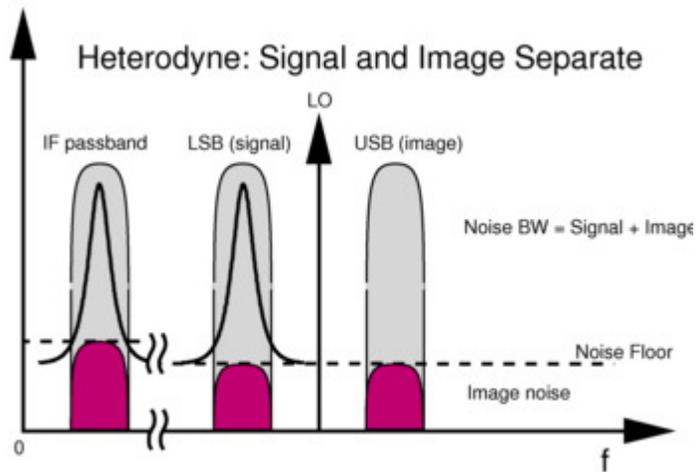
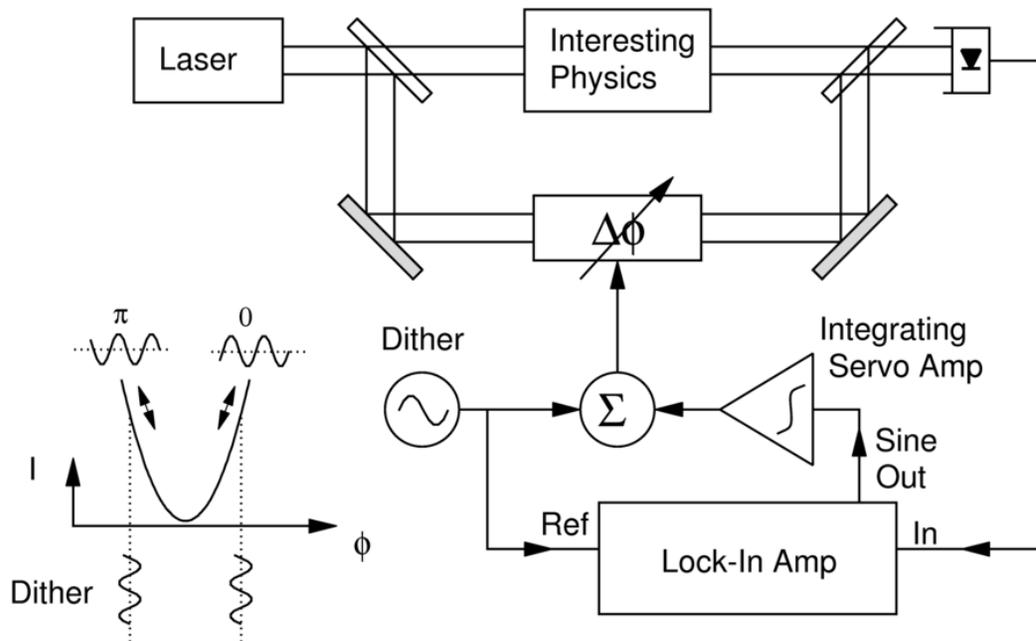


Image Frequency Noise

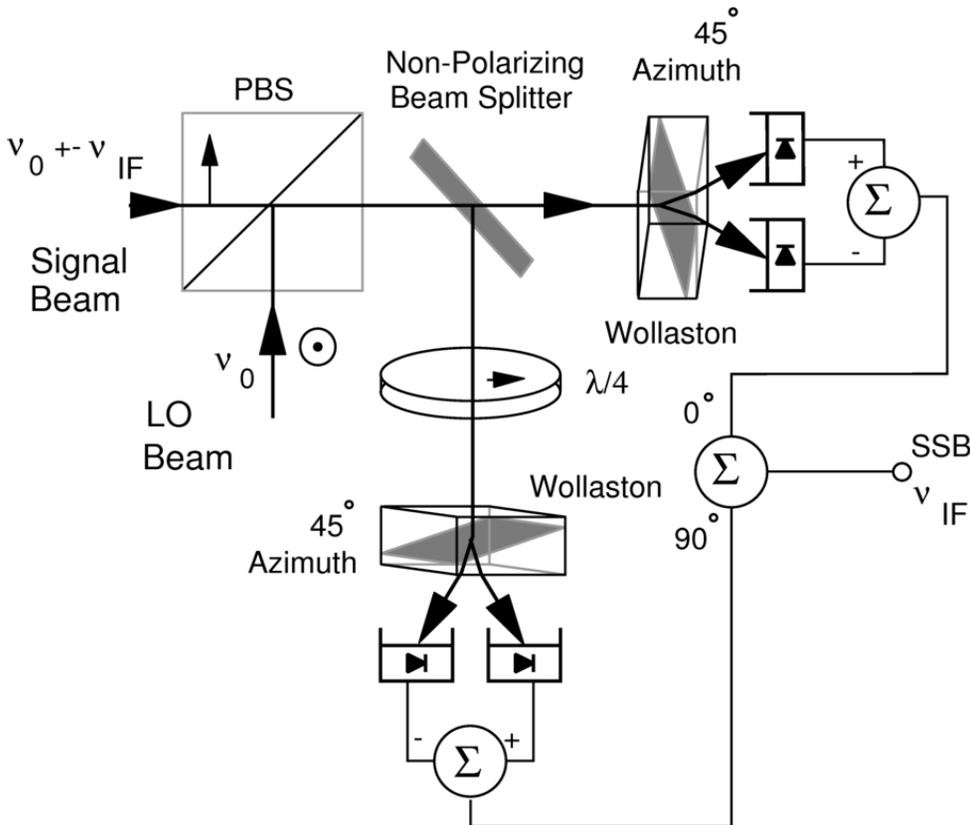
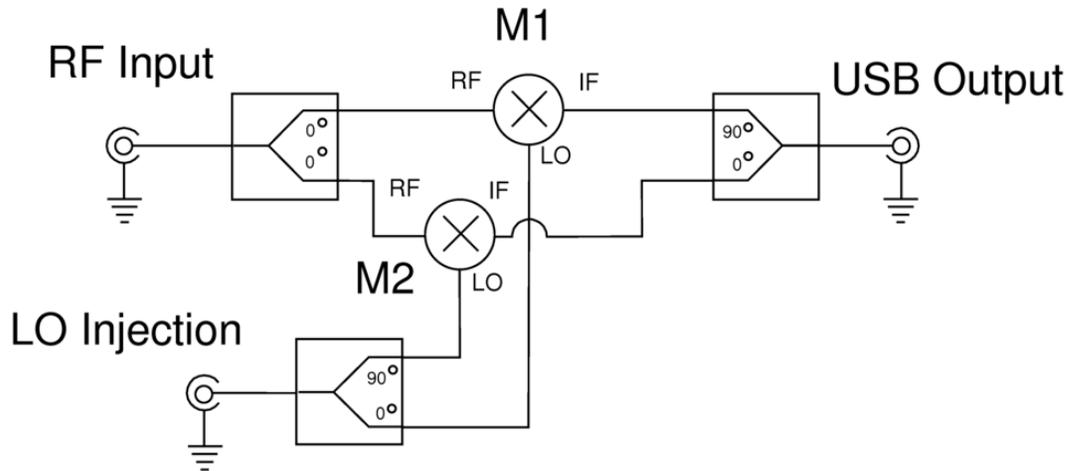
- Heterodyning folds sidebands: $f_c + \delta f$ and $f_c - \delta f$ both yield δf at the output
- Noise in the undesired (*image*) sideband corrupts measurements
- RF heterodyne systems (e.g. FM radios) filter out the image; hard at optical frequency
- Homodyne systems move the IF to DC: only one copy of the noise
 - Phase sensitive
- SSB systems reject the image by phasing: SNR same as homodyne
 - *Both phases preserved*

Homodyne and Fringe Surfing



- Heterodyne has 3 dB SNR penalty due to image frequency noise (alternatively, because $\langle \sin^2 \rangle = 0.5$)
- Fringe surfing (Homodyne with phase control) lets us sit on the fringe peak and avoid the 3 dB SNR loss
 - Hard due to limited phase shifter range
 - Falls apart at low SNR because the loop loses lock

Optical SSB



- Heterodyne has 3 dB SNR penalty, homodyne loses information
- Optical SSB avoids image noise
- Preserves both phase and amplitude information
- No PLL → *OK at low SNR*
- Complicated
- Lossless non-polarizing BS not so easy to make
 - Unresolved metal dot pattern probably best

Basic (Semiclassical) Noise Physics

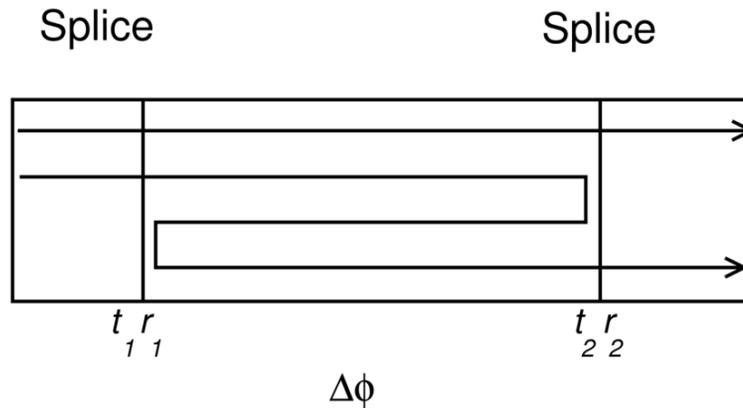
• Johnson Noise:

- 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), $T_N \ll T_{amb}$ (LNA)
- Central problem in LNA design: *Resistors are horribly noisy*

• Shot Noise:

- Photodetection is a Poisson process: variance = mean
- Shot noise limit:
 $i_{Nshot} = (2eI_{dc})^{1/2} > (4kT_N/R)^{1/2}$
when:
- $I_{dc} R_L > 50$ mV (300K)
- Signal power > 7 μ W in 50Ω (very quiet amp [35K])
- NB: It's easy to make currents with no shot noise

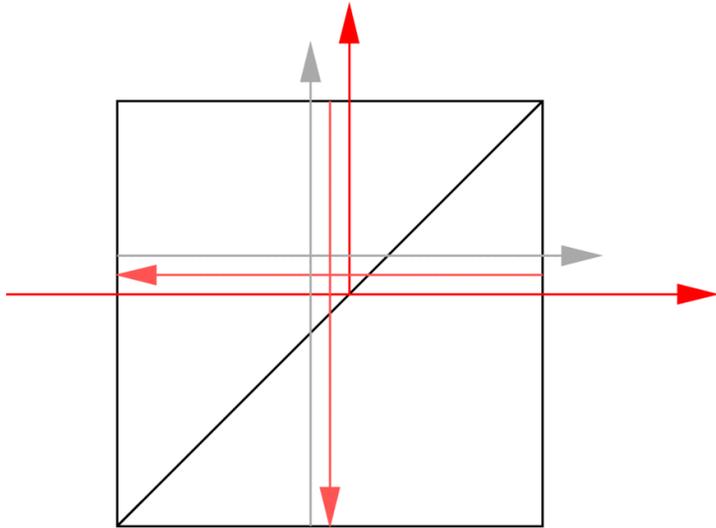
Coherence Fluctuation Noise



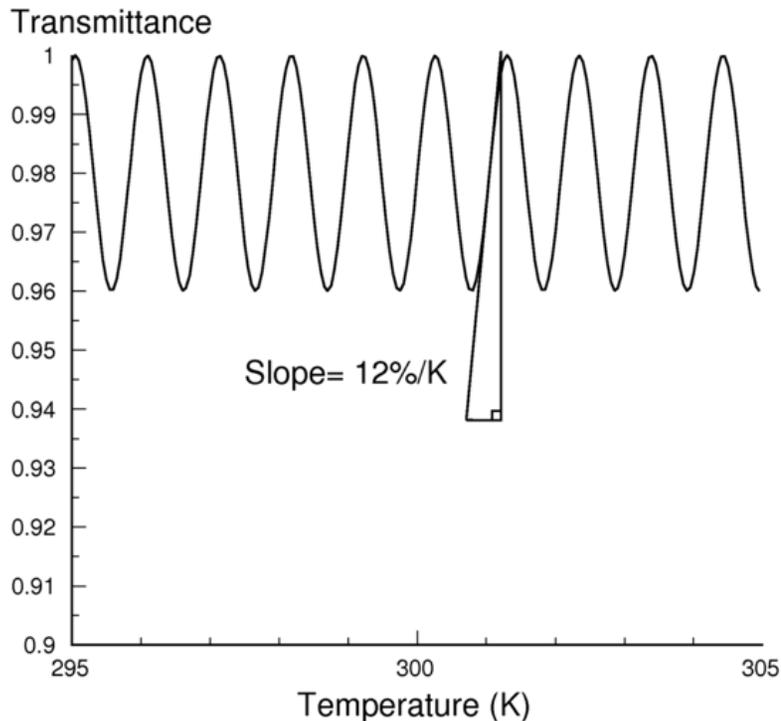
$$E = \sum_{n=0}^{\infty} t_{12} t_{21} (r_{12} r_{21})^n e^{i2n\Delta\phi}$$

- **Interference term doesn't go away, it turns to AC noise**
 - Delay $\ll t_c$: RIN only
 - Delay $\geq t_c$: spreads out over $\Delta\nu \sim 2/t_c$ –disaster
 - Double Rayleigh scatter or splices in fibres
- **Usually the dominant noise source when $\Delta t/t_c$ is not $\ll 1$**
 - Delay 1% of t_c : Max SNR = 40 dB in $2/t_c$ BW ($|\psi_1| = |\psi_2|$)
 - Can easily be > 60 dB over shot noise

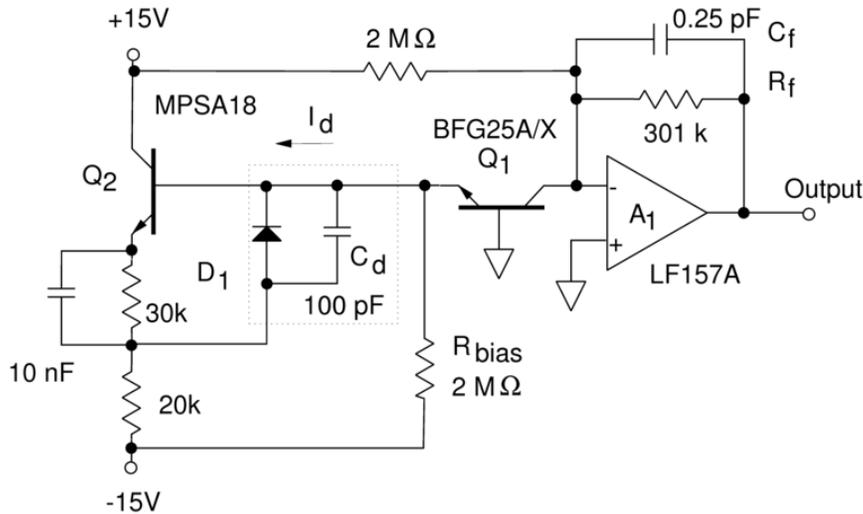
Etalon Fringes



- All optical systems are interferometers, usually unintentionally
- Etalon fringes cause drift: ordinary 25 mm PBS with 1% AR coatings drifts 120,000 ppm/K
- Demodulates phase noise and causes coherence fluctuations
- Dies off very slowly—even after 5 bounces from a good AR coating $((0.01)^5 \sim 10^{-10})$, a beam can produce 40 ppm p-v, or $\Delta P \sim 800$ ppm/K in a 20 cm path



Electronics: More Than Just Details



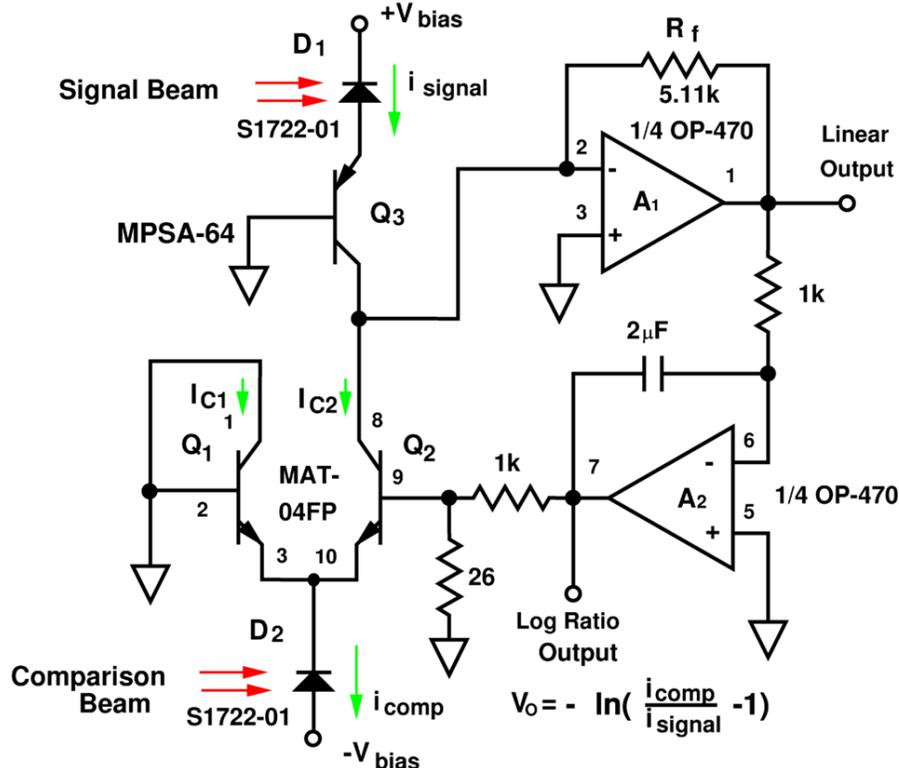
- **Lots of great measurements get destroyed by poorly designed front ends**

- Don't give up and use 50 Ω!

- **Improvements:**

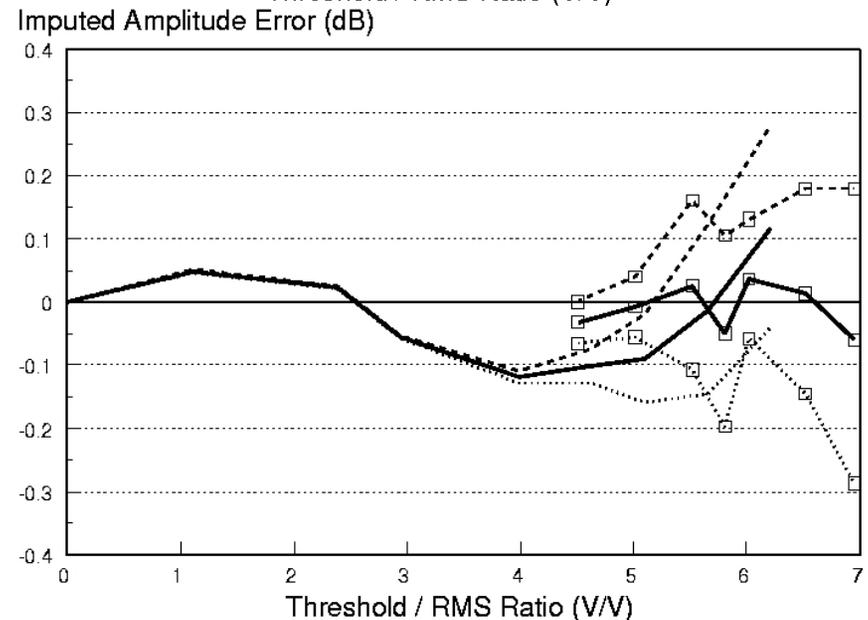
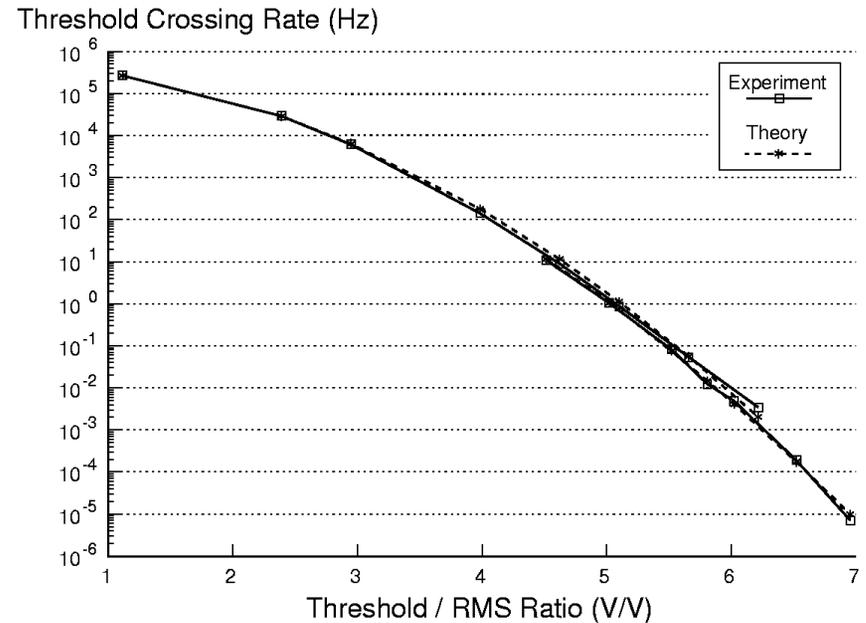
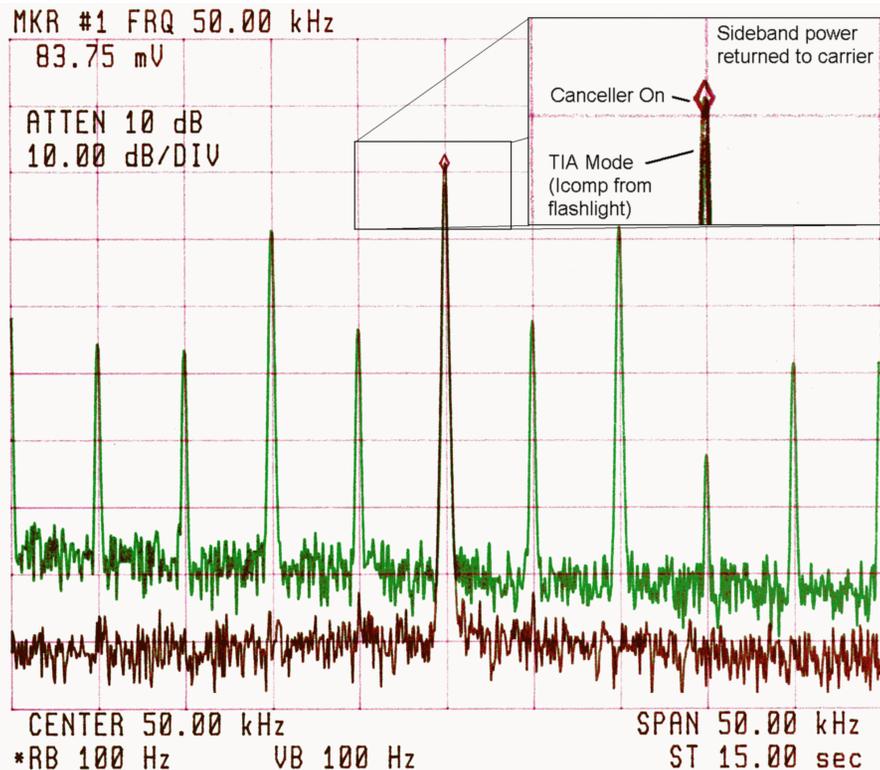
- **Bootstrap Cascode TIA** improves C-limited BW by up to 60 times while preserving SNR—a better amp

- **Laser noise canceller** eliminates both additive and multiplicative RIN contribution—like having a shot-noise limited laser

