

EE 437/538B: Integrated Systems

Capstone/Design of Analog Integrated Circuits and Systems

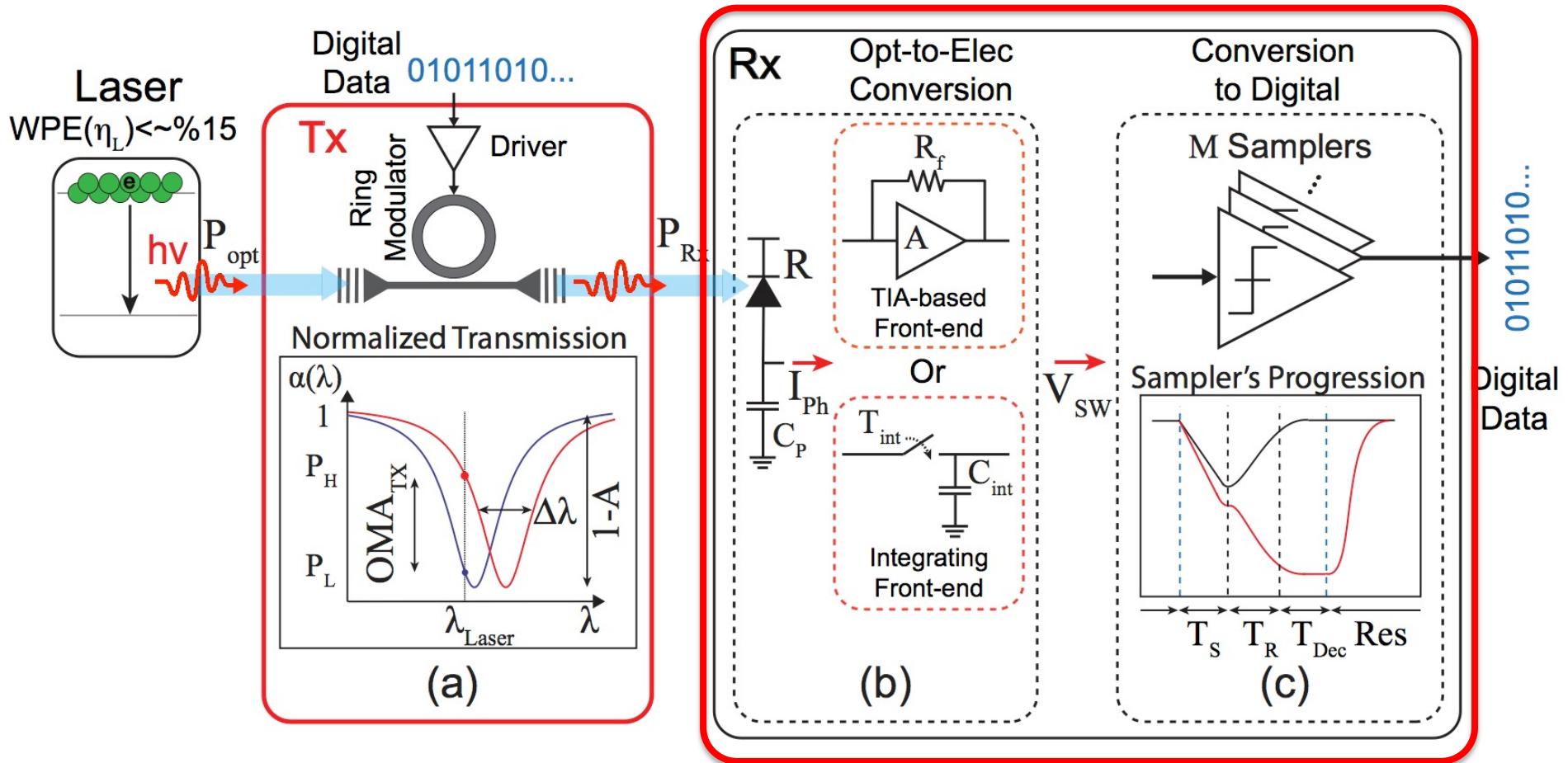
Lecture 7: Optical Rx (Part 2)

Prof. Sajjad Moazeni

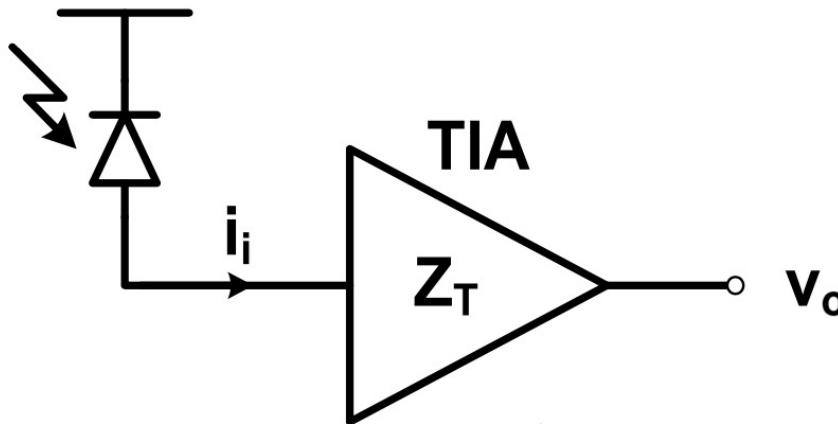
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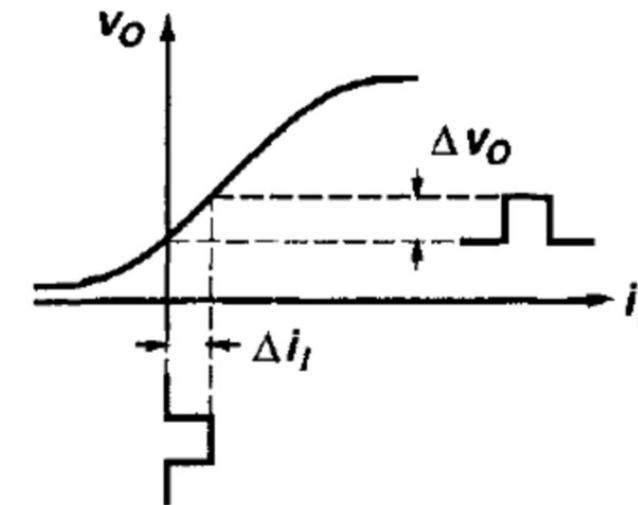
A Full Photonic Link



Transimpedance Amplifier (TIA)



$$\text{Transimpedance } Z_T = \frac{\Delta v_o}{\Delta i_i} \text{ } (\Omega)$$

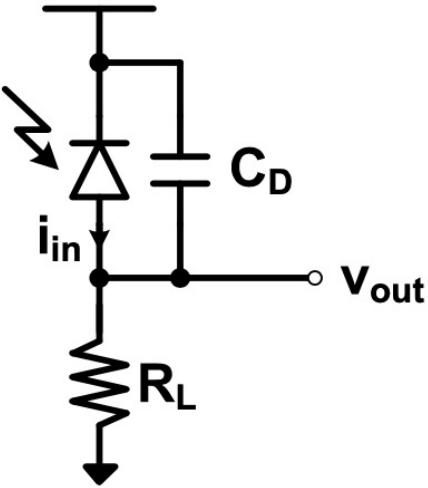


Also expressed in units of dBΩ by $20\log(|Z_T|)$

- Key design objectives
 - High transimpedance gain
 - Low input resistance for high bandwidth and efficient gain
- For large input currents, the TIA gain can compress and pulse-width distortion/jitter can result

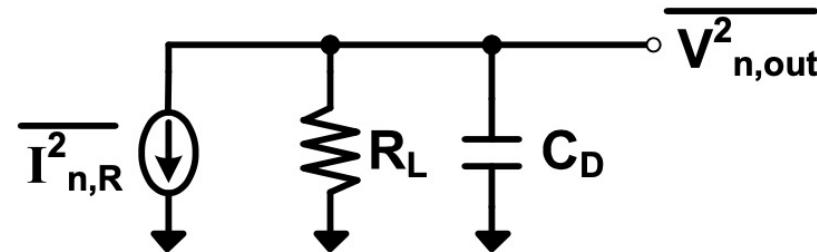
Resistive Front-End

[Razavi]



$$R_T = R_{in} = R_L$$

$$BW_{3dB} = \omega_p = \frac{1}{R_{in}C_D} = \frac{1}{R_LC_D}$$



$$\overline{V_{n,out}^2} = \int_0^\infty \overline{I_n^2} Z_T^2 df = \int_0^\infty \frac{4kT}{R_L} \left(\frac{R}{1+j2\pi fRC} \right)^2 df = \frac{kT}{C_D}$$