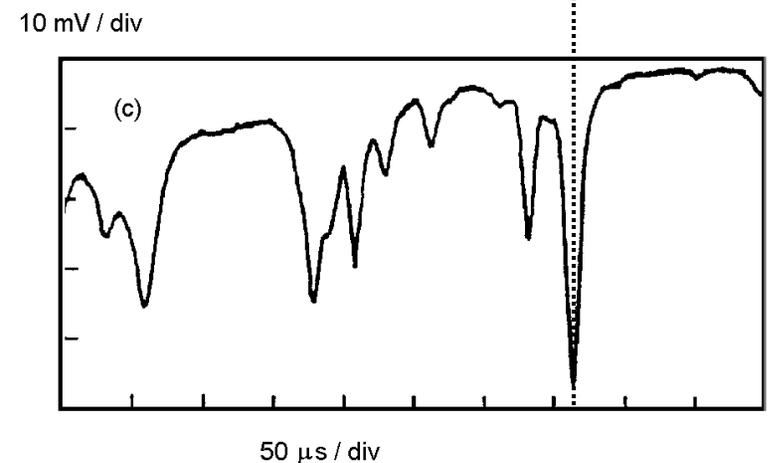
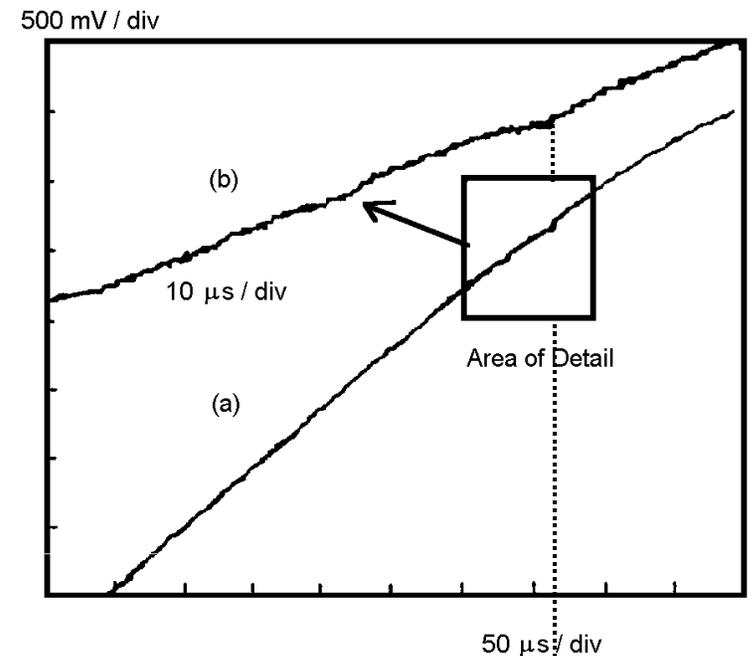
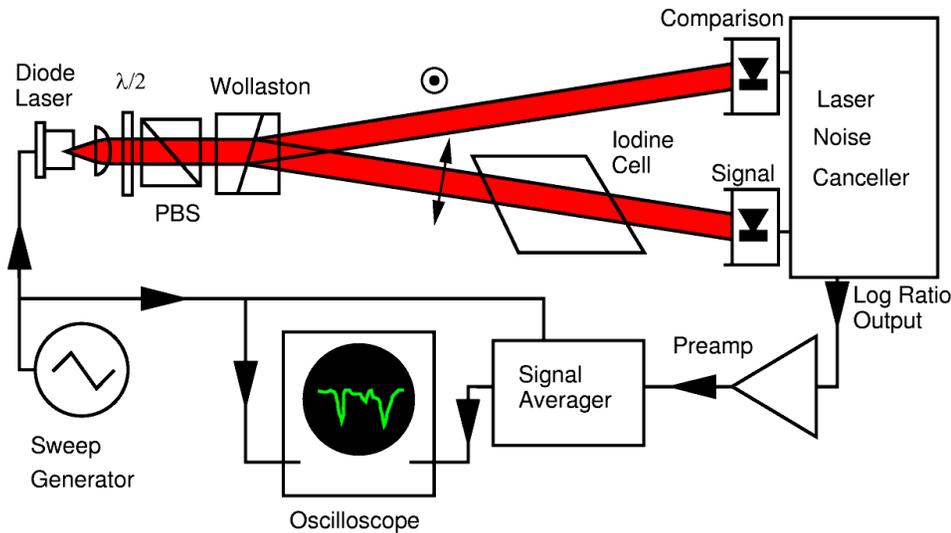


Laser Noise Cancellation

- Reduces additive and multiplicative laser noise by 50-70 dB
- All that's left is shot noise—the statistics are right on out to $> 7 \sigma$



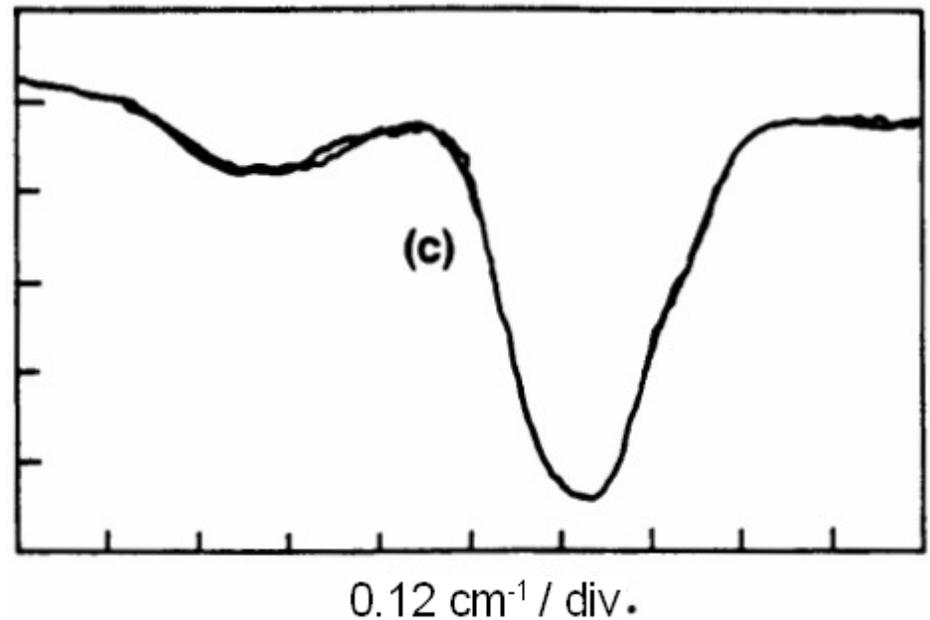
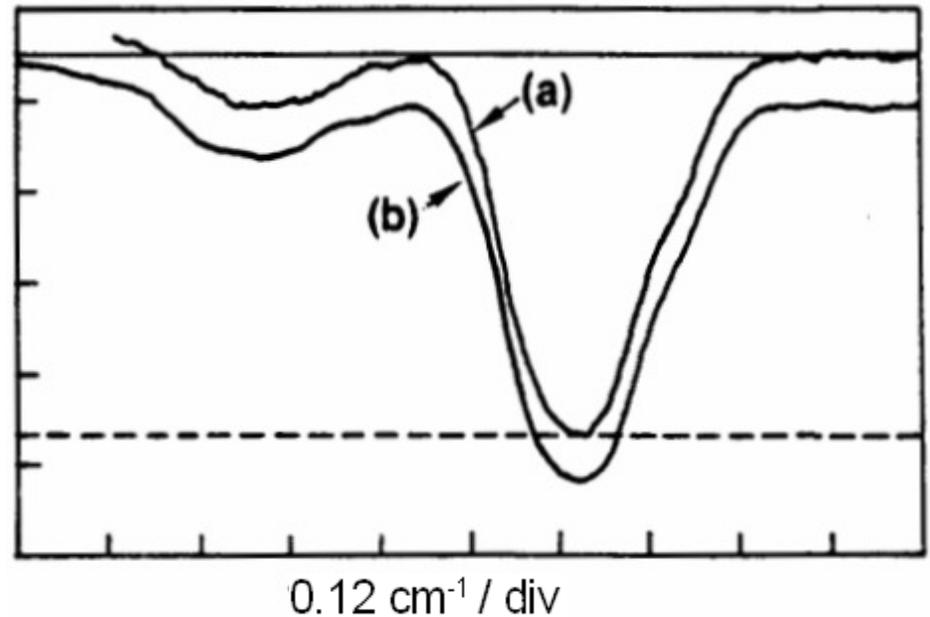
Example: Noise Canceller Spectroscopy



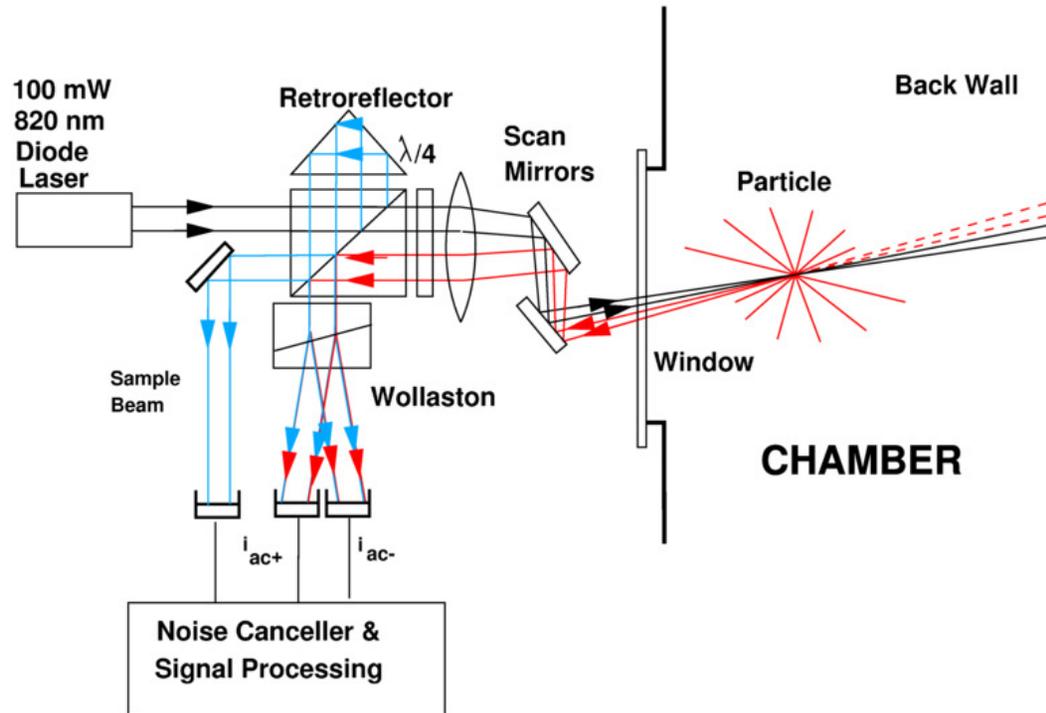
- Tunable diode laser has $\Delta I/I \sim 3:1$ (~30% in detail box)
- Even major absorption peaks barely visible on sloping BG
- Canceller eliminates slope (additive), makes peak heights independent of power (multiplicative)

Current Tuned Diode Laser Spectroscopy with Laser Noise Canceller

- I_2 absorption curves at absorptions of 250 ppm (a) and 98 ppm (b) are essentially identical despite huge intensity slope. ($0.12 \text{ cm}^{-1} / \text{div X}$)
- Sensitivity $\sim 1 \text{ ppm}$ even in a toy experiment, despite $\sim 30\% \Delta I/I$ background



Example: In Situ Coherent Lidar (ISICL)



- Doppler-based homodyne interferometer with differential laser noise canceller for detection
- Background light: 10^6 times detection limit (coherent), 10^8 times (incoherent plasma glow)
- Operates at the shot noise limit (10^{-11} false alarm rate) with 50 photons per particle despite huge background

Conclusion:

- **Optical detection is still hard**
- **Getting it right requires careful thought about both the optics and the electronics**
- **The best techniques (e.g. coherent detection and laser noise cancellation) can make seemingly impossible measurements surprisingly doable**

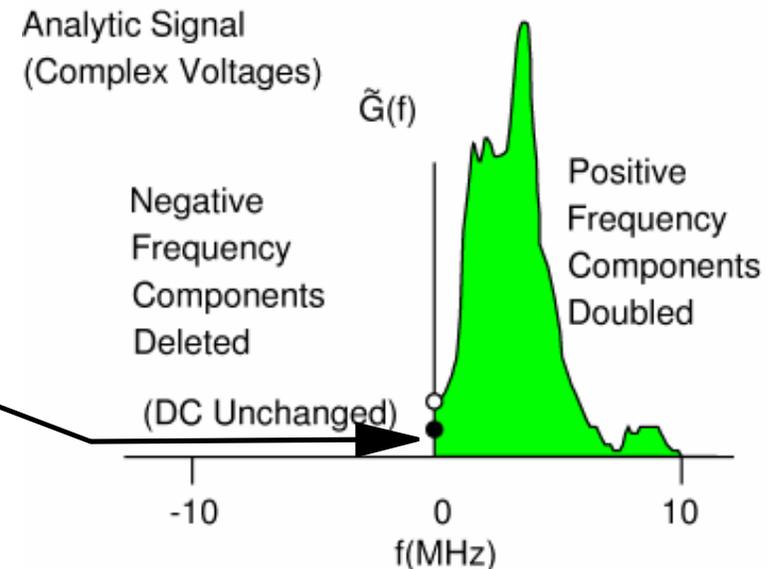
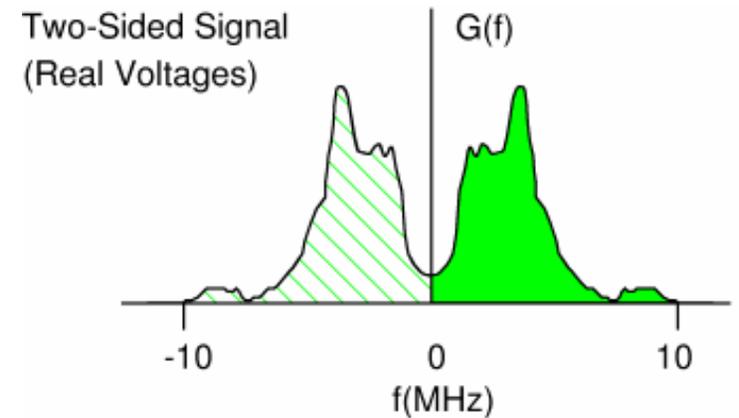
BACKUP CHARTS

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/cm²/sr)
 - ▶ Leakage, background, and capacitance go as the area
 - ▶ Reduce area, increase NA, consider immersion lens
 - ▶ High current density (>10 mA/cm²) 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), $T_N \ll T_{amb}$ (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 $> 7 \mu W$ 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 $\sim (\text{mean free path})/(\text{length of resistor})$

■ Technical noise (stay tuned)

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
 - ▶ $C_d \sim 100 \text{ pF/cm}^2$ for a good PIN device, fully depleted
- **Square law device:**
 - ▶ $P_{\text{opt}} = h\nu N$, $P_{\text{el}} = (eN)^2 R_L$
 - ▶ **Electrical power theoretically unlimited as $R_L \Rightarrow$ infinity**
 - ▶ Johnson noise is always $kT/\text{s/Hz}$: 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) $\sim N / 200$

- 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: $i_{\text{phot}} = 2 \mu\text{A}$
 - Photon arrival rate $N = i_{\text{phot}}/e = 12.4$ 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**

- ▶ $R_L = 1 \text{ M}\Omega$: 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

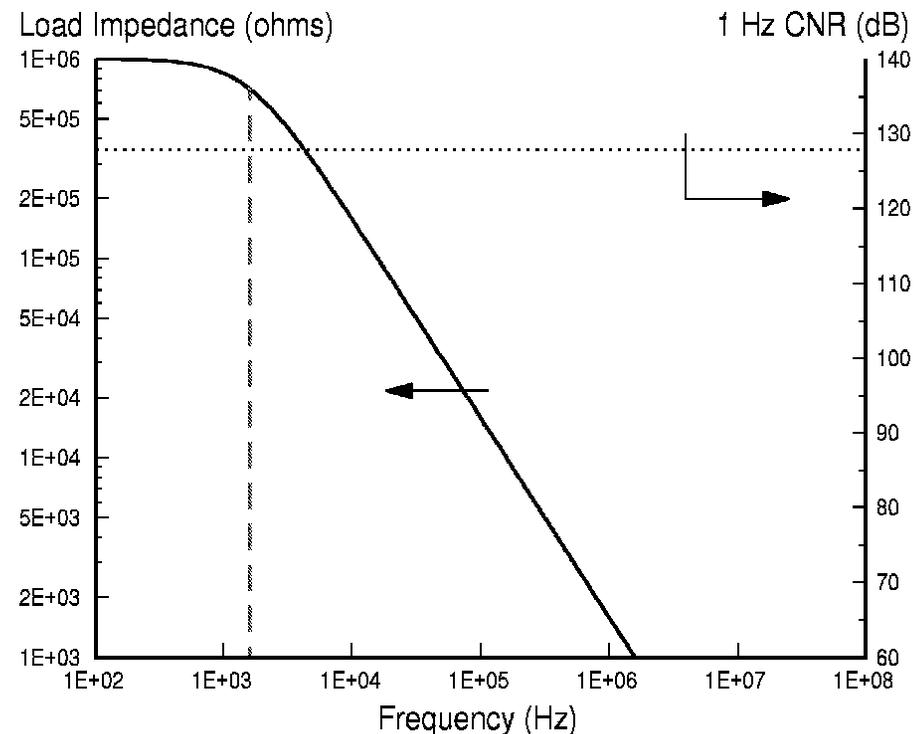
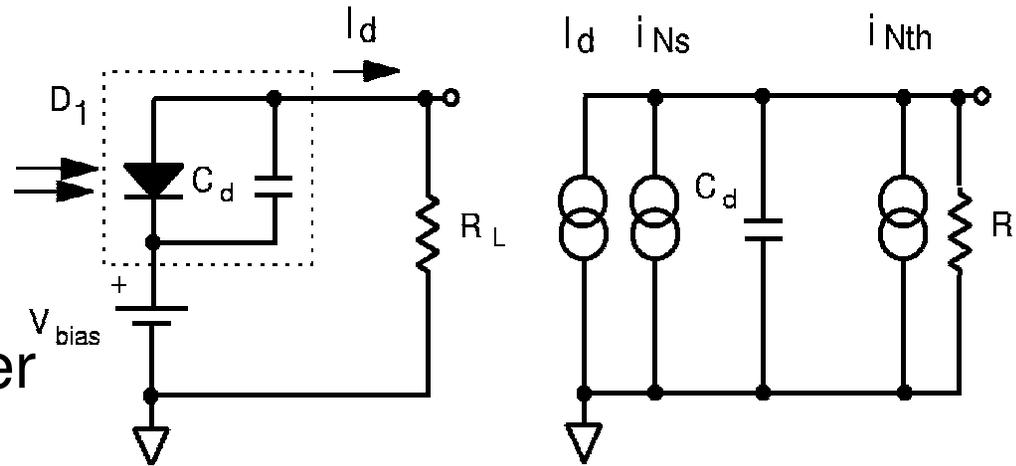
- **Optimization:**

- ▶ Lower R increases BW, but SNR drops due to Johnson noise

- ▶ Shot = Johnson when $IR = 2kT/e$ (~50 mV@300K)

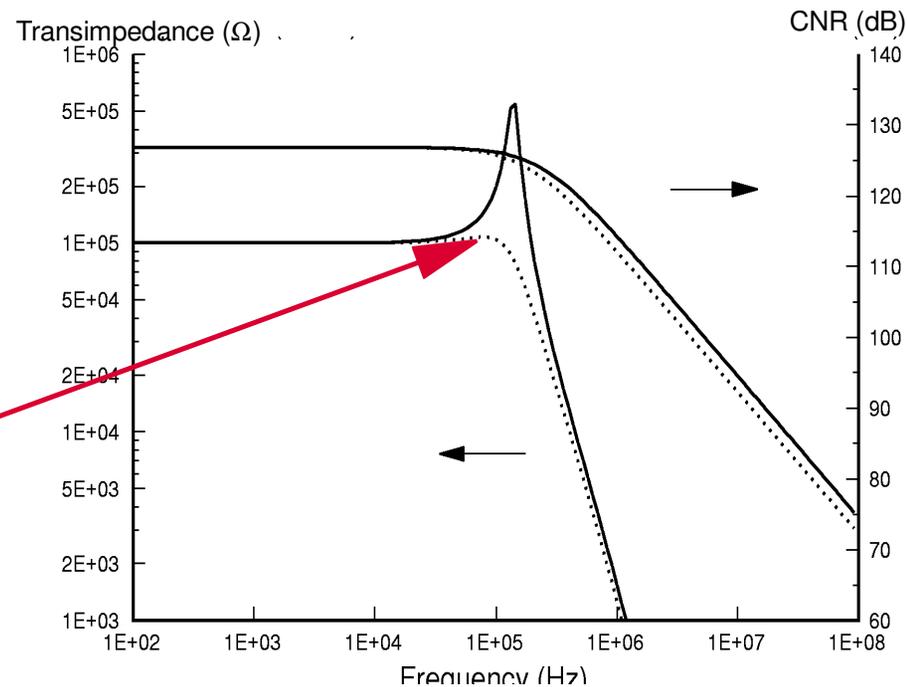
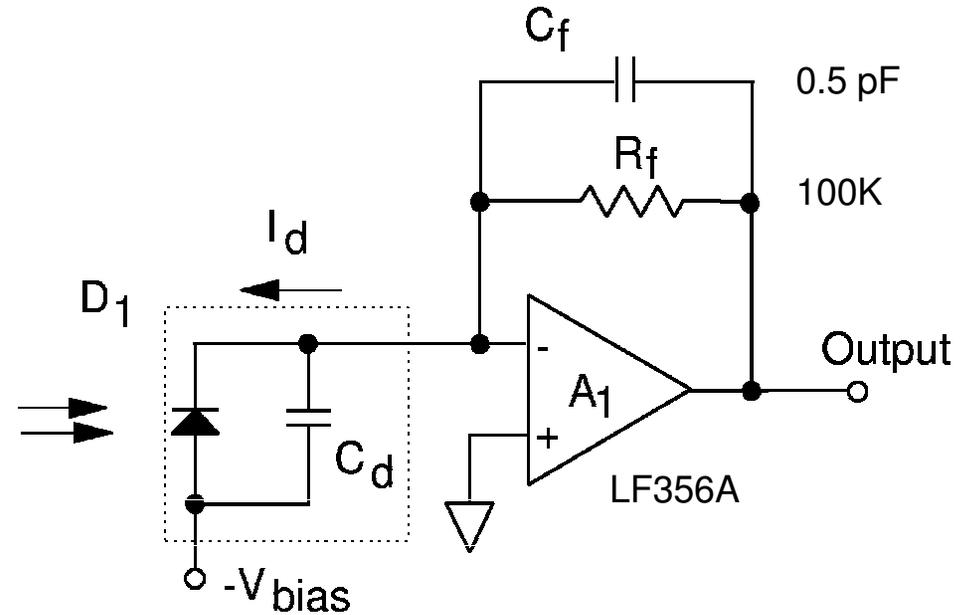
- ▶ **Optimum R drops ~ 200 mV**

- ▶ **$R_{opt} = 100\text{k}$, 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 $\sim 0.5(f_{RC} * GBW)^{1/2}$
- 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