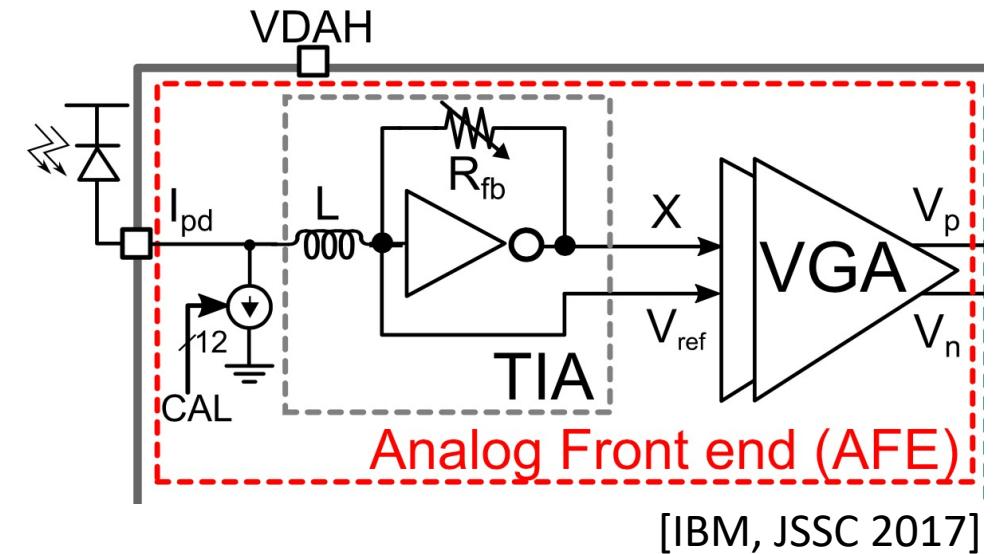
$$\overline{I_{n,in}^2} = \frac{\overline{V_{n,out}^2}}{R_L^2} = \frac{kT}{R_L^2 C_D}$$

$$I_{n,in,rms} = \frac{\sqrt{KT/C_D}}{R_L}$$

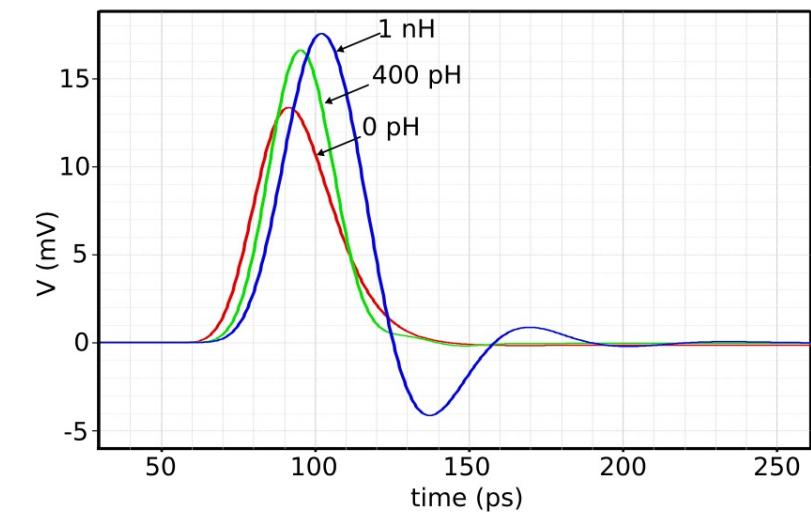
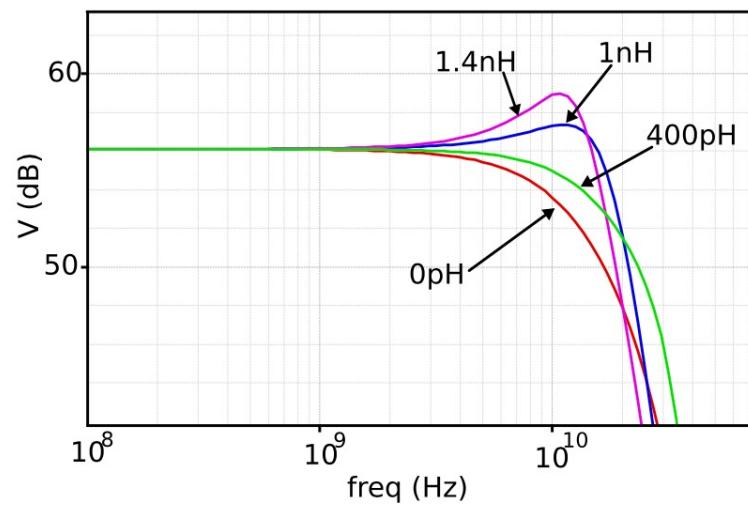
- Direct trade-offs between transimpedance, bandwidth, and noise performance

[Sam Palermo]

T-Coil/Inductive Input Stage

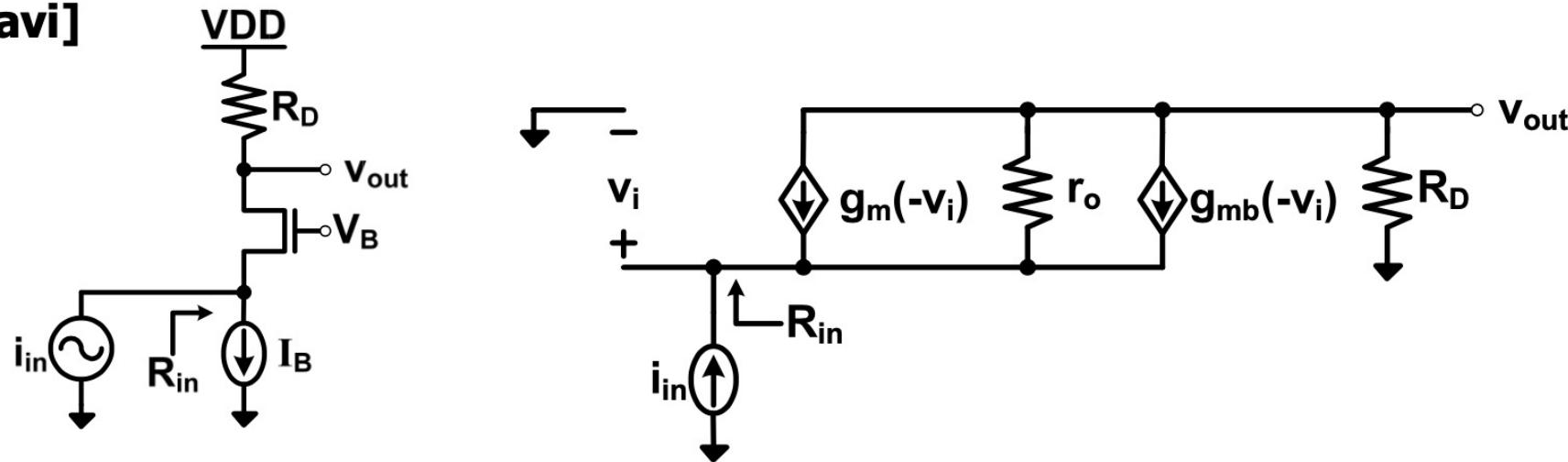


[IBM, JSSC 2017]



Common-Gate TIA

[Razavi]



$$R_T = R_D$$

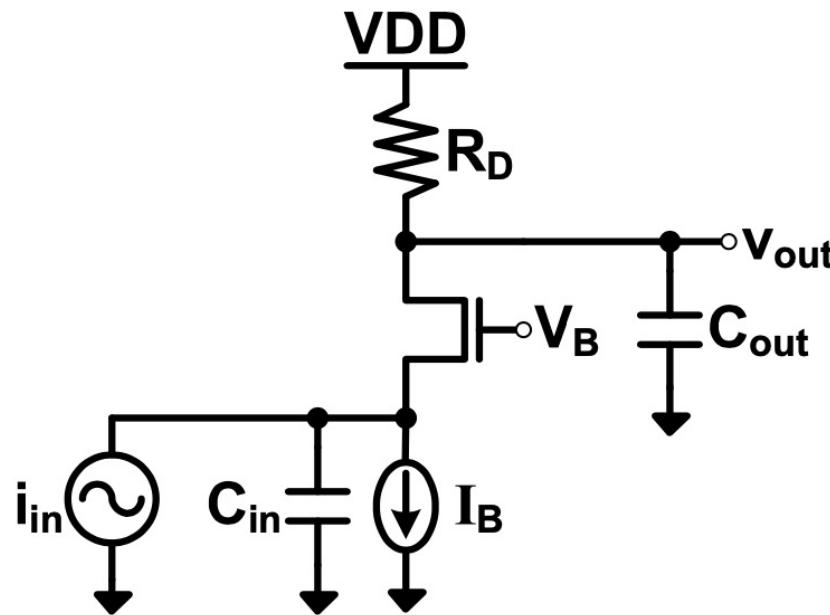
$$R_{in} = \frac{r_o + R_D}{1 + (g_m + g_{mb})r_o} \approx \frac{1}{g_m}$$