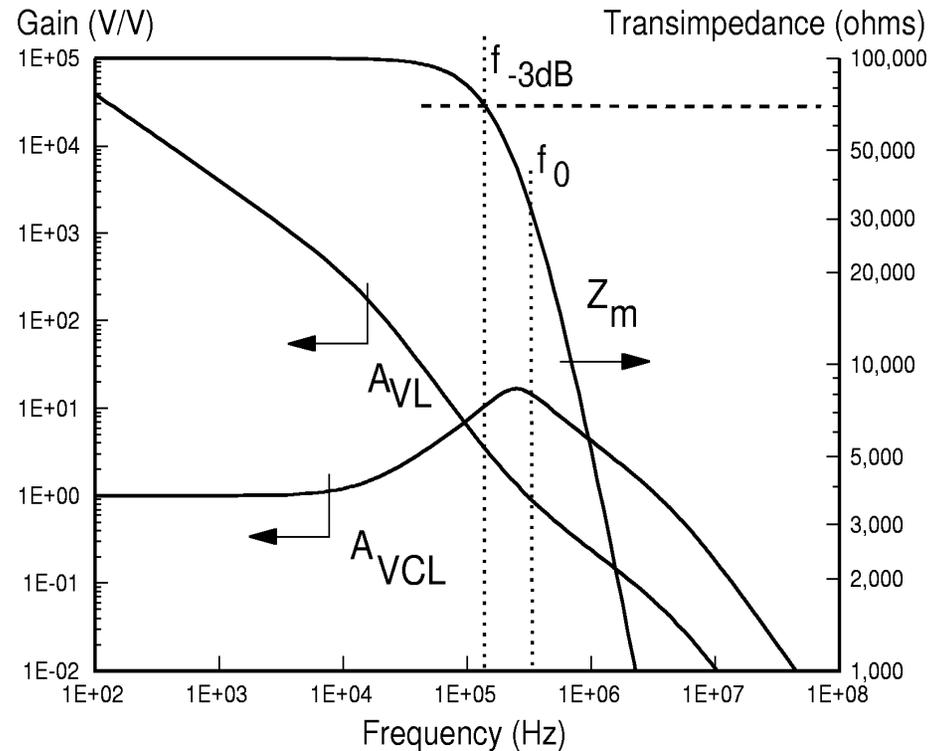
Transimpedance Amp

■ Transimpedance BW

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

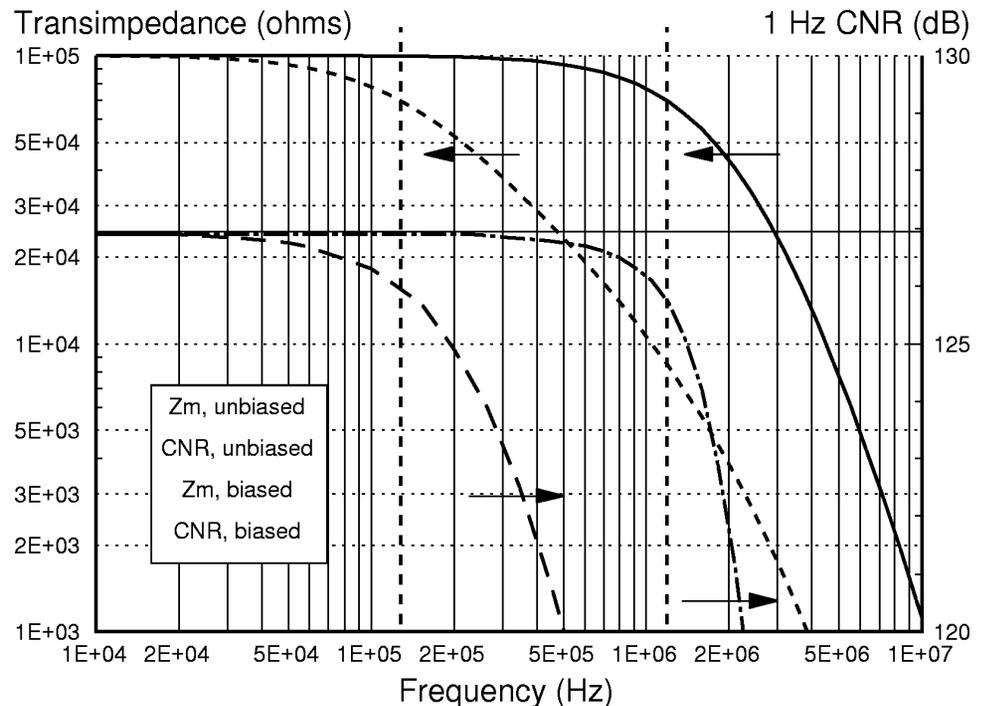
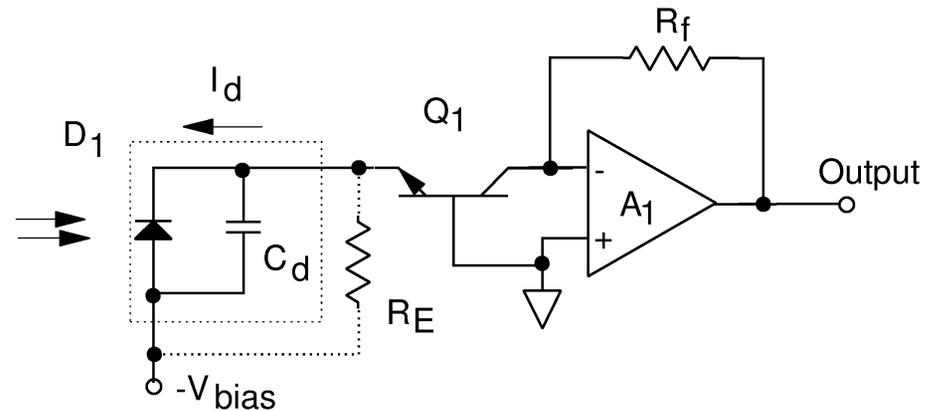
■ Low noise

- ▶ Amplifier noise dominates at large R_f
- ▶ Active devices can have $T_N \ll 300K$ ($T_N = e n_{IN} / 4k$)
- ▶ ~ 10K for good bipolar op amps
- ▶ Even lower for FETs but needs inaccessible impedance levels



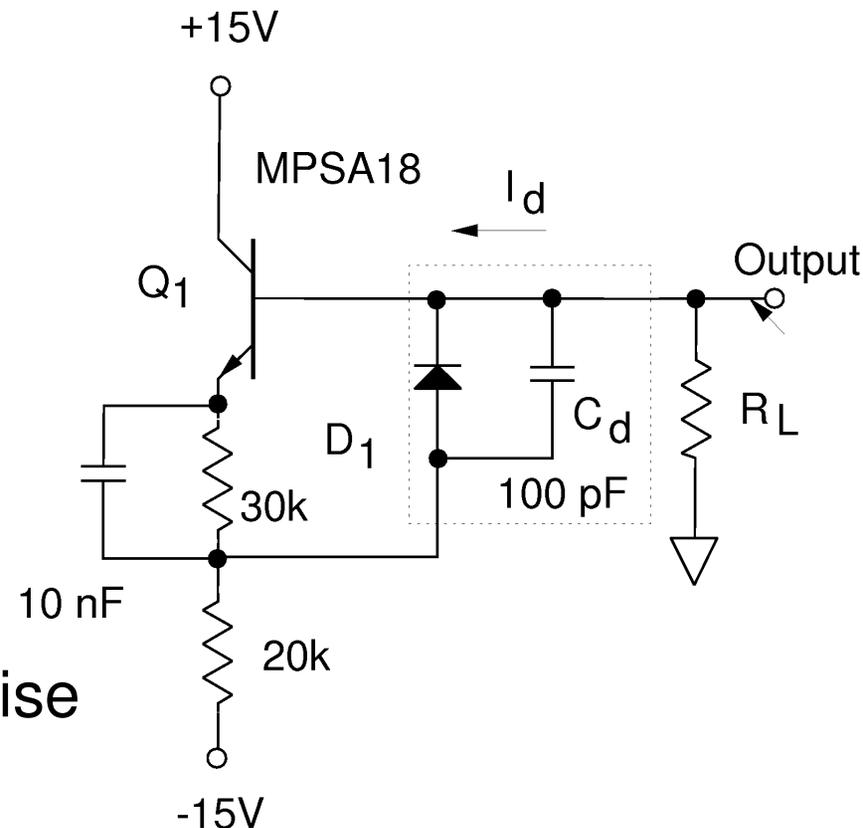
Cascode TIA

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



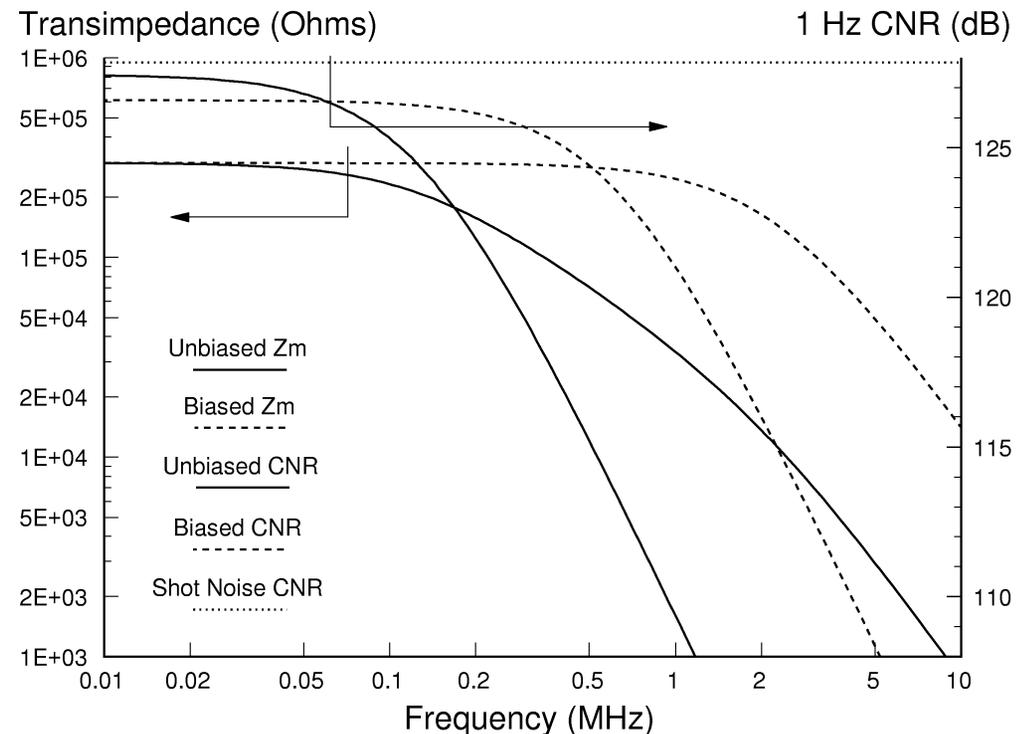
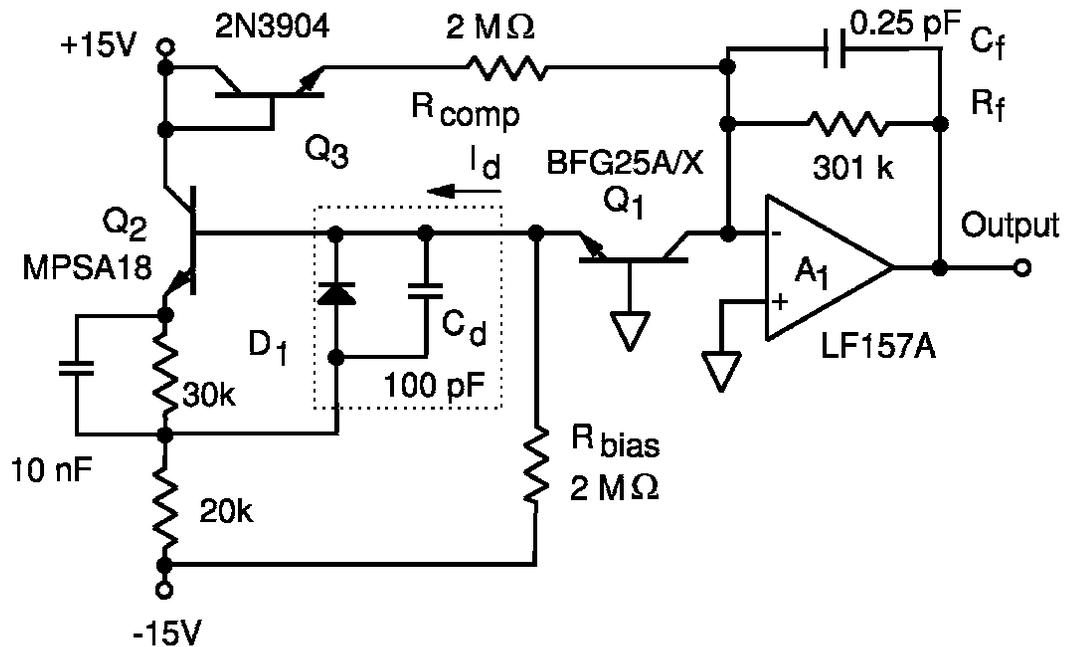
Bootstrapping

- Bootstrap transistor
 - ▶ Follower forces cold end of 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 $I_{dc}=300 \mu\text{A}$, $R_L=100 \text{ k}\Omega$
- Superbeta transistor
 - ▶ $\beta \sim 1000$: 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



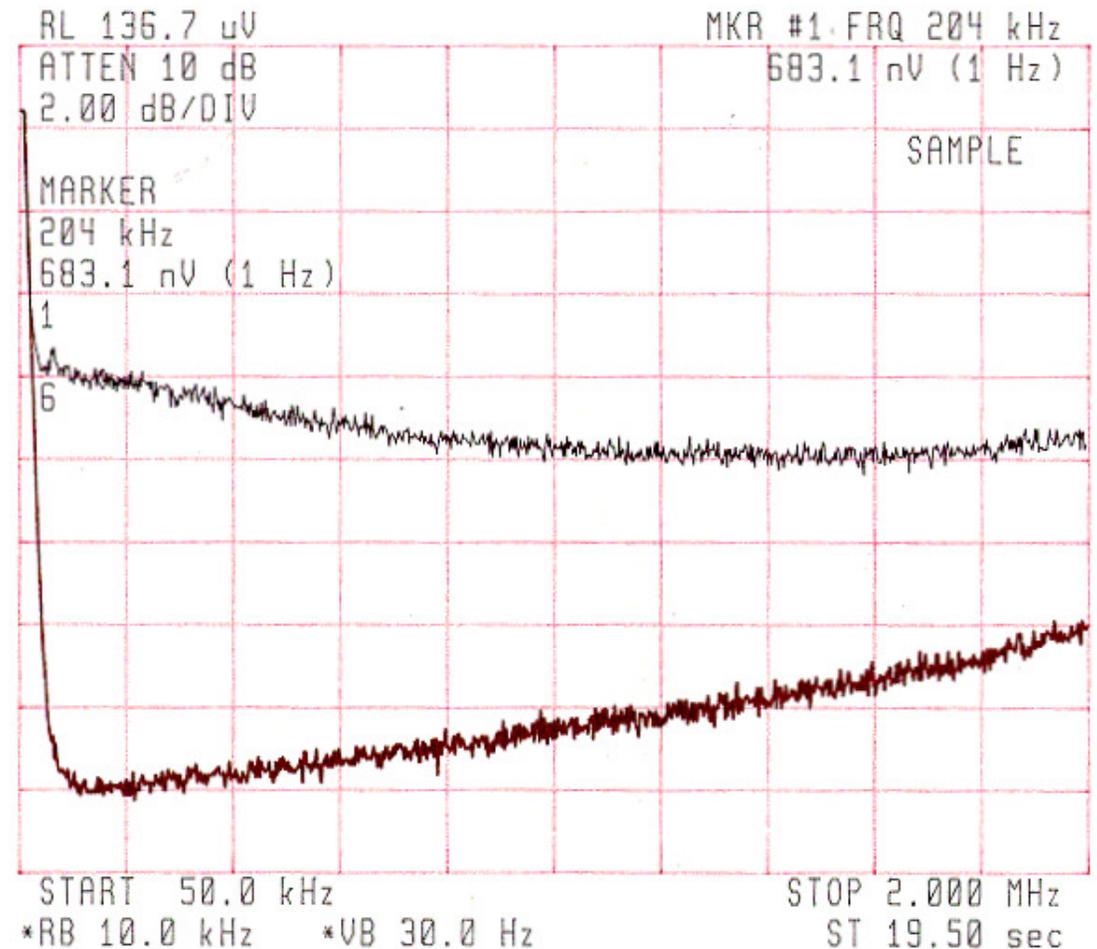
Bootstrapped Cascode TIA

- 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 μ A
- Not much more juice available here:
 - ▶ optical fix needed next time



Bottom: Dark noise

Top: 2 μ A photocurrent

Noise Physics Again

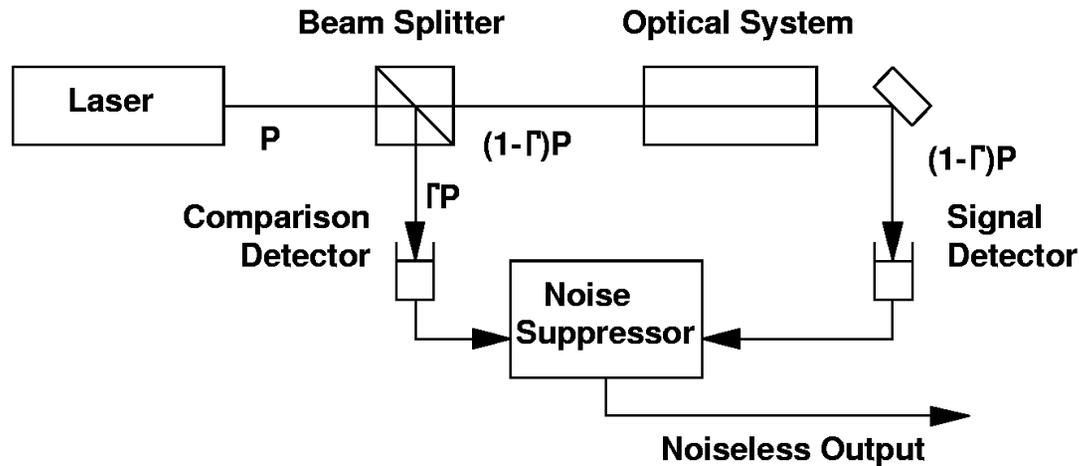
- Technical Noise
 - ▶ Usually dominant in laser measurements, especially bright field
 - ▶ Dominates in large-signal limit ($p_N \sim P_{\text{opt}2}$)
 - ▶ Laser RIN, demodulated FM noise, wiggle noise, below-threshold side modes, mode partition noise, coherence fluctuations microphonics, $1/f$ noise, 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

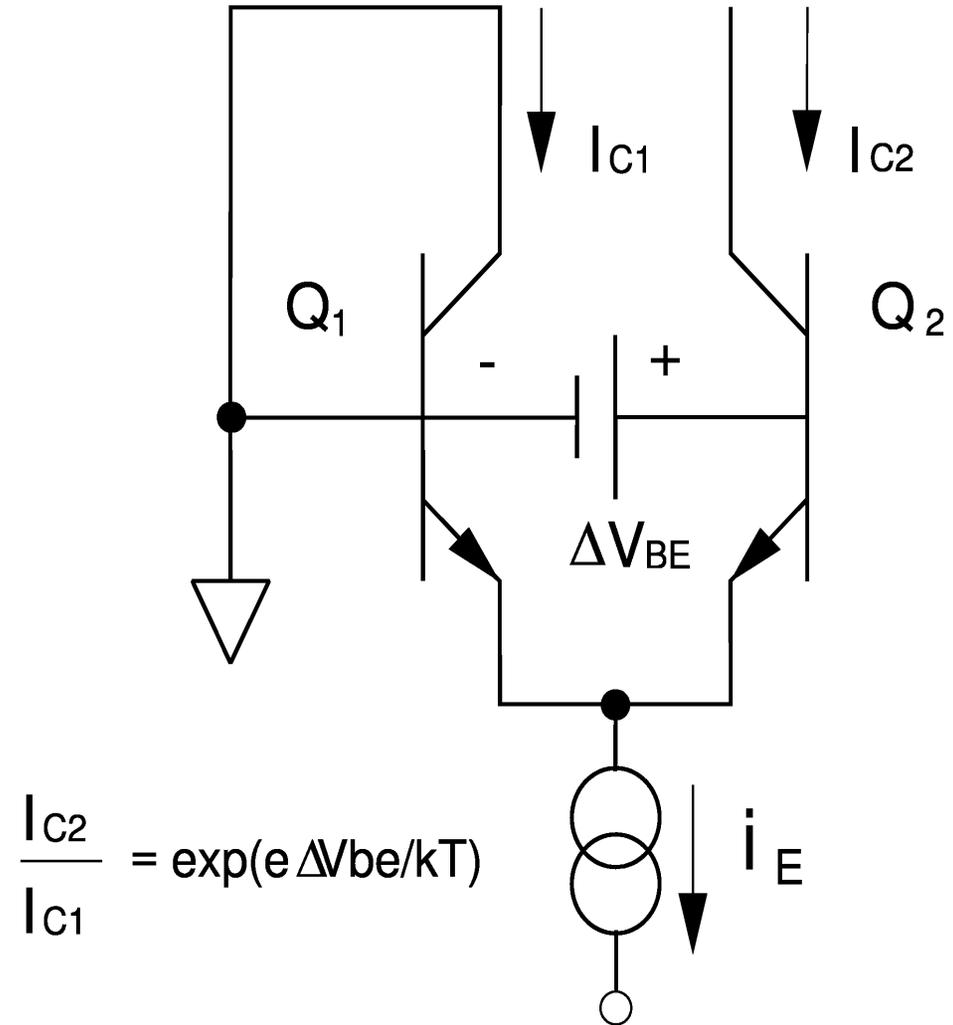
Differential Detection Ought To Be Perfect



- 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:
 $\Rightarrow I_{sig}/I_{comp} == I_{sig}/I_{comp}$ (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

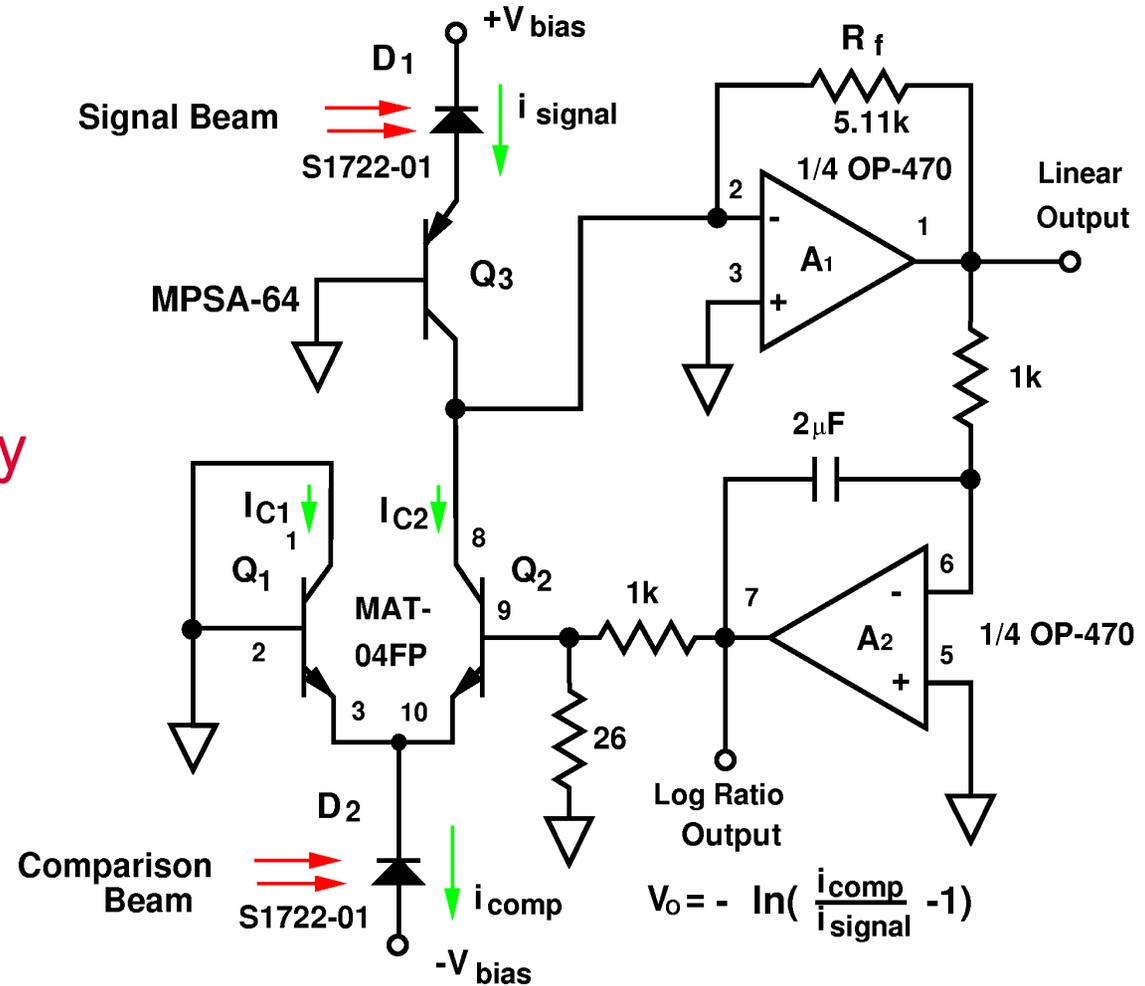
BJT Differential Pair

- With fixed ΔV_{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 ΔV_{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 ΔV_{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 (ΔV_{be})
- $1k::26\Omega$ divider gets rid of kT/e factor in ΔV_{be}
 [$2V \iff \exp(1)$]