- Input resistance (input bandwidth) and transimpedance are decoupled

[Sam Palermo]

Common-Gate TIA Frequency Response

[Razavi]



Neglecting transistor r_o :

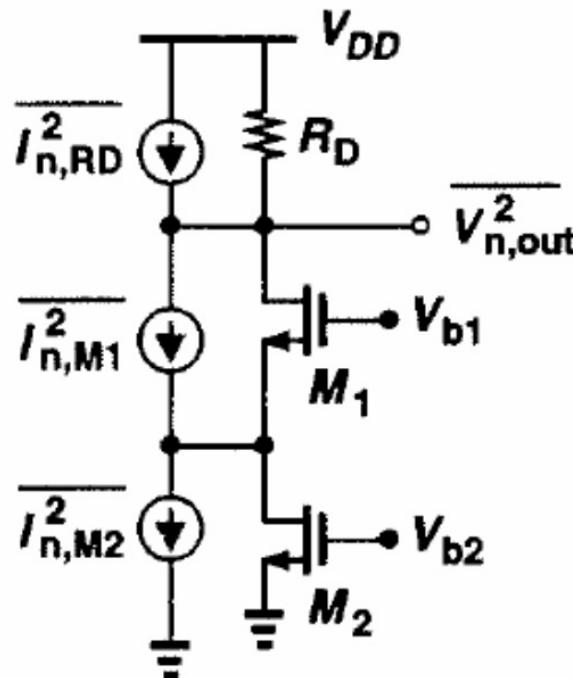
$$\frac{v_{out}}{i_{in}} = \frac{R_D}{\left(1 + s \frac{C_{in}}{g_{m1} + g_{mb1}}\right)(1 + sR_DC_{out})}$$

- Often the input pole may dominate due to large photodiode capacitance (100 – 500fF)

[Sam Palermo]

Common-Gate TIA Noise

[Razavi]



Neglecting transistor r_o :

$$\overline{V_{n,out}^2} = \left(\overline{I_{n,M2}^2} + \overline{I_{n,RD}^2} \right) R_D^2 = 4kT \left(\frac{2}{3} g_{m2} + \frac{1}{R_D} \right) R_D^2 \quad \left(\frac{\text{V}^2}{\text{Hz}} \right)$$

$$\overline{I_{n,in}^2} = 4kT \left(\frac{2}{3} g_{m2} + \frac{1}{R_D} \right) \quad \left(\frac{\text{A}^2}{\text{Hz}} \right)$$

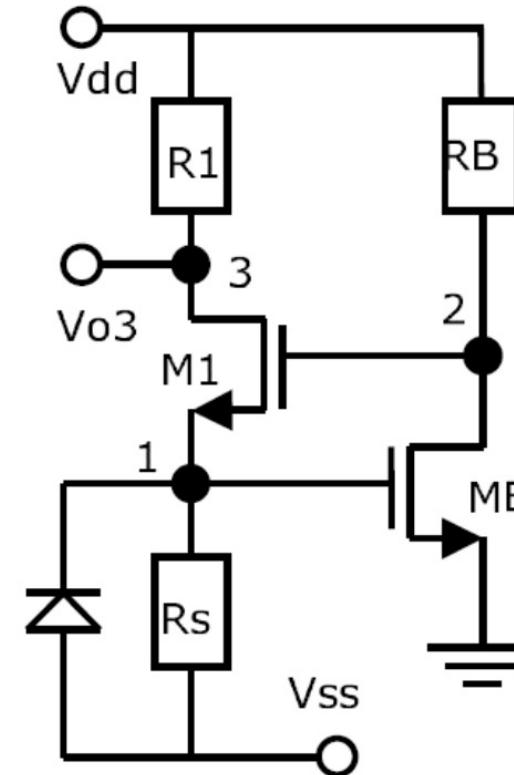
- Both the bias current source and R_D contribute to the input noise current
- R_D can be increased to reduce noise, but voltage headroom can limit this
- Common-gate TIAs are generally not for low-noise applications
- However, they are relatively simple to design with high stability