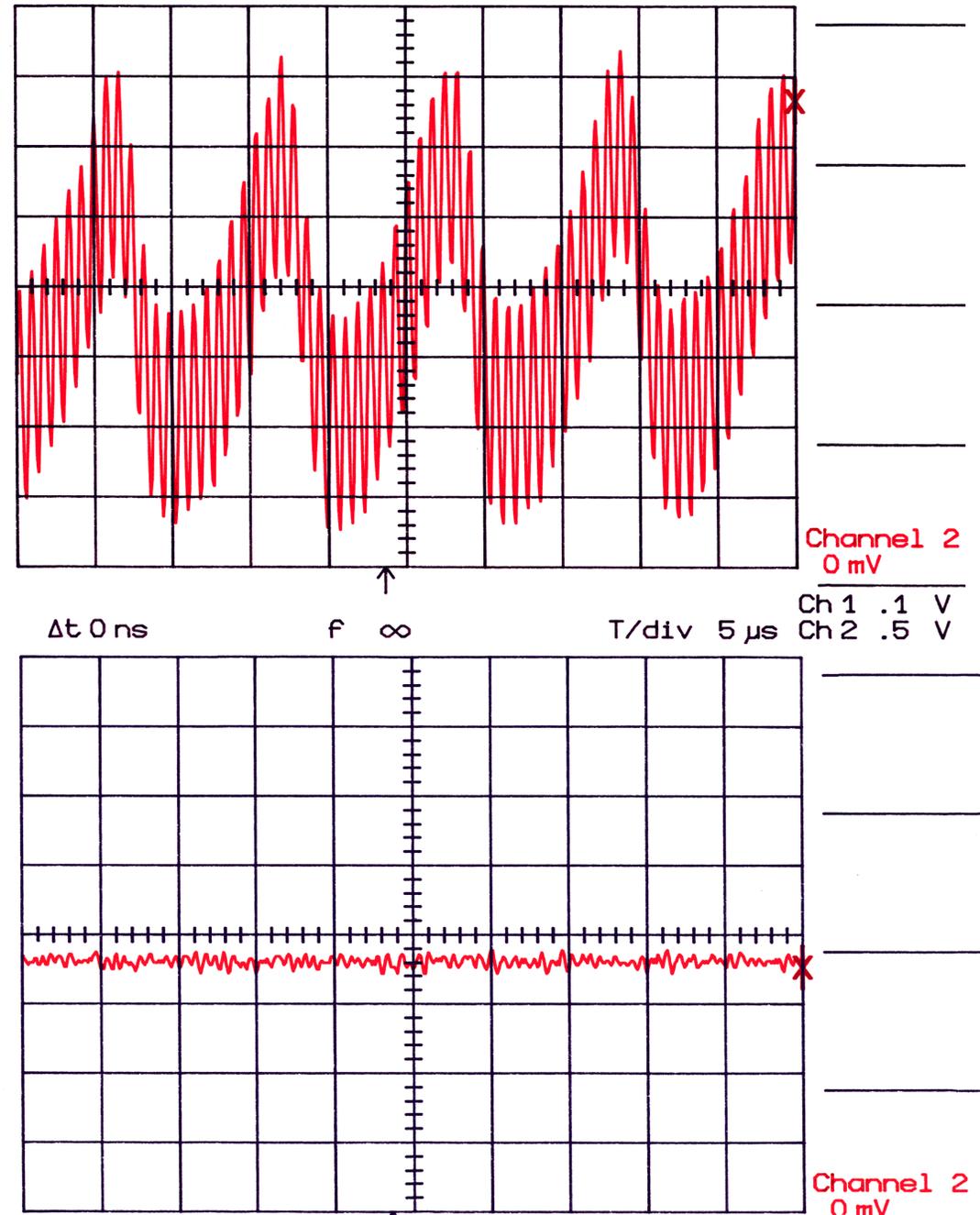
Performance: Cancellation

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)

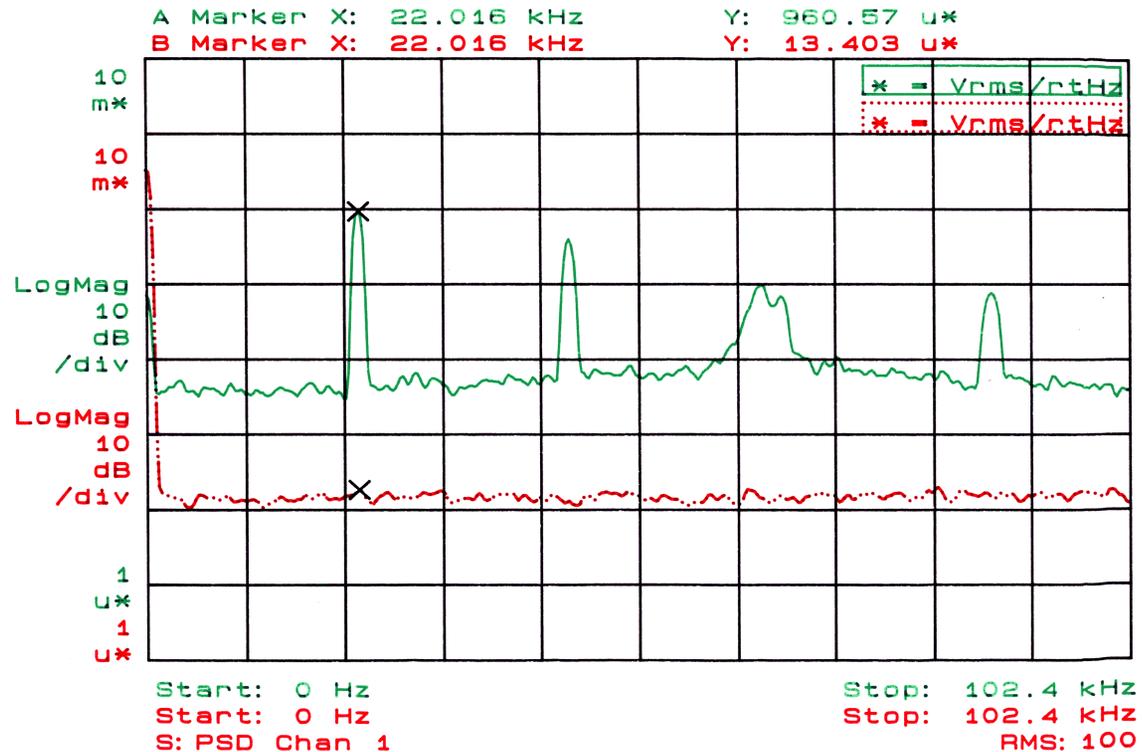
3N3904 discrete BJT
0.75 mW P_{sig} , 1.5 mW P_{comp}



Performance: Cancellation

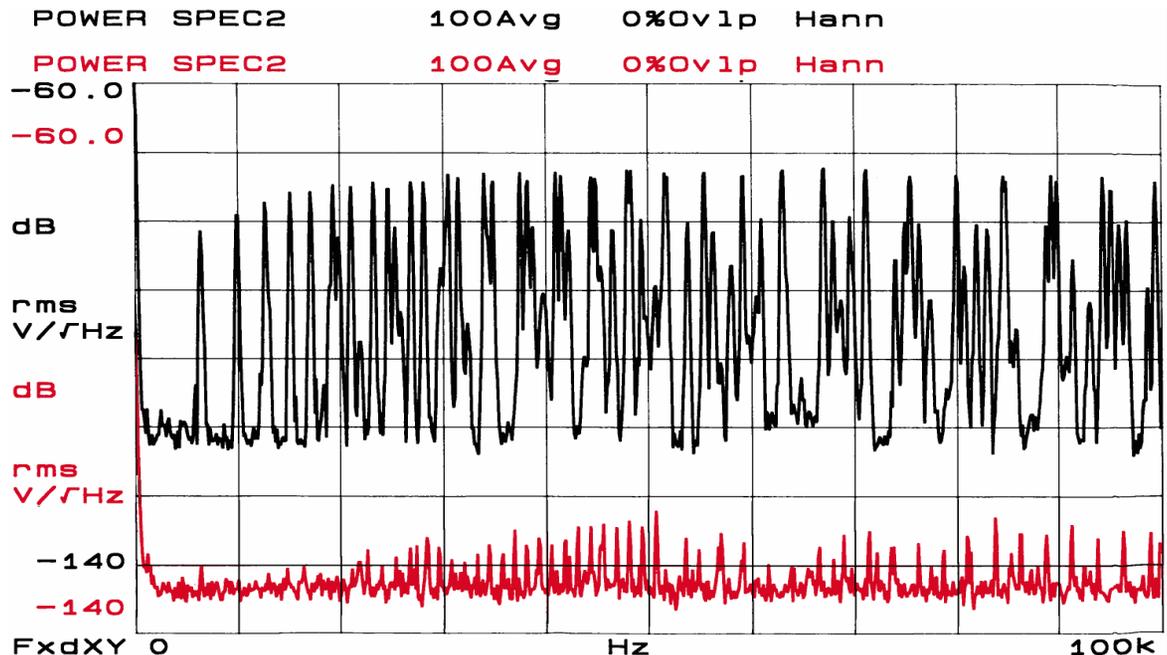
He-Ne in quiescent period
 Upper: TIA mode, showing
 noise and 22 kHz ripple
 Lower: Cancellation to
 0.5 dB above shot noise

AVERAGE COMPLETE



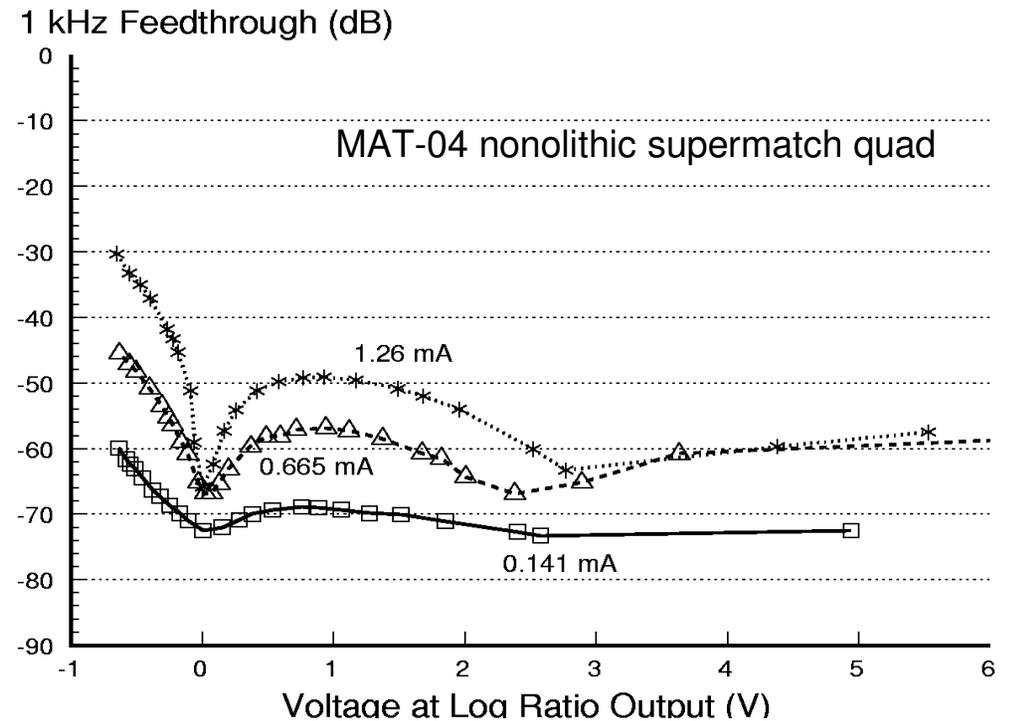
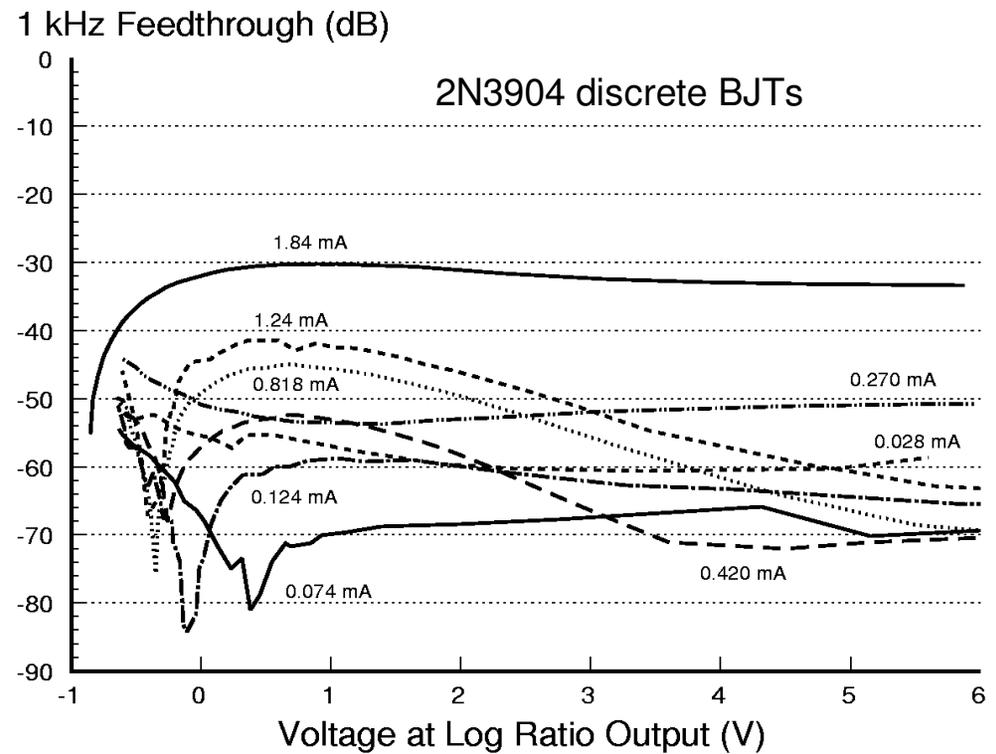
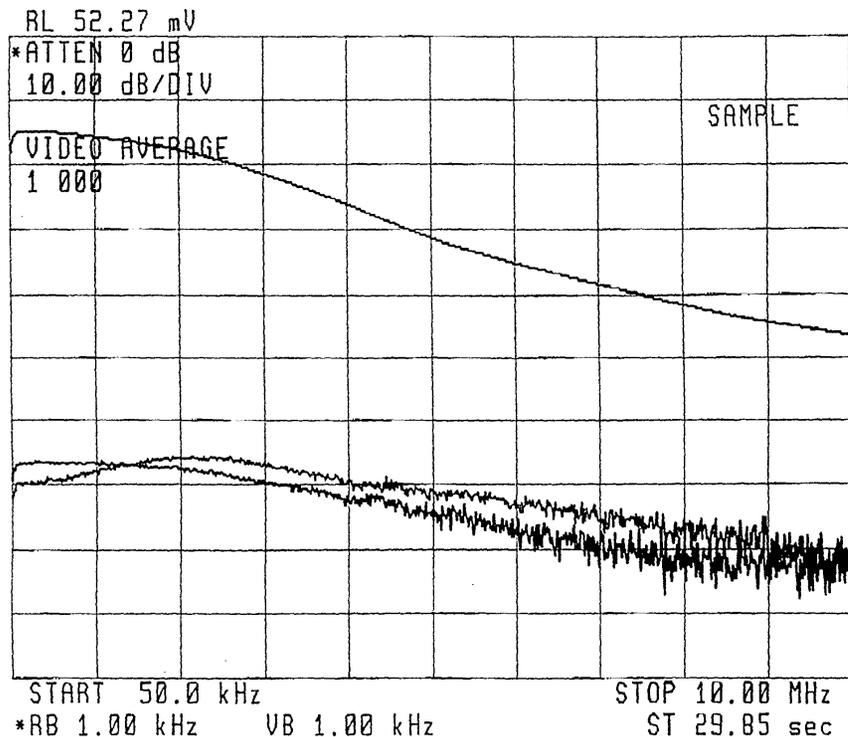
Envelopes of 100 scans,
 showing mode beats sweeping
 Upper: TIA mode
 Lower: >50 dB cancellation,
 even with multiple modes

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



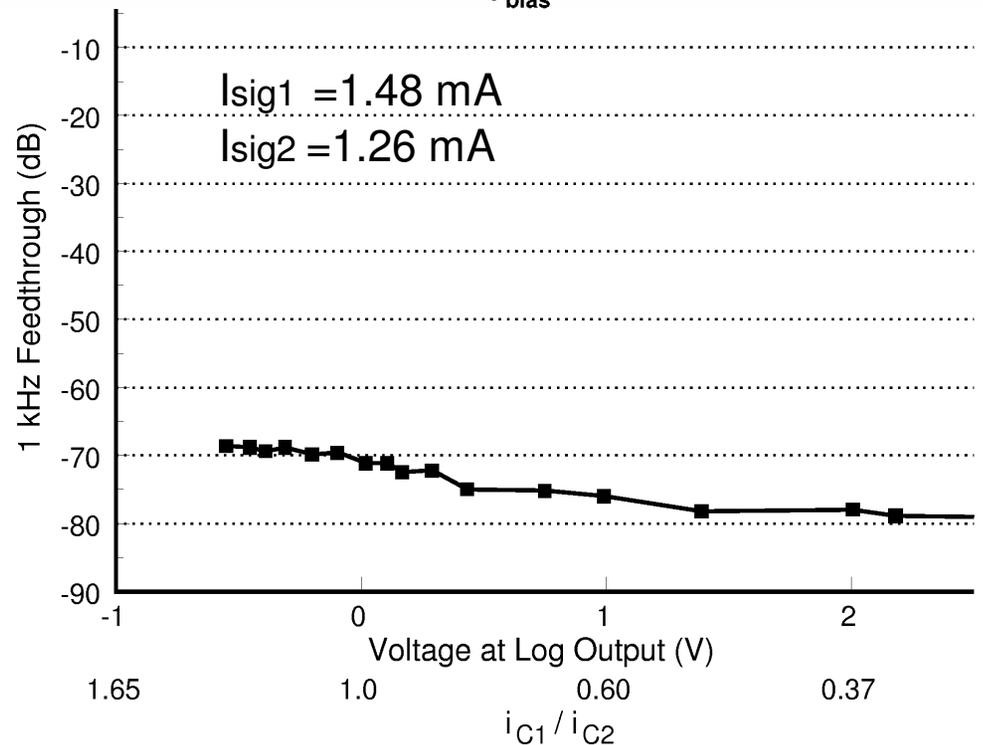
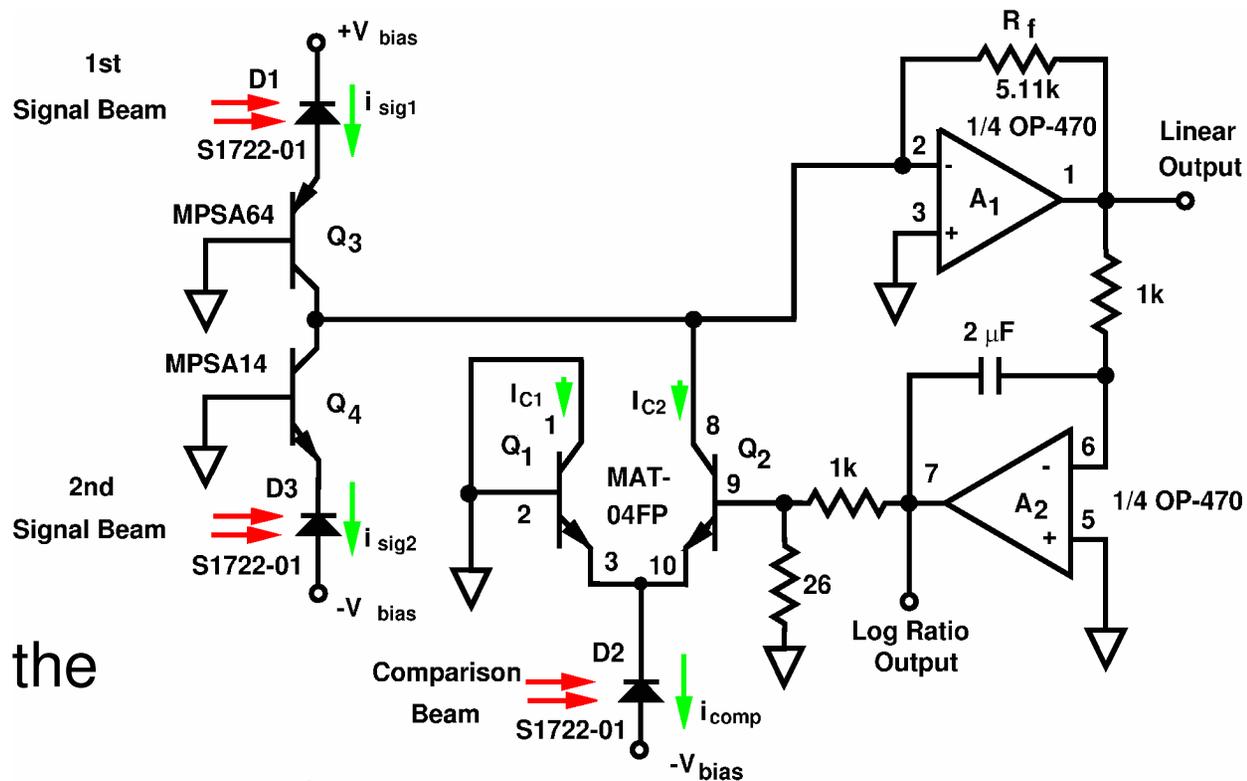
Performance: Cancellation

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



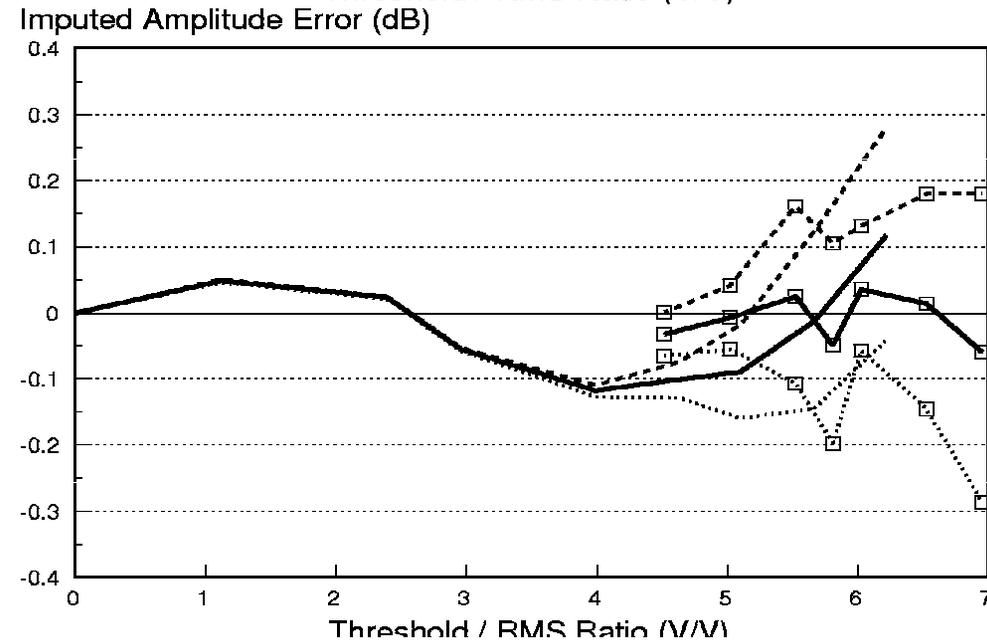
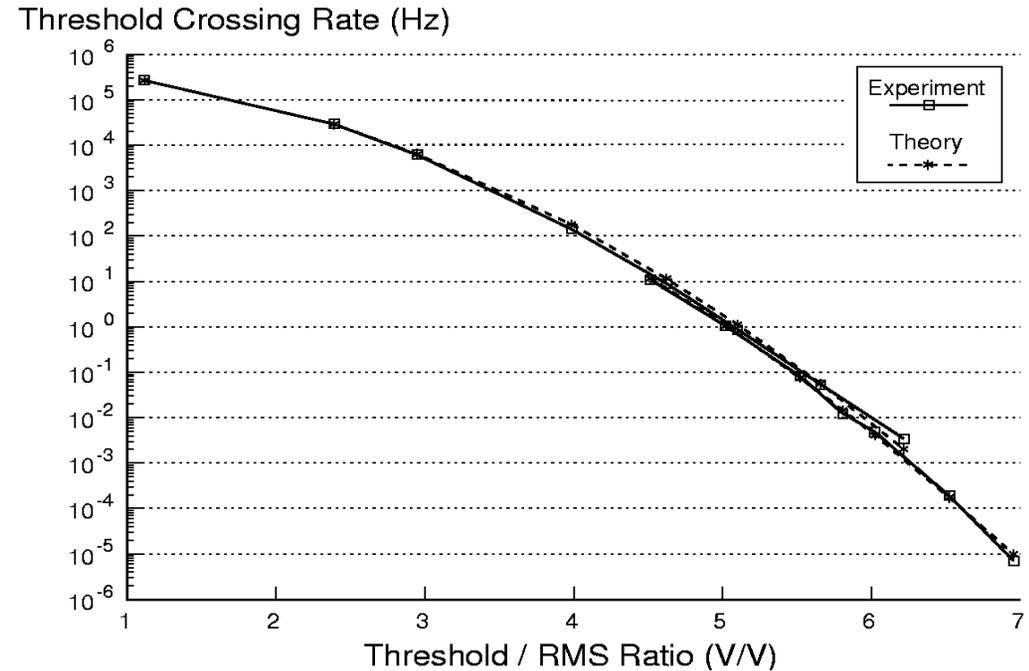
Differential Version