[Sam Palermo]

Regulated Cascode (RGC) TIA

- Input transistor gm is boosted by common-source amplifier gain, resulting in reduced input resistance
- Requires additional voltage headroom
- Increased input-referred noise from the common-source stage

[Park ESSCIRC 2000]



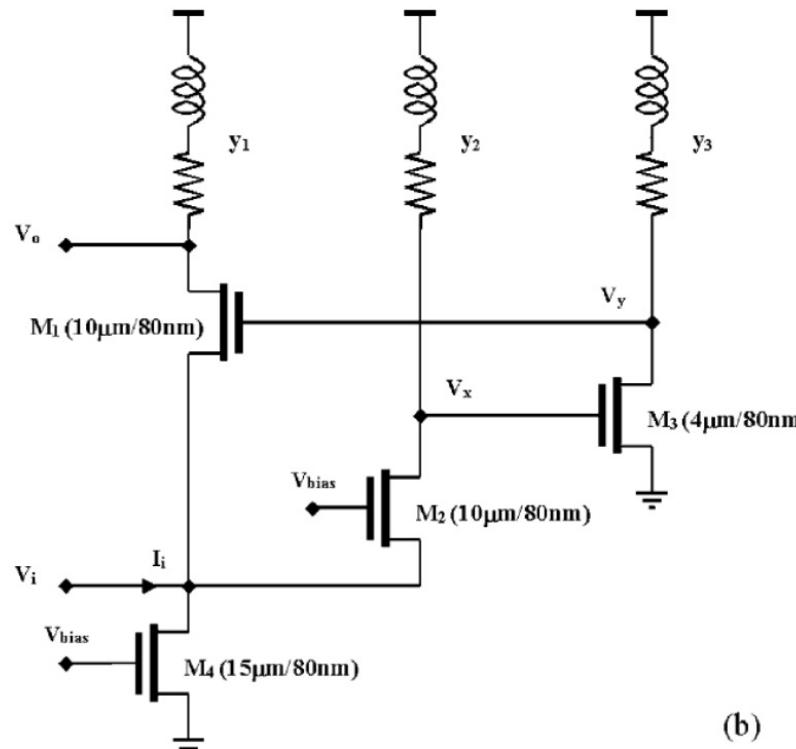
$$Z_{in}(0) \equiv \frac{1}{g_{m1}(1 + g_{mB}R_B)}$$

[Sam Palermo]

CMOS 20GHz TIA

- An additional common-gate stage in the feedback provides further gm-boosting and even lower input resistance
- Shunt-peaking inductors provide bandwidth extension at zero power cost, but very large area cost

[Kromer JSSC 2004]



(b)

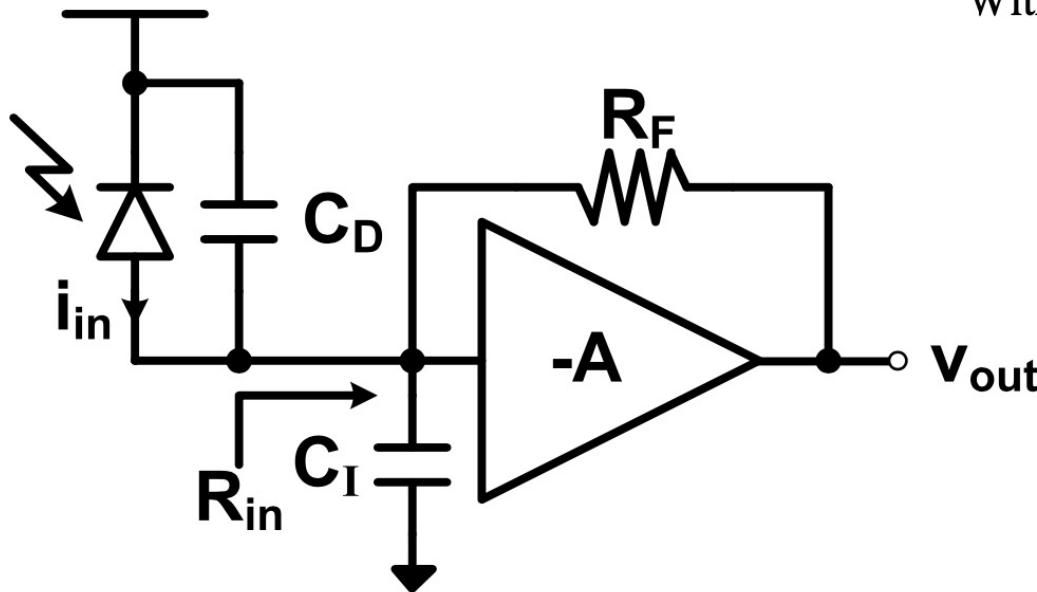
$$Z_i \approx \frac{1}{g_{m1} (1 + |A_2 A_3|) + j\omega C_{i,tot}}$$