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



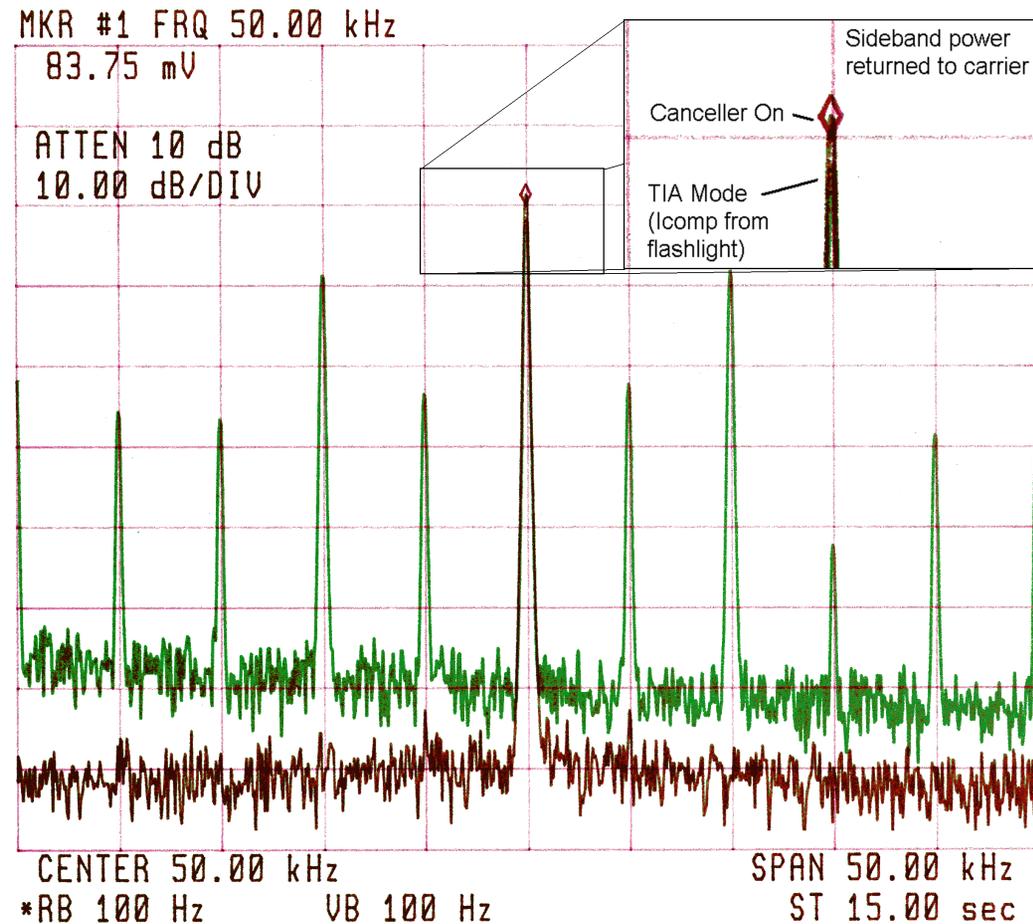
Shot Noise False Alarm Rate

- 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 μ Hz)
- Imputed error ~ 0.1 dB over full range (1-parameter fit to exact noise BW)



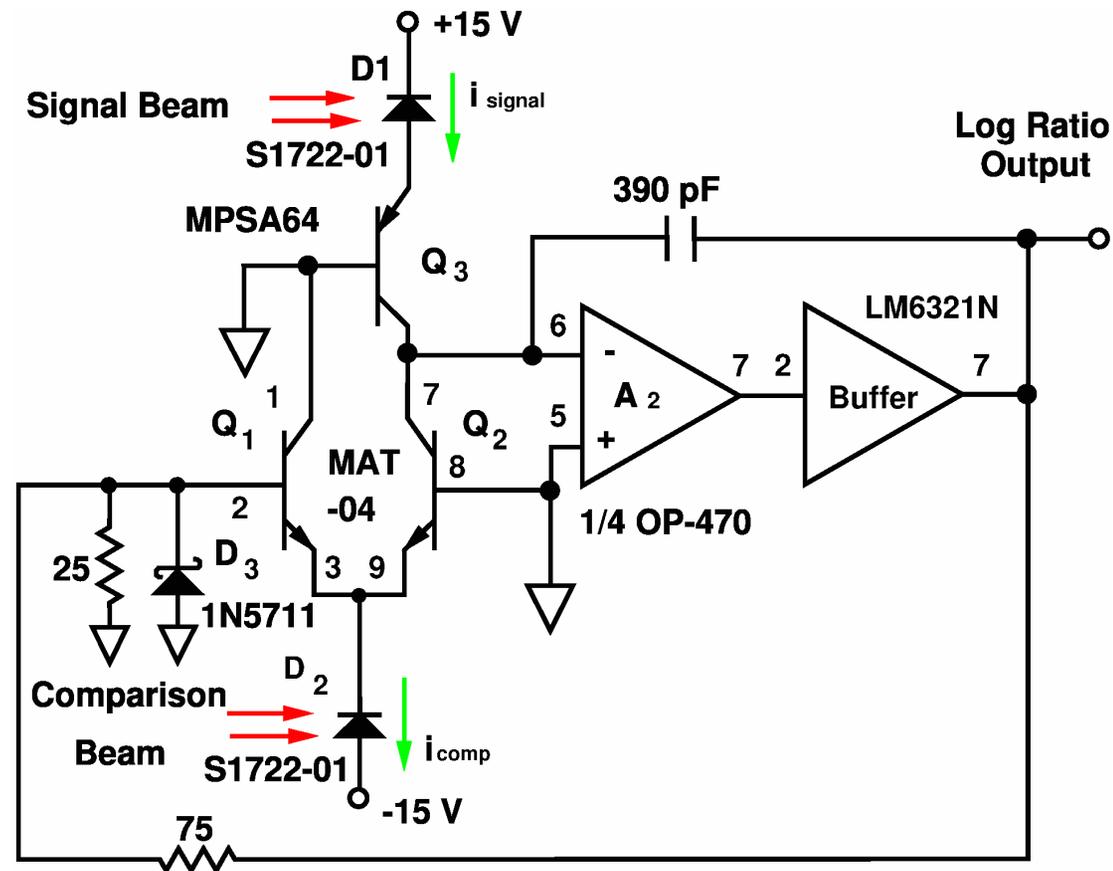
Multiplicative Noise

- 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!



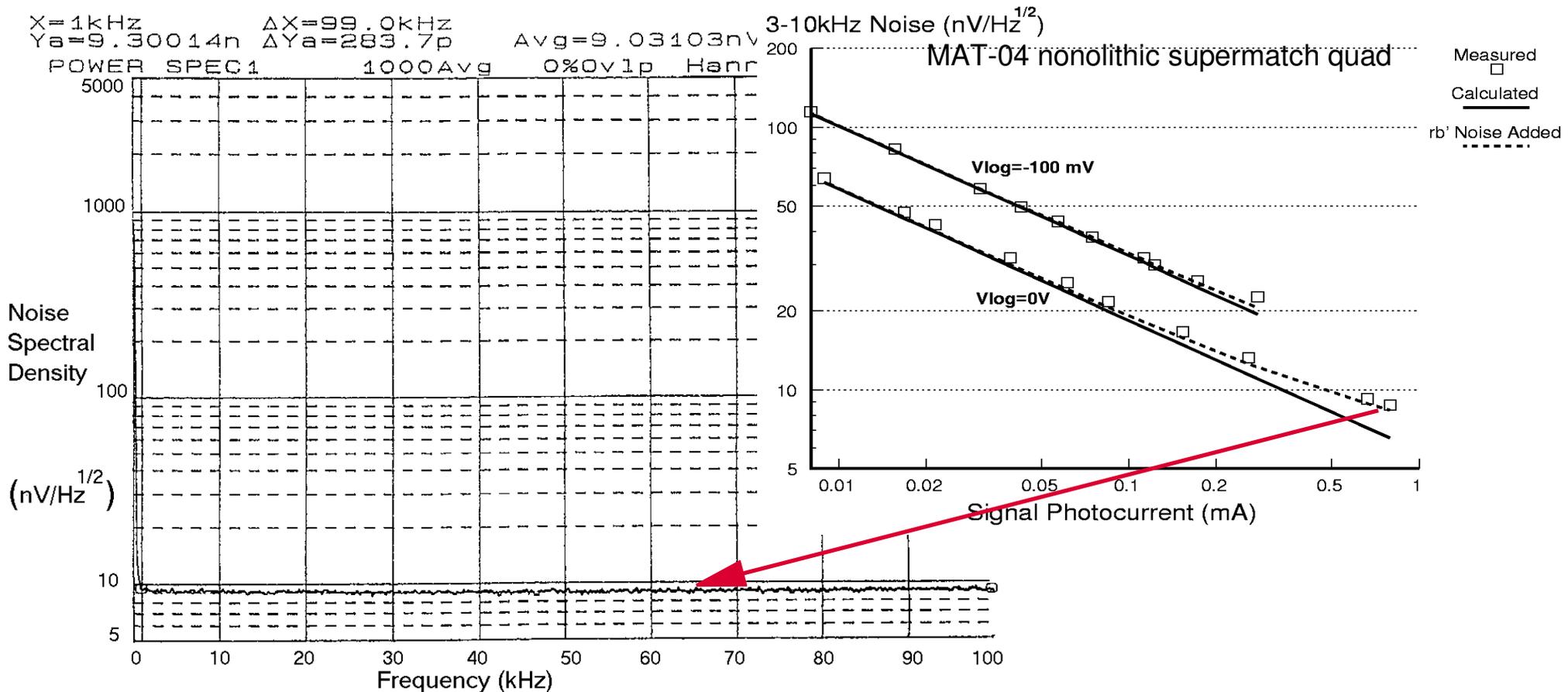
Log-Ratio Only Version

- 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



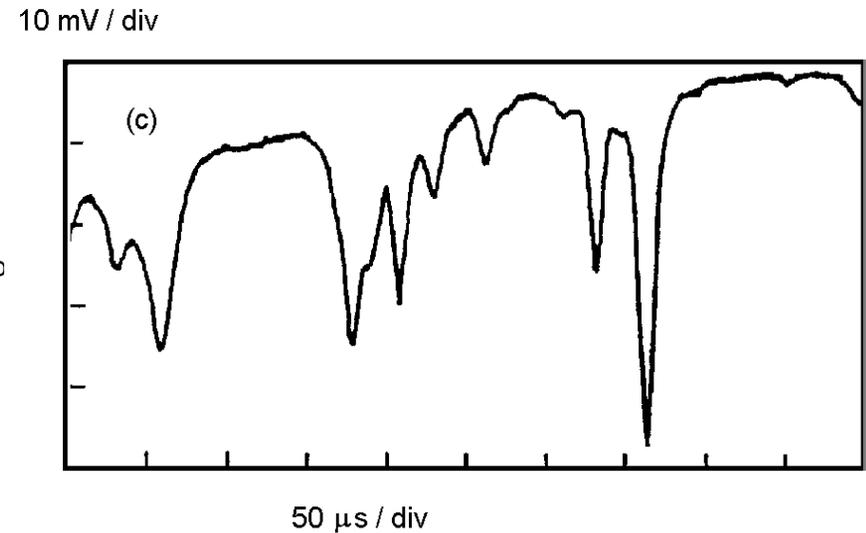
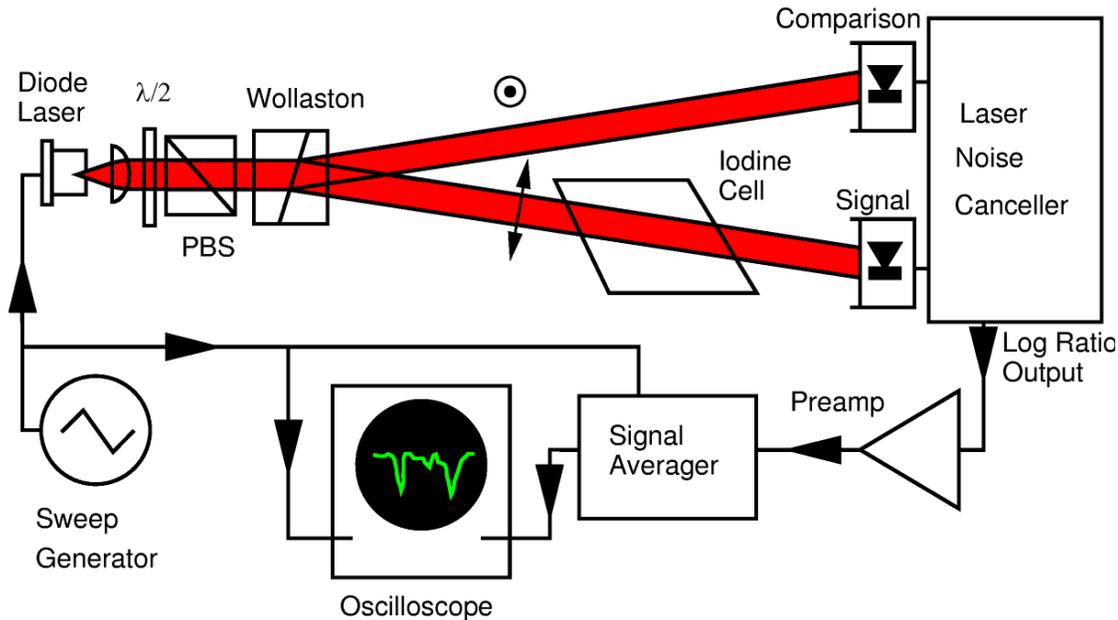
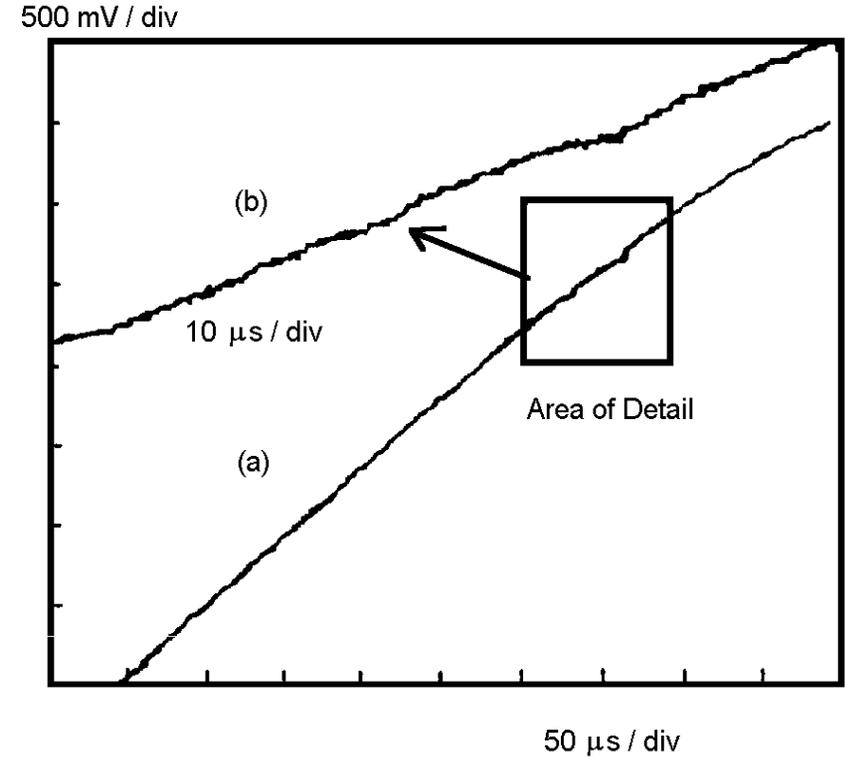
Performance: Log Noise Floor

- 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 $dP/d\omega$ ($\Delta P \sim 30\%$ 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

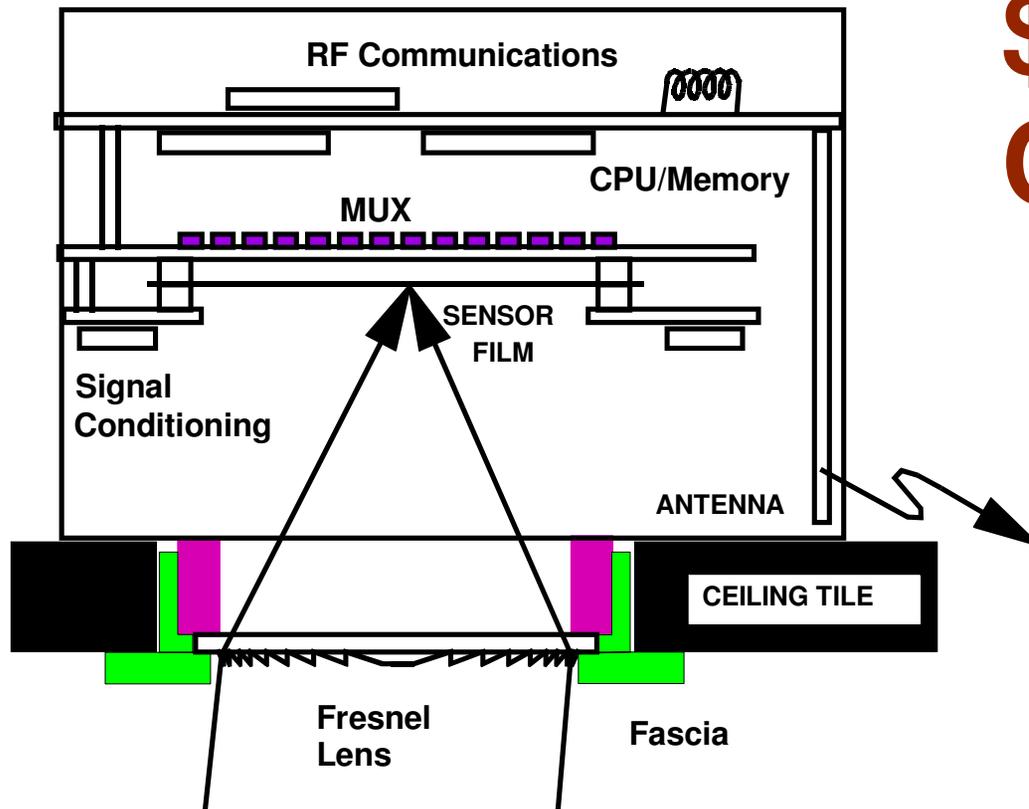
Setup & Testing

- 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_{comp} in log ratio mode (ΔV_{be} constant)
 - ▶ Compare I_{comp} and I_{sig} to ΔV_{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

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

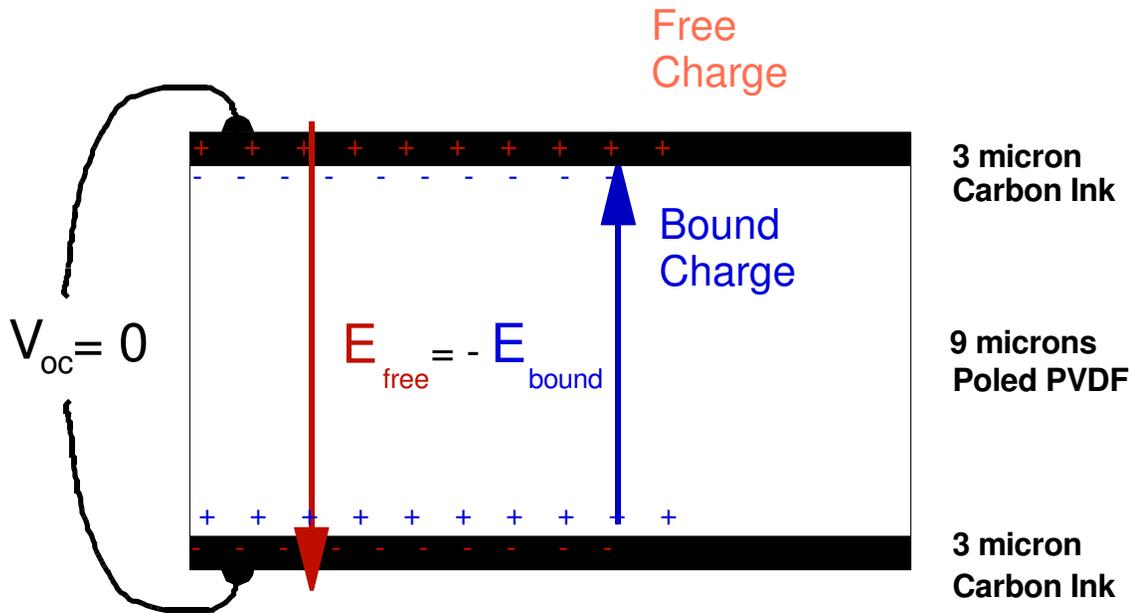
\$10 Pyroelectric Camera



Array of Distributed Pyroelectric Sensors

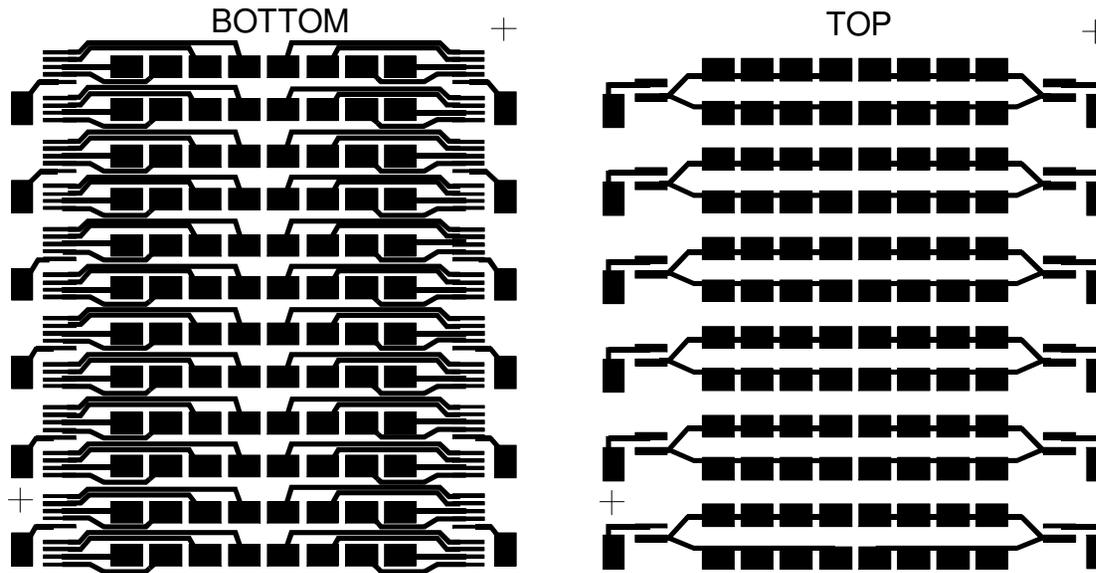
- Sensors Mounted In Ceiling
 - ~ 100 pixels/sensor
- 100-1000 Sensors Per Store (100-200 sq ft each)
- Base Manufacturing Cost: \$50-100

Pyroelectric Effect



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

Multiplexed Pyroelectric Array



Footprints IR Sensor Photomask Rev C: POSITIVE TONE

Phil Hobbs, June 25, 1999

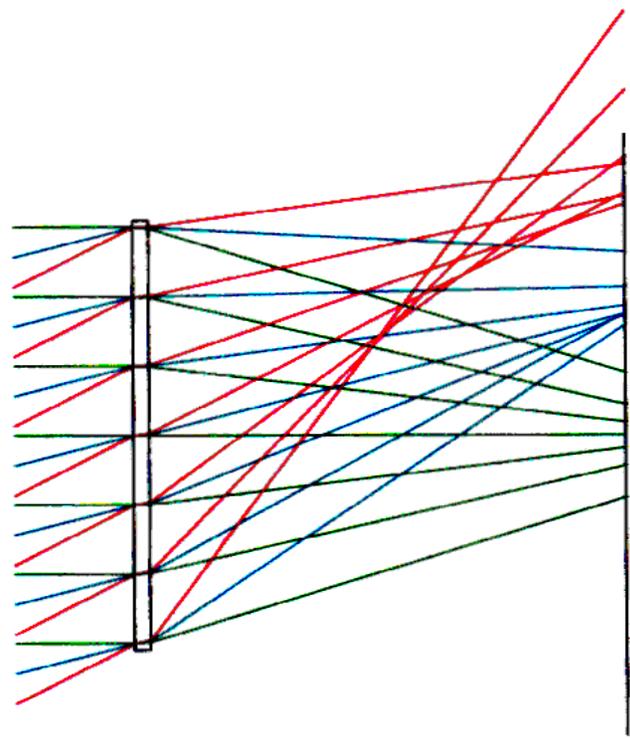
IR FPA sensitivity, porch-light cost

- Free-Standing PVDF Film In Air
- 8 x 12 Array, 6 mm Pitch
(Tee-shirt Lithography)
- Needs Fancy Multiplexer

IRstart1
OPTICAL SYSTEM LAYOUT

UNITS: MM
DES: Budd

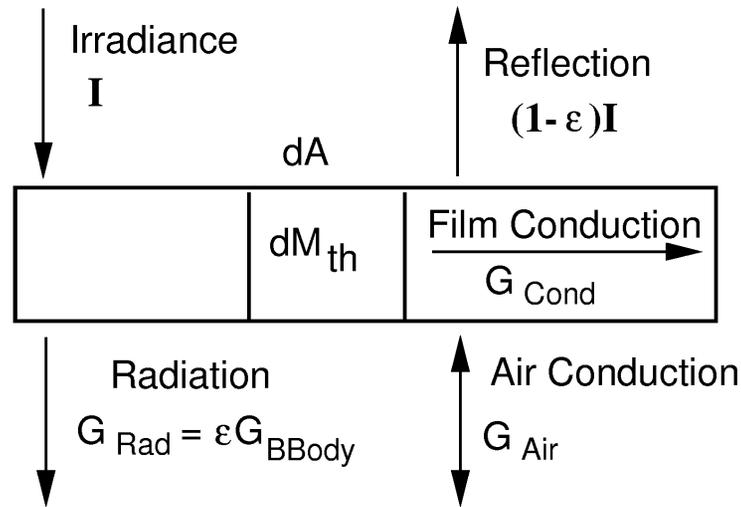
25



Thermal Design

Slow is Beautiful

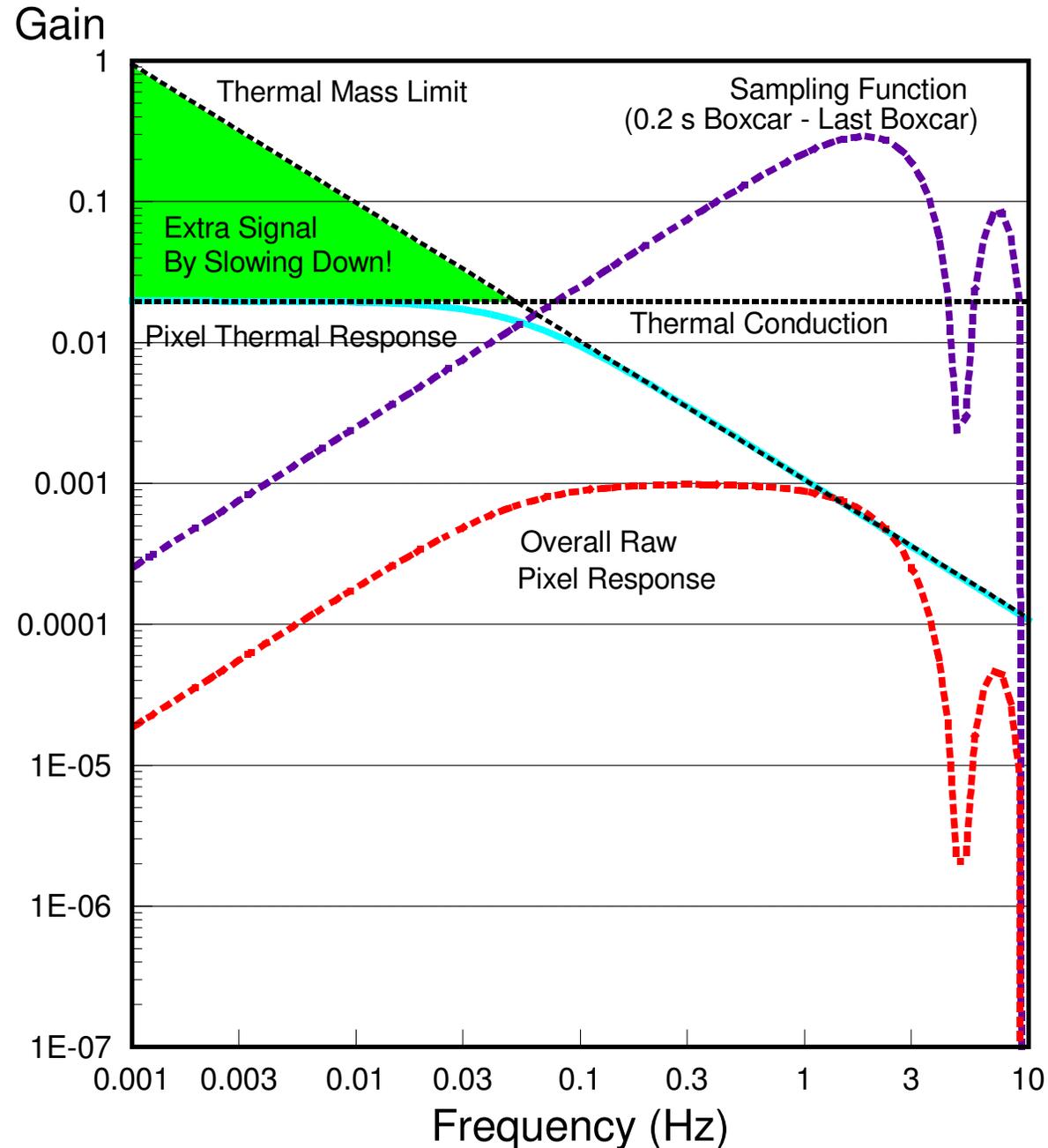
- Signal Power $\sim G^{-2}$
 - Johnson Noise Is Flat
 - (Fluctuation PSD $\sim G$)
 - Bandwidth $\sim G/M_{th}$
 - Johnson-Limited SNR $\sim 1/G$
- \Rightarrow Insulate the Sensor & Filter Data To Recover BW



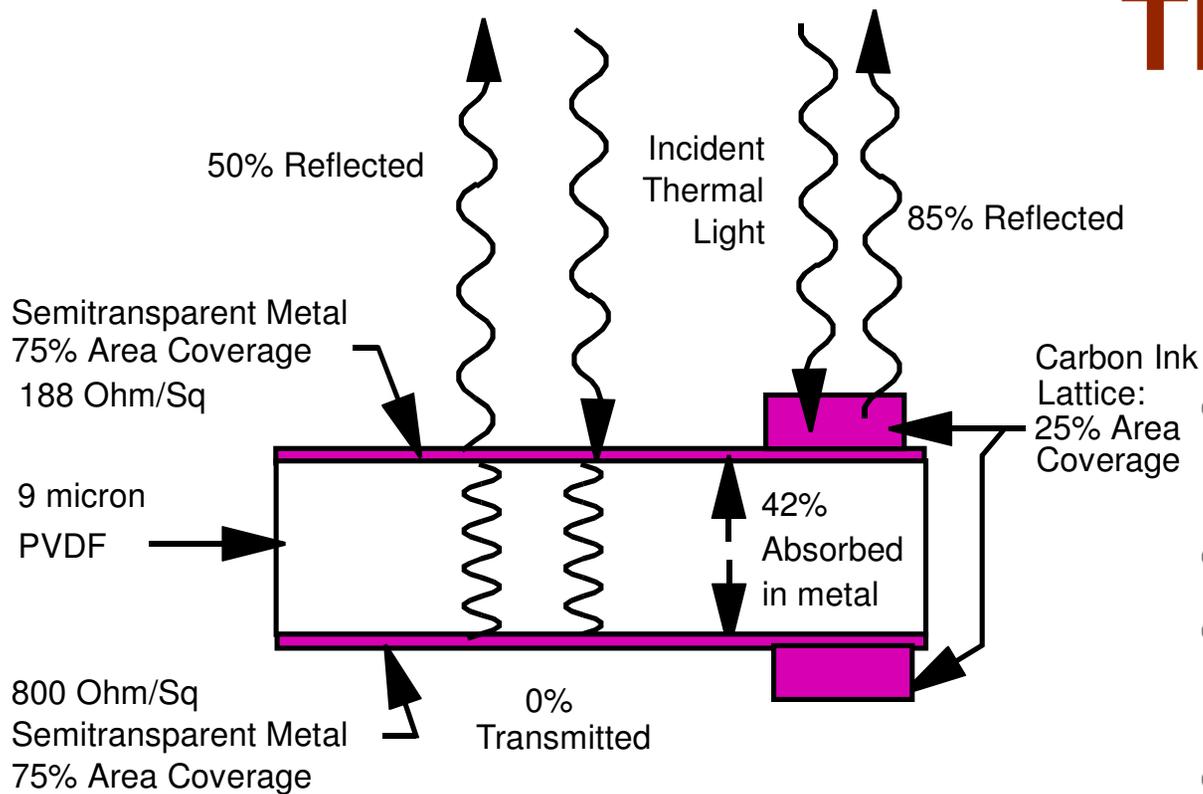
$$G_{Total} = G_{Rad} + G_{Cond} + G_{Air}$$

$$\Delta T = \epsilon I / G_{Total}$$

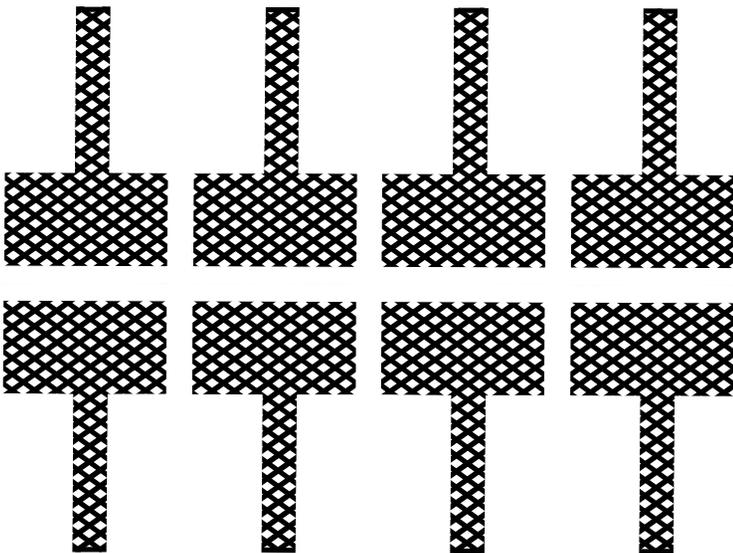
$$dT/dt = (\epsilon I - G_{Total} \Delta T) / (dM_{th} / dA)$$



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 ΔT
- Ink lattice on tuned metal should give ~ 20 dB more signal



Sensor Design: Multiplexer

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

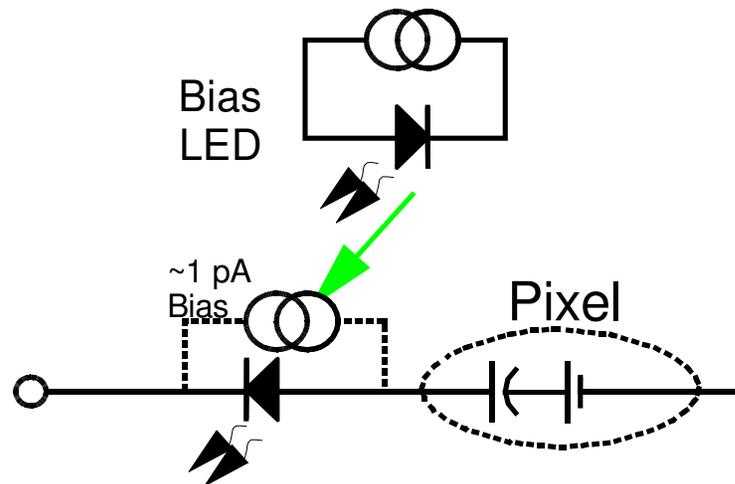
- Nanoamp Leakage
- Control And Data Paths Not Separate
- **Unidirectional And Nonlinear: Bias Required**

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

- 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 V $< V_F < +0.5$ V**

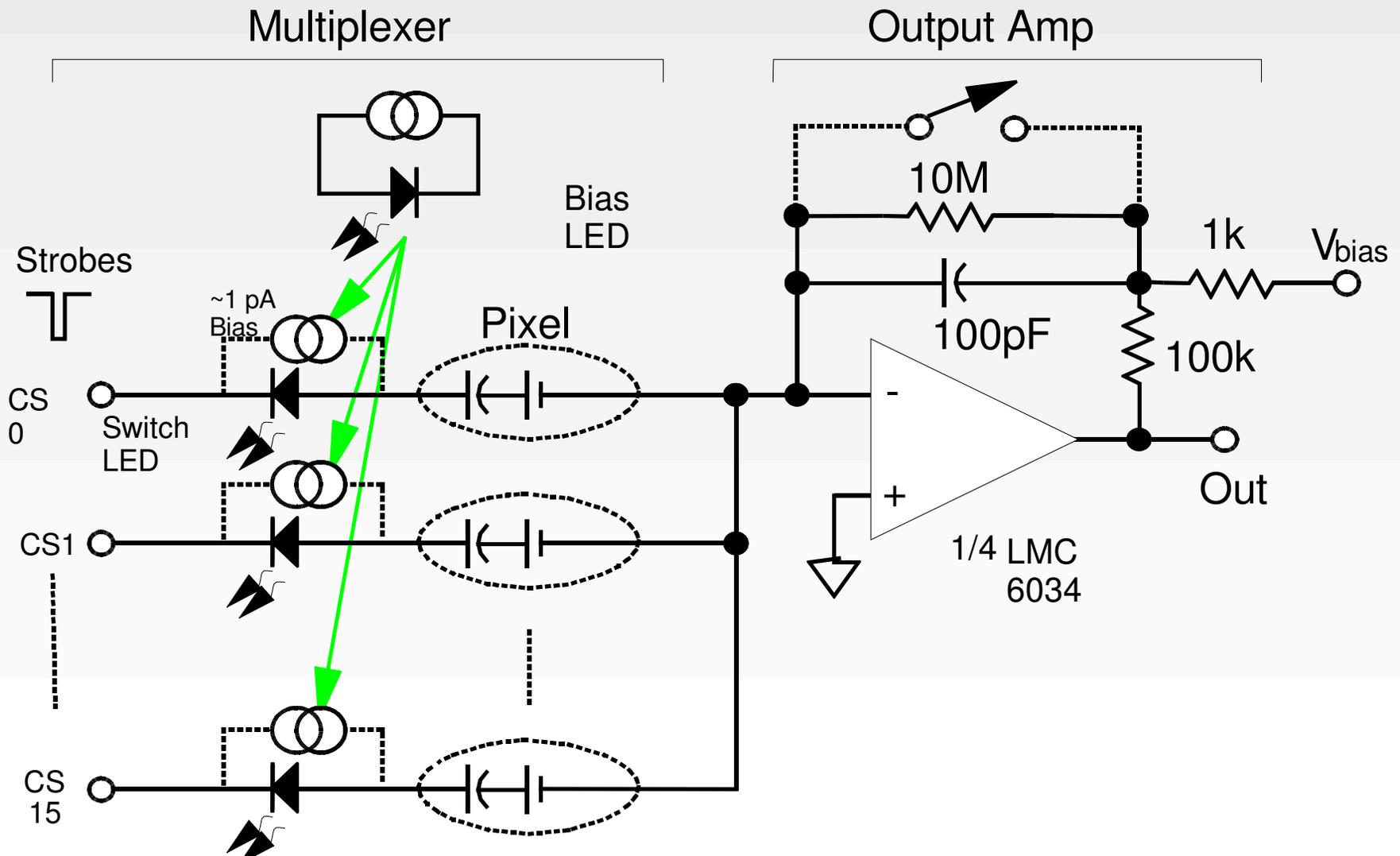
Biasing Hack

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

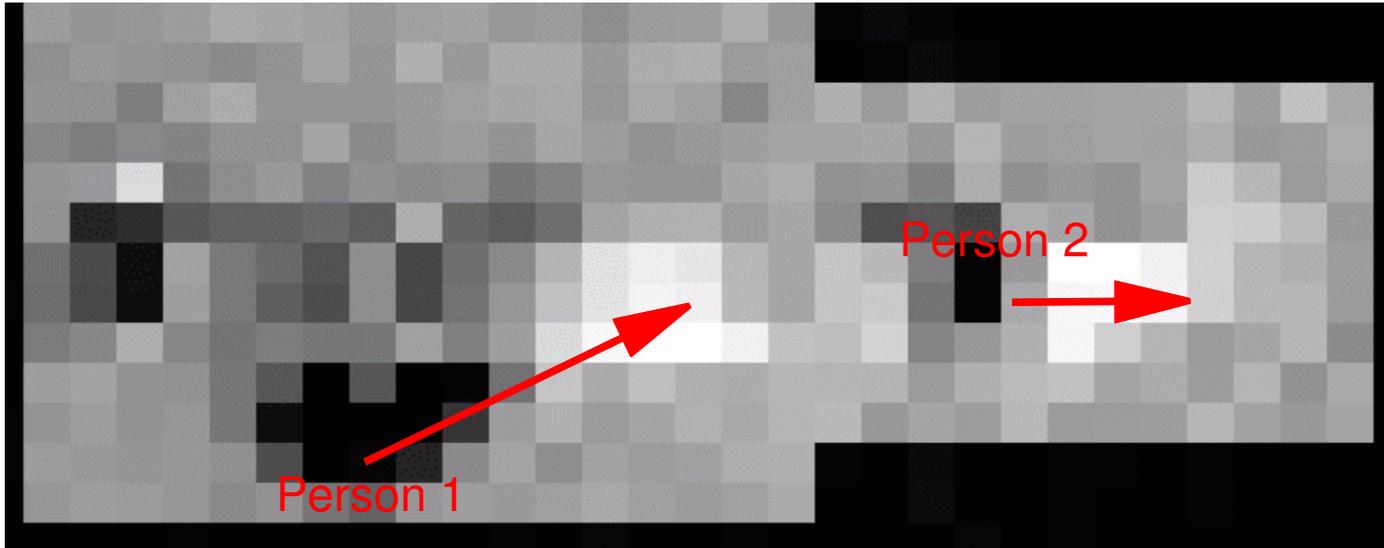


- LED Is a Photodiode Too
- Use Diffused Light From CPU-Throttled LEDS
- 1 mA LED Drive => 1 pA Bias
- **Switch + Adjustable Bias = 1 LED @ \$0.05/Pixel**

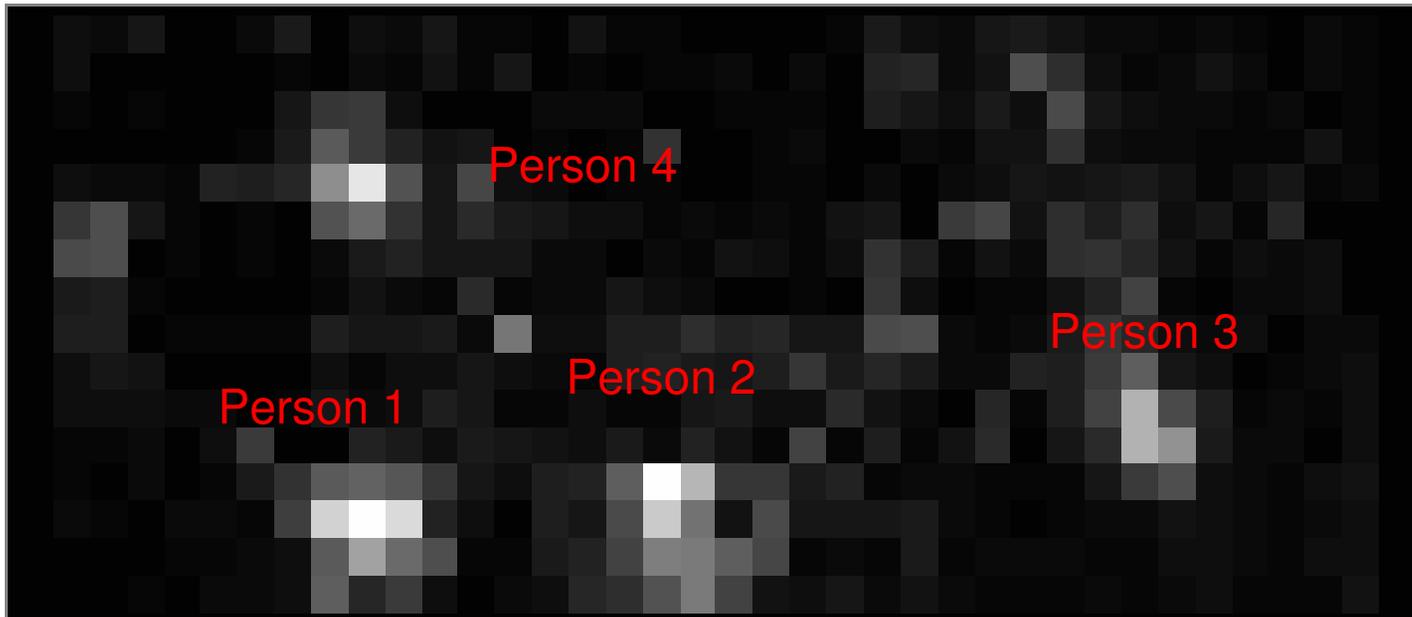
LED Mux Schematic



Footprints Data



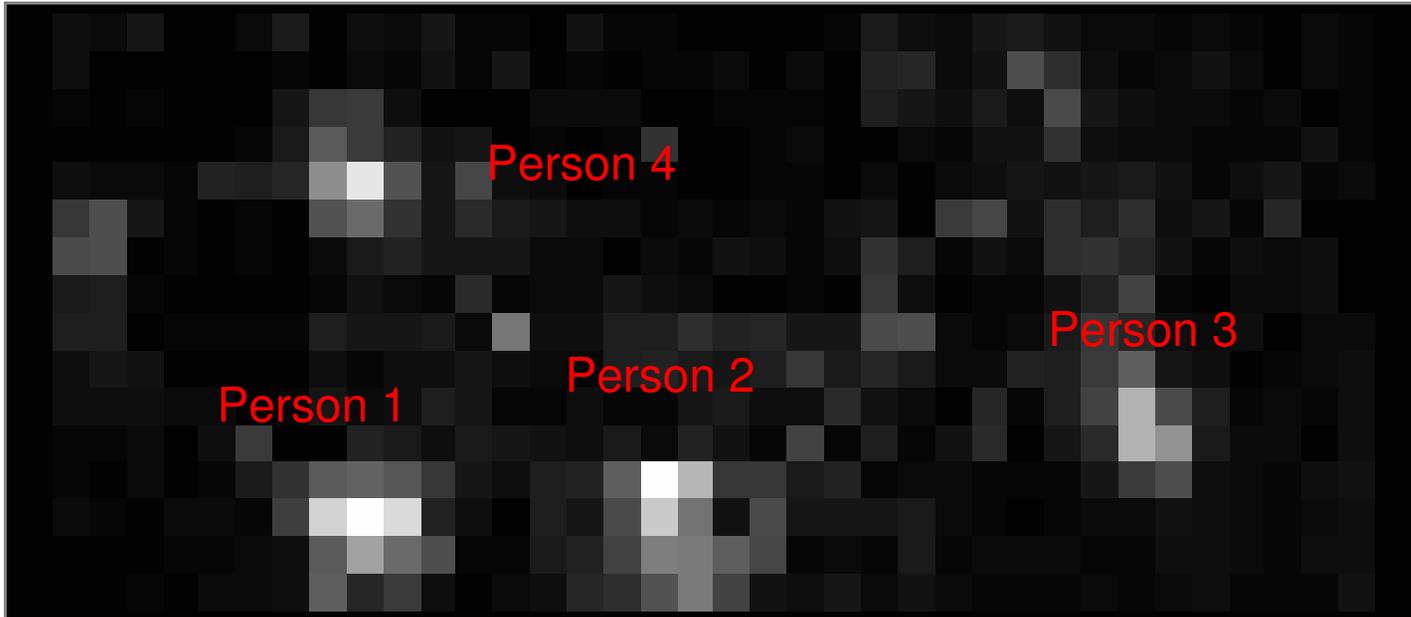
(Raw data,
1 sq ft pixels,
28 um metallized
PVDF)



(Pseudo-integral,
1 sq ft pixels, 4 um
carbon ink on 9 um
PDF)

Footprints Data

1714nox6.avi



(Pseudo-integral,
1 sq ft pixels, 4 um
carbon ink on 9 um
PDF)

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 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

$$I_{dc} \propto \underbrace{\left(|\psi_1|^2 + |\psi_2|^2 \right)}_{\text{DC}} + \underbrace{2 \operatorname{Re} \left\{ \psi_1 \psi_2^* \right\}}_{\text{Interference}}$$

- ▶ 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 $\gg \gg$ 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

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
 - ▶ $NF = 10 \log[(SNR \text{ before}) / (SNR \text{ after})]$ (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)
 - ▶ $T_N \ll T_{\text{ambient}}$! (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 $T_N = T_{\text{amb}} / 2$,
 - ideal BJT base has $T_N = T_{\text{amb}} / (2\beta)$ --same noise voltage, β 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 100 Ω or 25 Ω)
- ▶ 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?