$$A_2 = g_{m2} R_2 \quad A_3 = -g_{m3} R_3$$

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[Sam Palermo]

Feedback TIA w/ Ideal Amplifier



With Infinite Bandwidth Amplifier:

$$Z_T(s) = -R_T \left(\frac{1}{1 + s/\omega_p} \right)$$

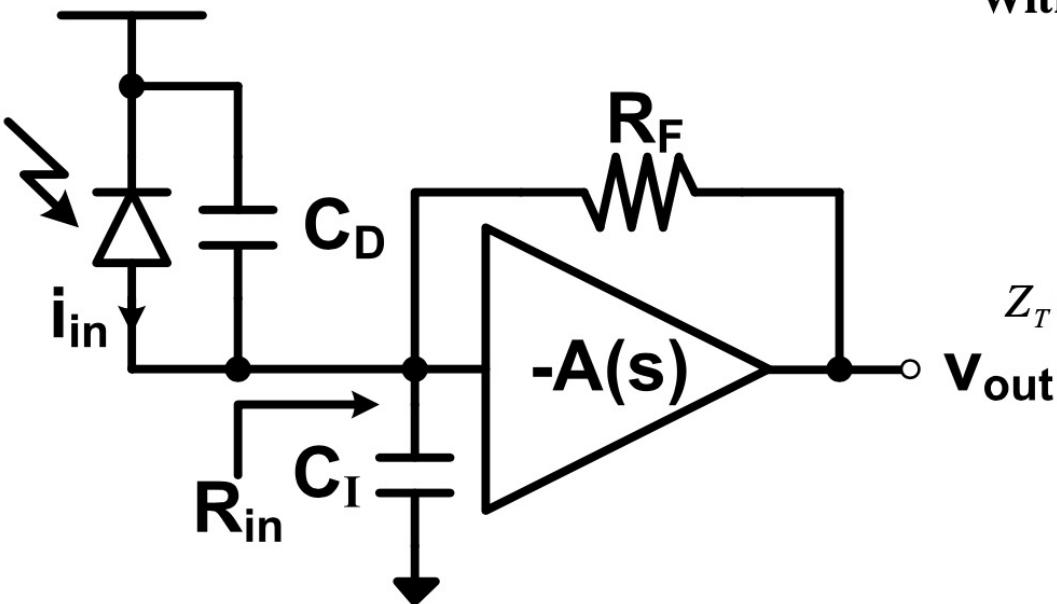
$$R_{in} = \frac{R_F}{A+1}$$

$$R_T = \frac{A}{A+1} R_F$$

$$\omega_p = \frac{1}{R_{in} C_T} = \frac{A+1}{R_F (C_D + C_I)}$$

- Input bandwidth is extended by the factor $A+1$
- Transimpedance is approximately R_F
- Can make R_F large without worrying about voltage headroom considerations