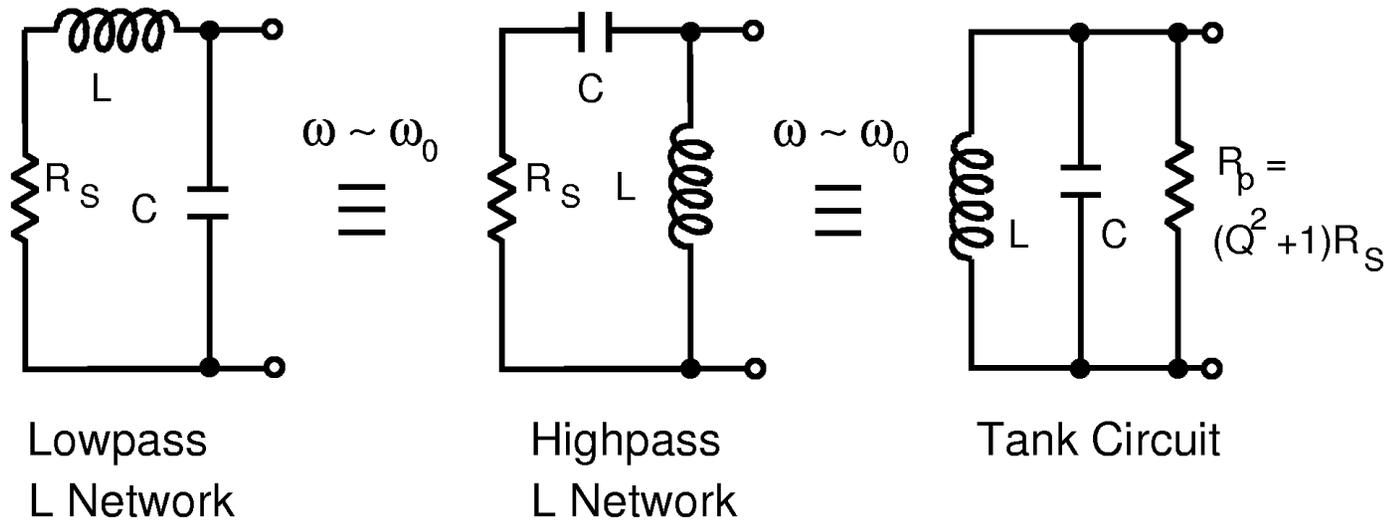
- ▶ Bode theorem specifies tradeoff between BW and efficiency

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

- $|G|_2$ is the return loss (fraction of power reflected from the load)
- RC has 1.03 dB average passband loss (to 3 dB points)
- Choose $|G|_2=0.21$ (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
 - ▶ $|G|_2=0.5$ gives 9x BW @ 3 dB loss

L-Network or Series Peaking

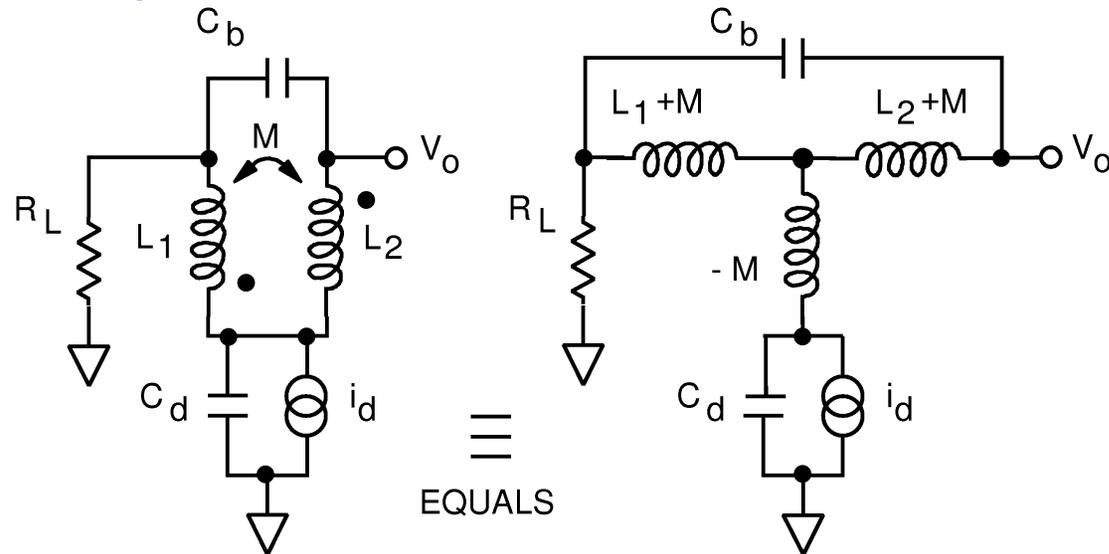
► Simplest Reactive Network



- Moves RC bandwidth from DC to f_0 (same BW, settling time doubled)
 - $Q = X/R$ [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 $Q^2 + 1$**
 - 50Ω , $Q = 10 \Rightarrow$ effective RL = $5k\Omega$ (pure resistance at ω_0)
 - Can also be used at baseband for a 1.4x BW increase

Constant-Resistance T-Coil

► Tektronix Vertical Amplifier Secret

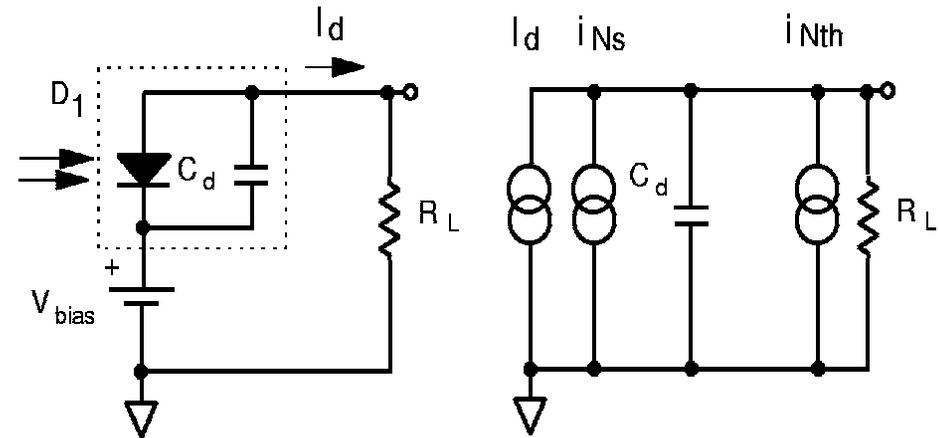


Doesn't waste current in R while there's C to charge

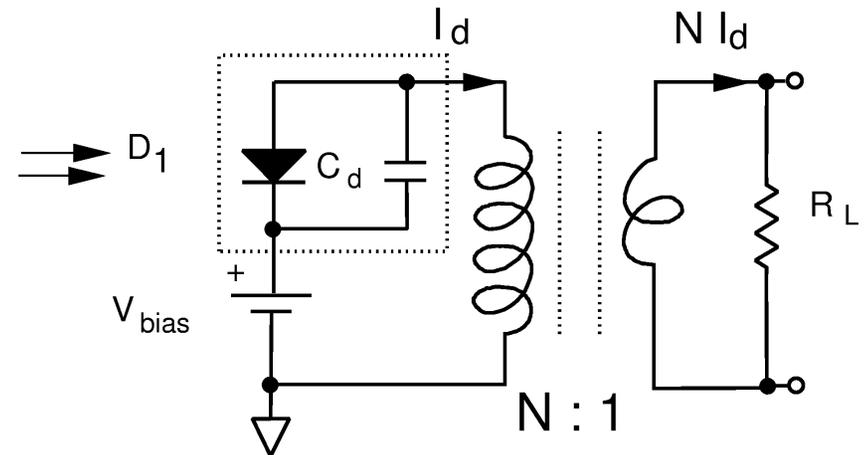
- 2.8x BW increase (at 3 dB points)
- No overshoot or ringing
- **Design equations available**
- Best simple network for baseband use (lowpass characteristic)
- Disadvantage: Load resistor and output are different nodes
 - Harder to get $T_N < 300K$ (may have to put active device in for R)

Example: 5 pF PD, DC-50 MHz

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



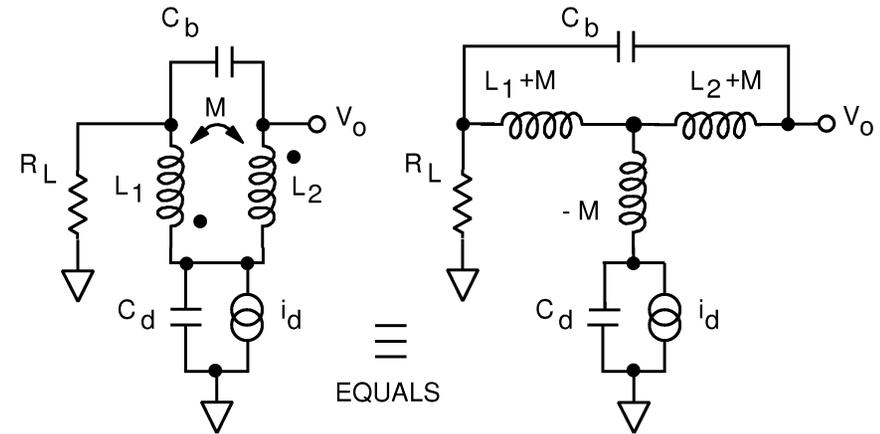
- 3:1 Turns Ratio Transformer (450 Ω)
 - ▶ $BW = 1/[2\pi(5\text{pF})(450\Omega)] = 70$ MHz
 - ▶ Shot noise limit: $I_{\text{phot}} \geq 115$ μA (300K), 13 μA (35K)
 - ▶ (DC current x AC resistance > 50 mV (300K), > 6 mV (35K))
 - ▶ *9 dB SNR improvement (Johnson limit)*



Example: 5 pF PD, DC-50 MHz

■ Constant-Resistance T-Coil:

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

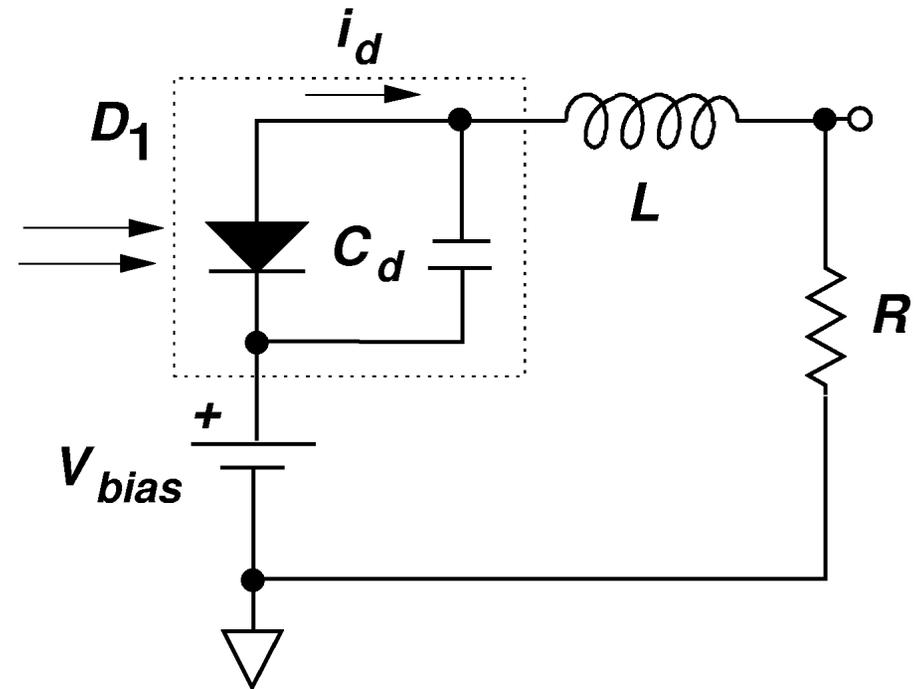


■ Bode Limit:

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



Detectors With Gain

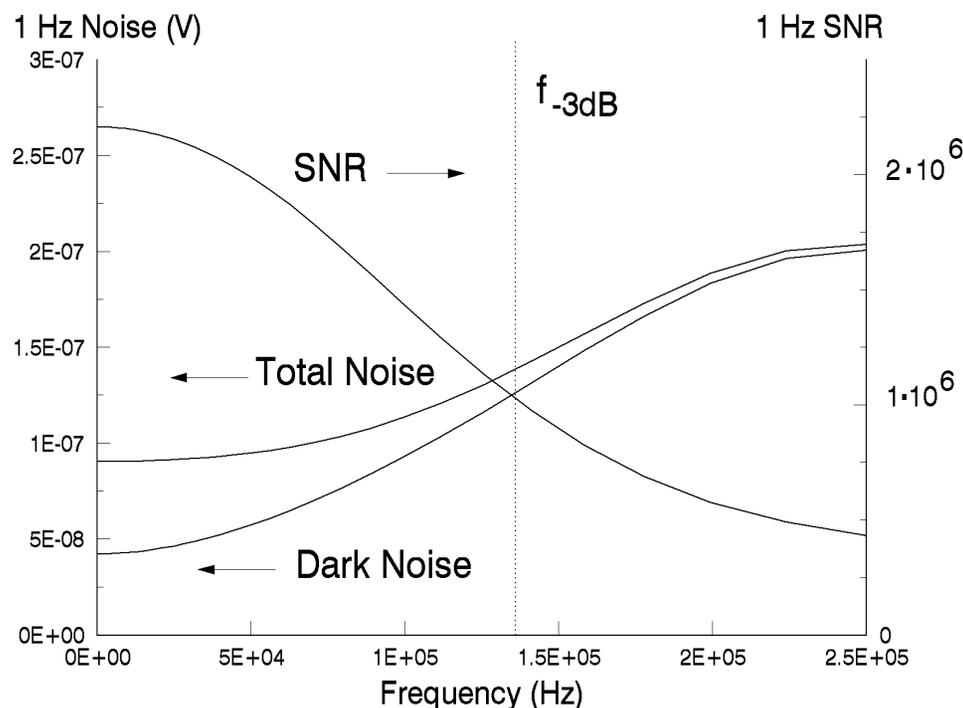
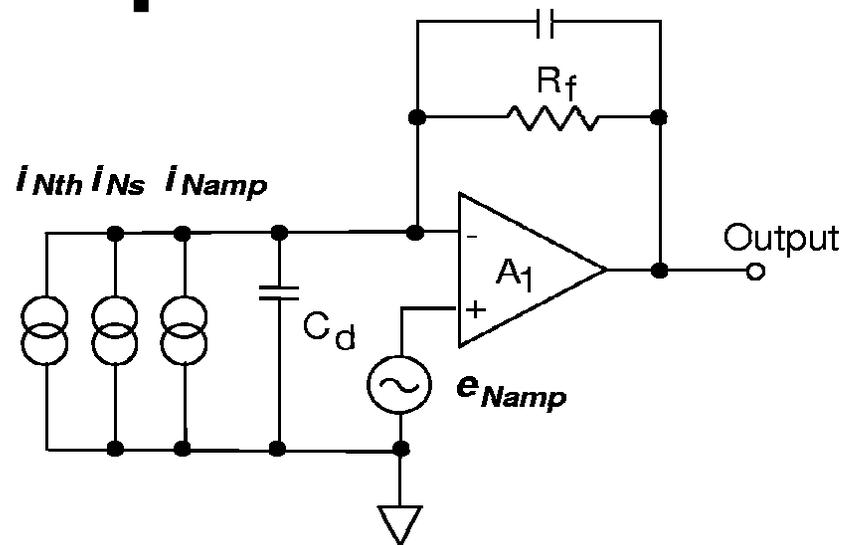
- **Electron Multiplication:** used in PMTs, APDs, & LLLCCDs
 - ▶ Gain applied to electrons before front end amplifier
 - ▶ Front end noise contribution reduced by M
 - ▶ Allows low load resistances => **increased BW**

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

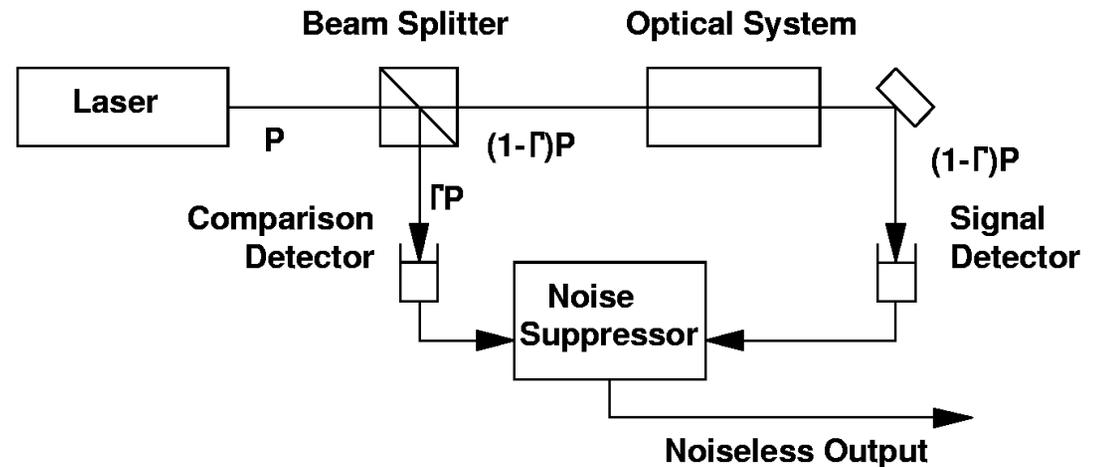
DIY Op Amps

- 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



Differential & Ratiometric Detection

- The beam that goes through the sample has our desired signal but is corrupted by laser noise.
- If we take a sample of the beam before it goes through the sample, it will have the identical laser noise but no desired signal.
- Dividing the two, or subtracting them when they are nearly equal, will suppress the noise and leave the signal.

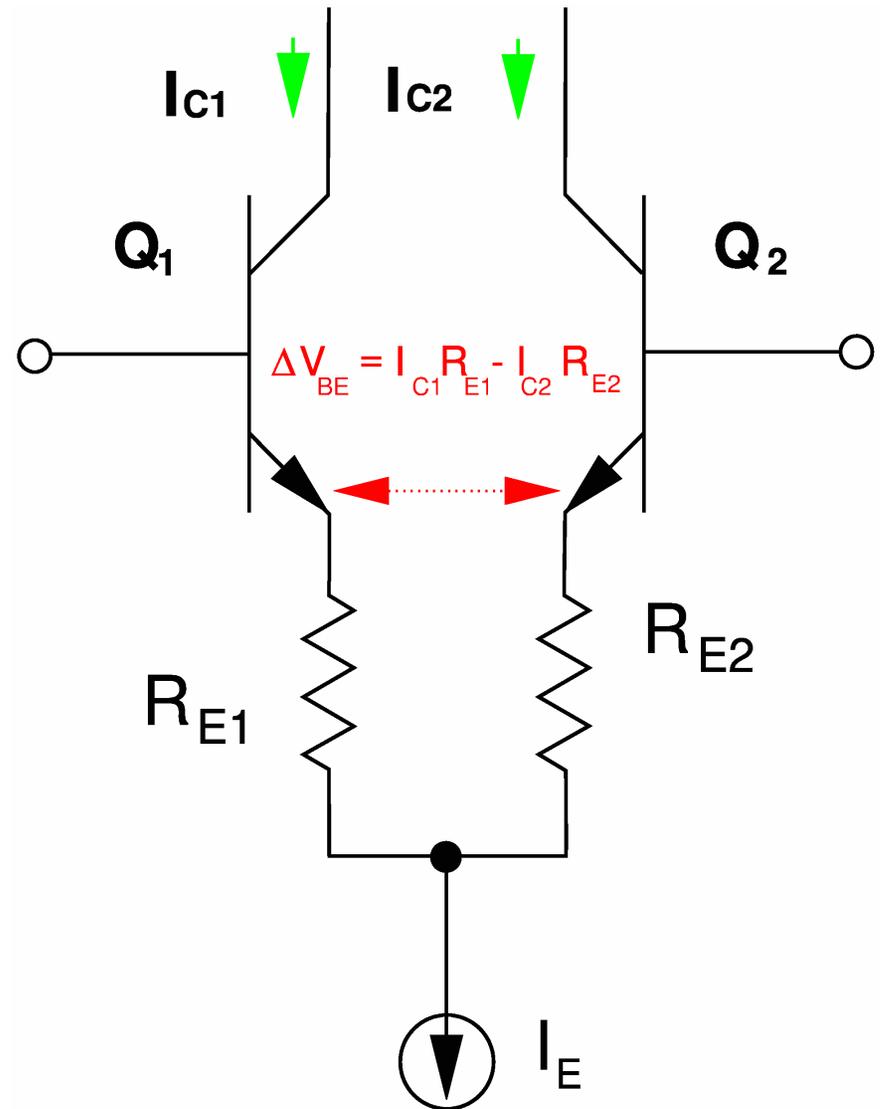


Noise Definitions

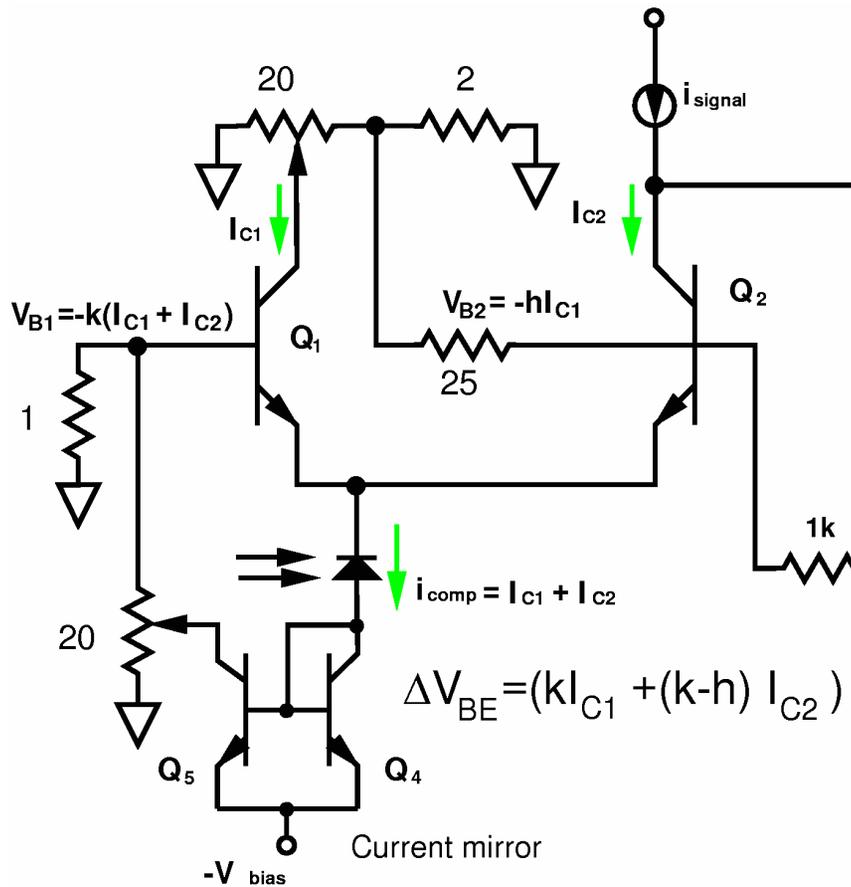
- Noise statistics are ensemble averages or short-time averages
 - ▶ They can be time-varying
- Signals at different frequencies add in power since beat term averages to zero
- Noise best specified as power spectral density (PSD): for reasonable bandwidths, think of this as noise in 1 Hz BW
 - ▶ p_N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

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

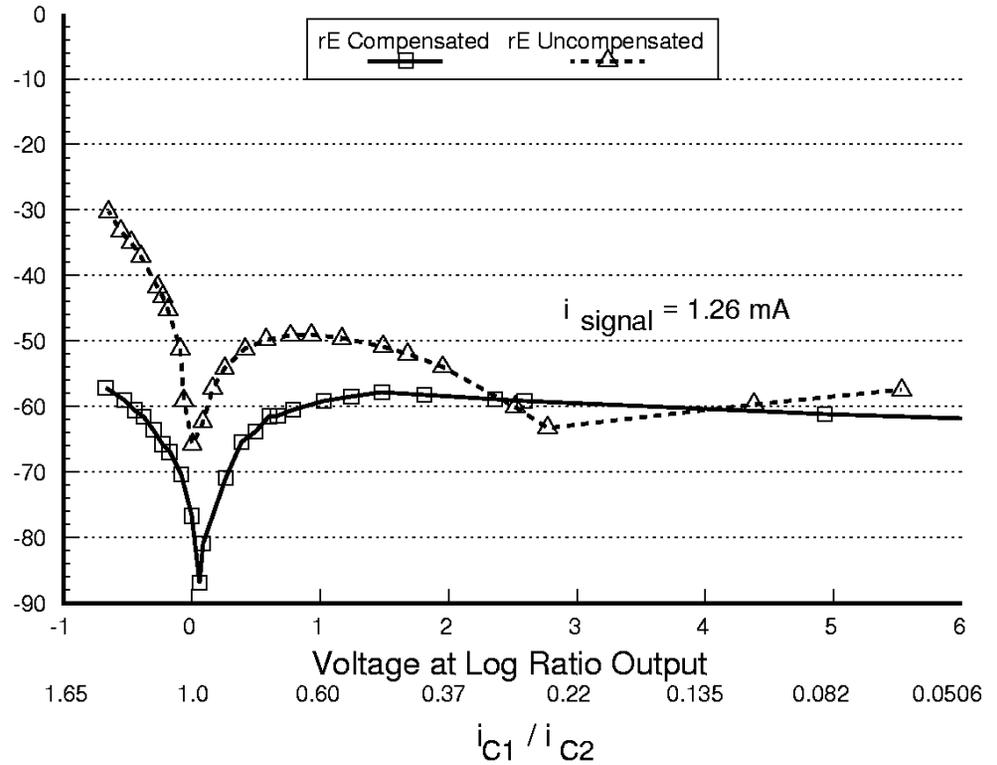


RE Compensator

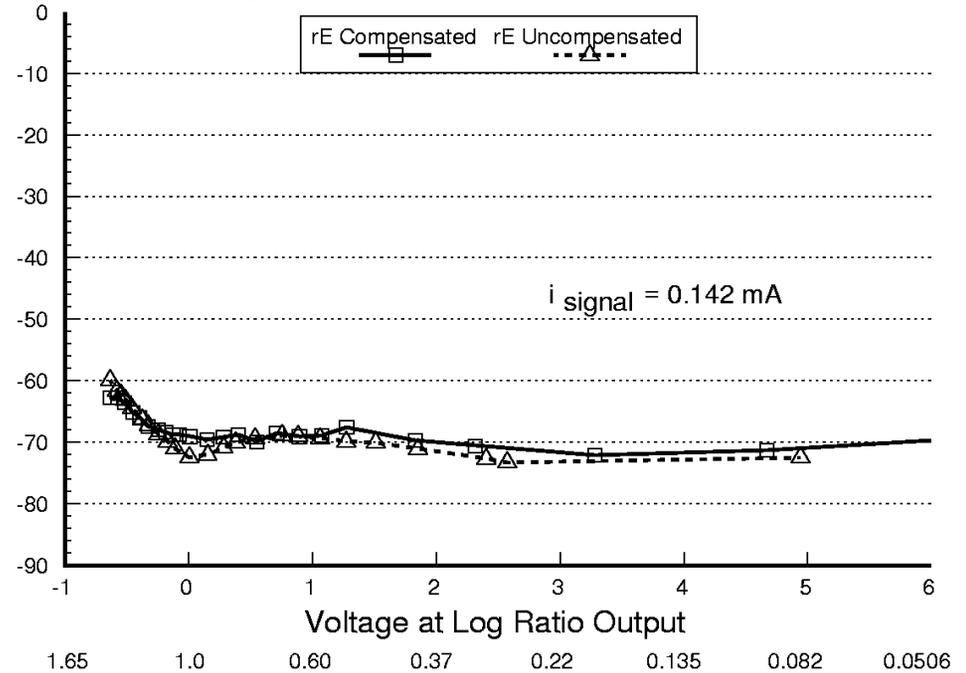


- Requires a current mirror plus a few extra resistors
- Flattens out rejection curve, 10-25 dB improvement

1 kHz Feedthrough (dB)

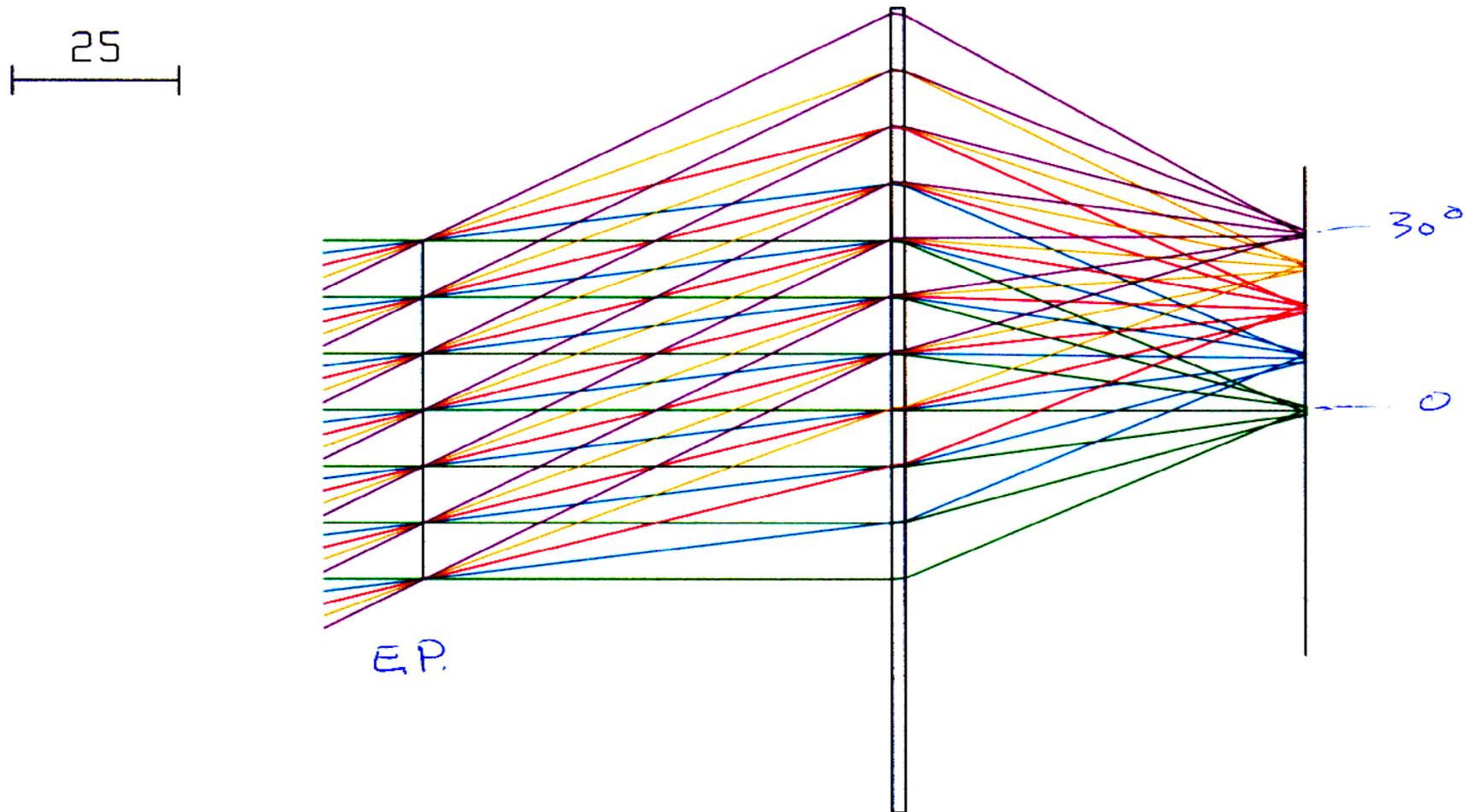


1 kHz Feedthrough (dB)



IRnewpupil1side
OPTICAL SYSTEM LAYOUT

UNITS: MM
DES: Budd



FULL FIELD
30deg



GEOMETRICAL
SPOT SIZE
0.7524

FULL FIELD



0.7 FIELD



ON-AXIS



-0.274 -0.137 0.000 0.137 0.274

FOCUS SHIFT

0.7 FIELD
22deg



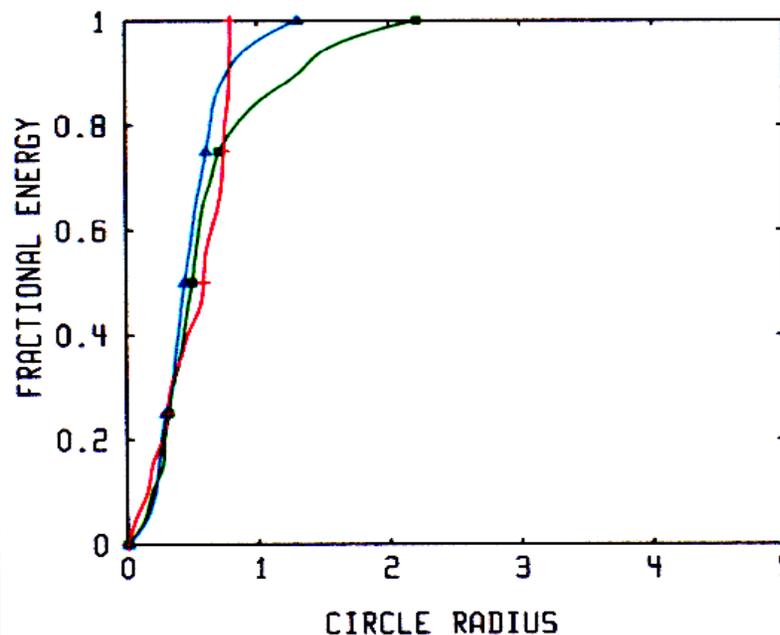
GEOMETRICAL
SPOT SIZE
0.5231

ON-AXIS
0deg



GEOMETRICAL
SPOT SIZE
0.5626

10



RADIAL ENERGY
DISTRIBUTION

◻ FULL FIELD
△ 0.7 FIELD
+ ON-AXIS

UNITS mm

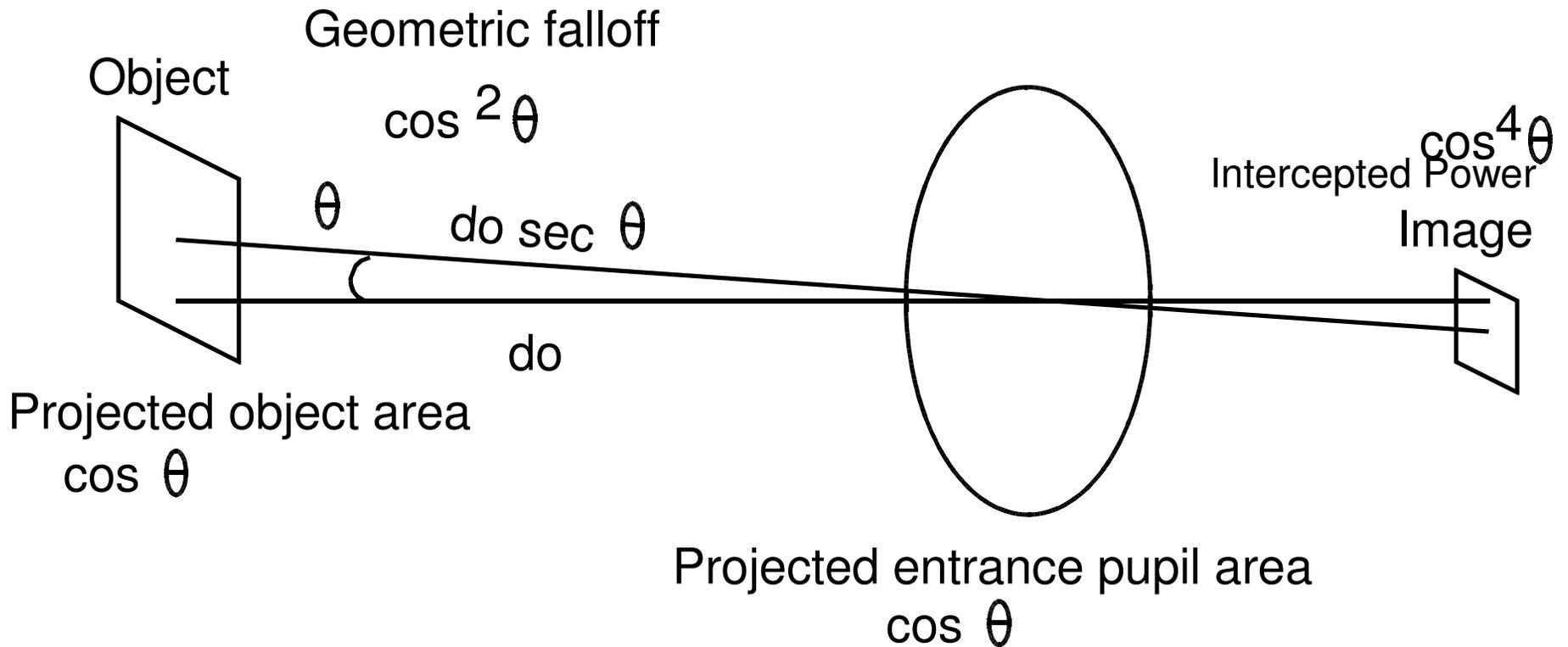
SPOT SIZE & FOCUS SHIFT: UNITS mm
WAVELENGTHS (microns)
WV1: 11

IRnewpupil1side
SPOT DIAGRAM ANALYSIS

Budd
19 Jan 01
11:52 AM

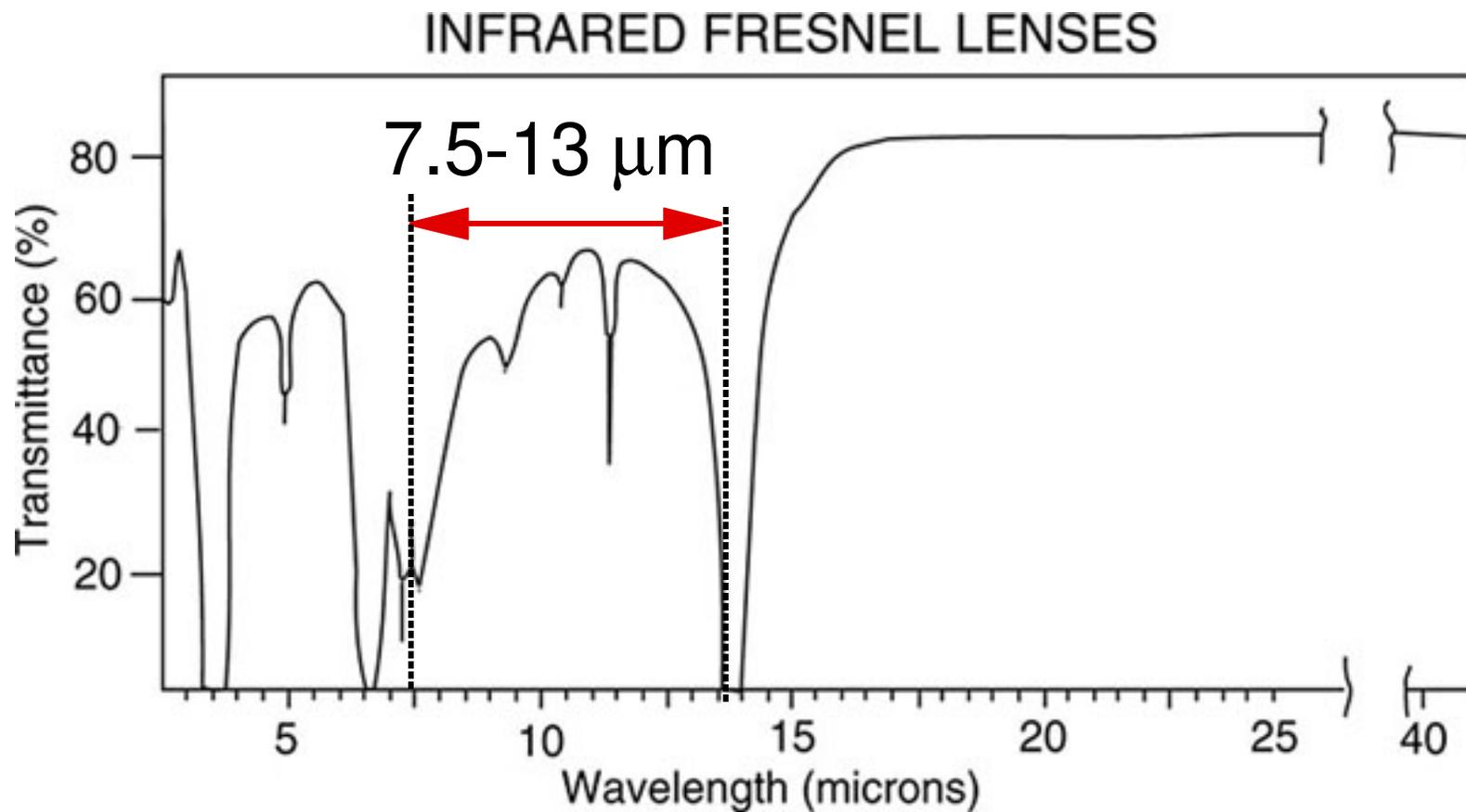
Optical Design

Radiometry



Optical Design

Moulded Polyethylene Fresnel Lenses



FULL FIELD
30deg



GEOMETRICAL
SPOT SIZE
6.681

0.7 FIELD
22deg



GEOMETRICAL
SPOT SIZE
3.09

ON-AXIS
0deg



GEOMETRICAL
SPOT SIZE
5.436

100

FULL FIELD



0.7 FIELD

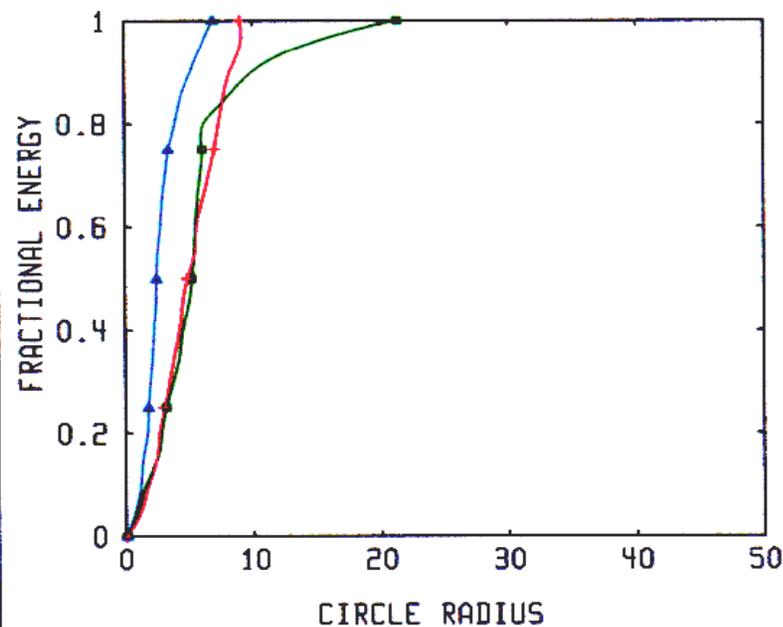


ON-AXIS



-0.318 -0.159 0.000 0.159 0.318

FOCUS SHIFT



RADIAL ENERGY
DISTRIBUTION

□ FULL FIELD
△ 0.7 FIELD
+ ON-AXIS

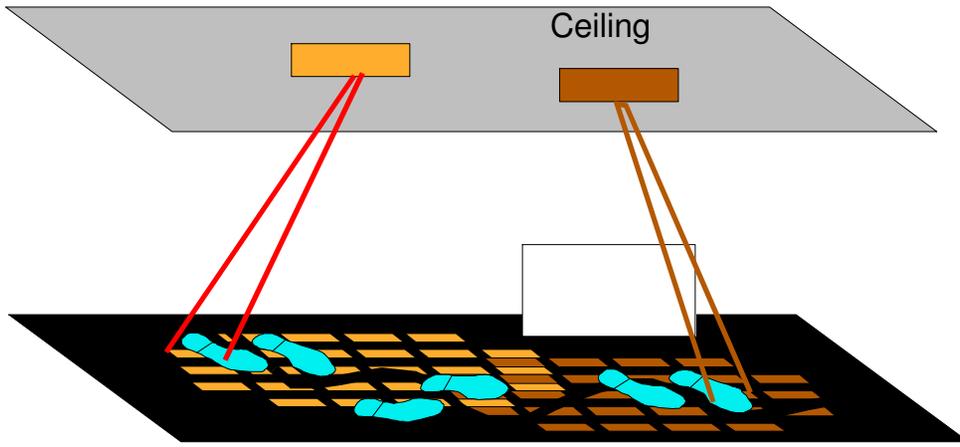
UNITS mm

SPOT SIZE & FOCUS SHIFT: UNITS mm
WAVELENGTHS (microns)
WV1: 11

IRstart1
SPOT DIAGRAM ANALYSIS

Budd
19 Jan 01
11:52 AM

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)

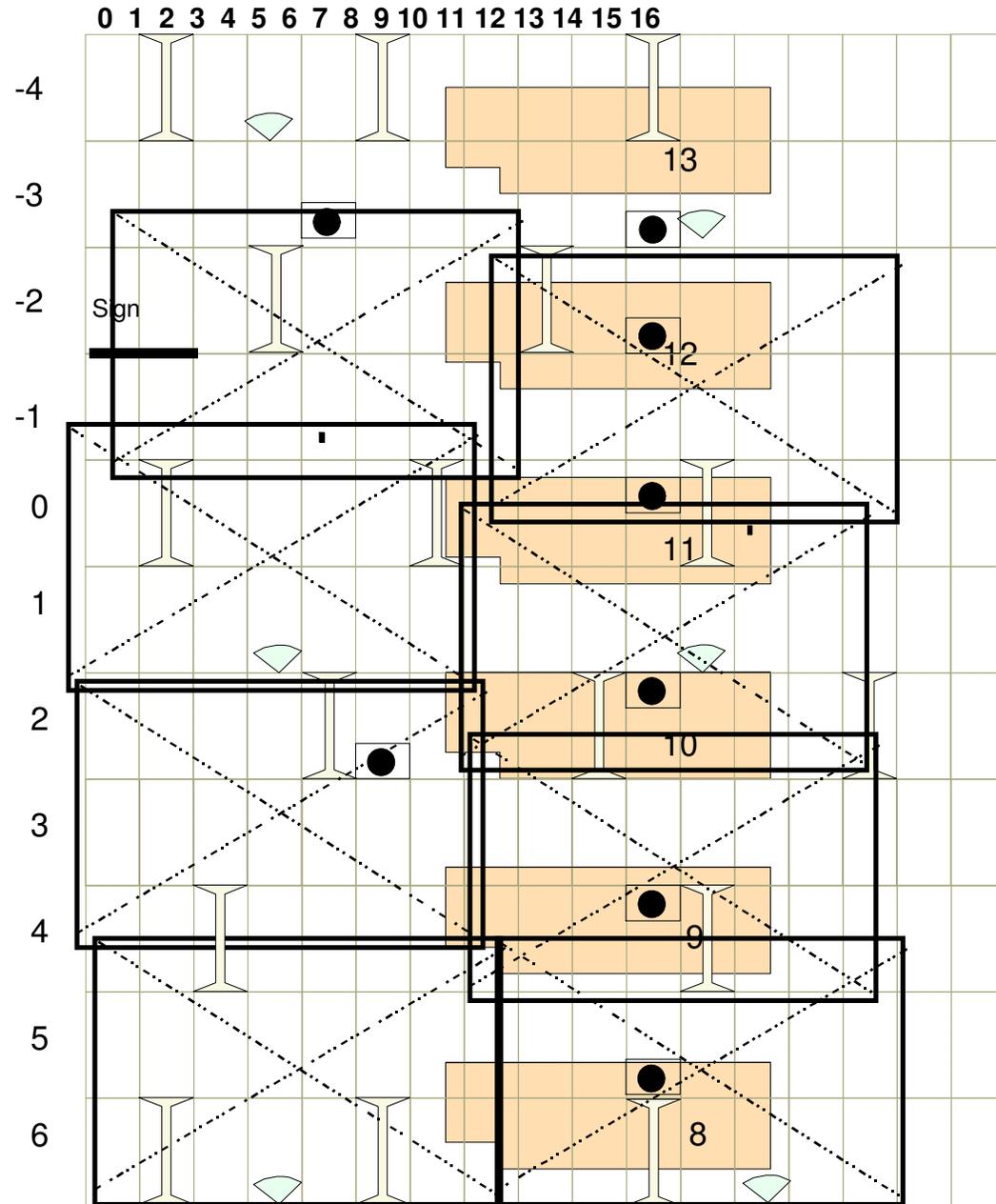
- Distribute Cheap Sensors In The Ceiling
- Extract Trajectories Automatically

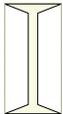
Typical Sensor Layout

Box Store

NE NJ

Ceiling Height 17 ft 6 in



-  Fluorescent Fixture
-  Security Camera
-  Ceiling tile
-  Sprinkler
-  Sensor FOV

What It *Doesn't* Show