Feedback TIA w/ Finite Bandwidth Amplifier



With Finite Bandwidth Amplifier :

$$A(s) = \frac{A}{1 + \frac{s}{\omega_A}} = \frac{A}{1 + sT_A}$$

$$Z_T(s) = -R_T \left(\frac{1}{1 + s/(\omega_o Q) + s^2/\omega_o^2} \right)$$

$$R_T = \frac{A}{A+1} R_F$$

$$\omega_o = \sqrt{\frac{A+1}{R_F C_T T_A}}$$

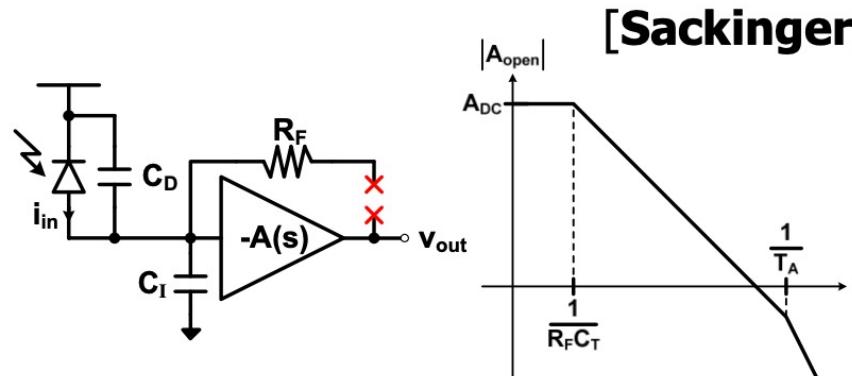
$$Q = \frac{\sqrt{(A+1)R_F C_T T_A}}{R_F C_T + T_A}$$

$$R_{in} = \frac{R_F}{A+1}$$

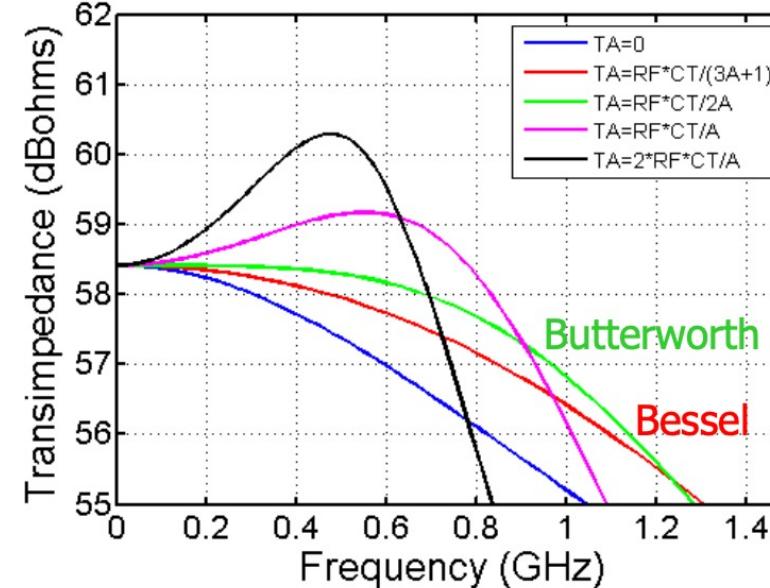
- Finite bandwidth amplifier modifies the transimpedance transfer function to a second-order low-pass function

Feedback TIA w/ Finite Bandwidth Amplifier

- Non-zero amplifier time constant can actually increase TIA bandwidth!!
- However, can result in peaking in frequency domain and overshoot/ringing in time domain
- Often either a Butterworth ($Q=1/\sqrt{2}$) or Bessel response ($Q=1/\sqrt{3}$) is used
 - Butterworth gives maximally flat frequency response
 - Bessel gives maximally flat group-delay



2nd-Order TIA Frequency Response



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[Sam Palermo]

Feedback TIA Transimpedance Limit

If we assume a Butterworth response for maximally flat frequency response :

$$Q = \frac{1}{\sqrt{2}} \quad \Rightarrow \quad \omega_A = \frac{1}{T_A} = \frac{2A}{R_F C_T}$$

For a Butterworth response :

$$\omega_{3dB} = \omega_0 = \sqrt{\frac{(A+1)\omega_A}{R_F C_T}} = \frac{\sqrt{(A+1)2A}}{R_F C_T} \approx \sqrt{2} \text{ times larger than } T_A = 0 \text{ case of } \frac{A+1}{R_F C_T}$$

Plugging $R_T = \frac{A}{A+1} R_F$ into above expression yields the maximum possible R_T for a given bandwidth

$$\sqrt{\left(\frac{A+1}{A}\right) R_T C_T} \geq \omega_{3dB}$$

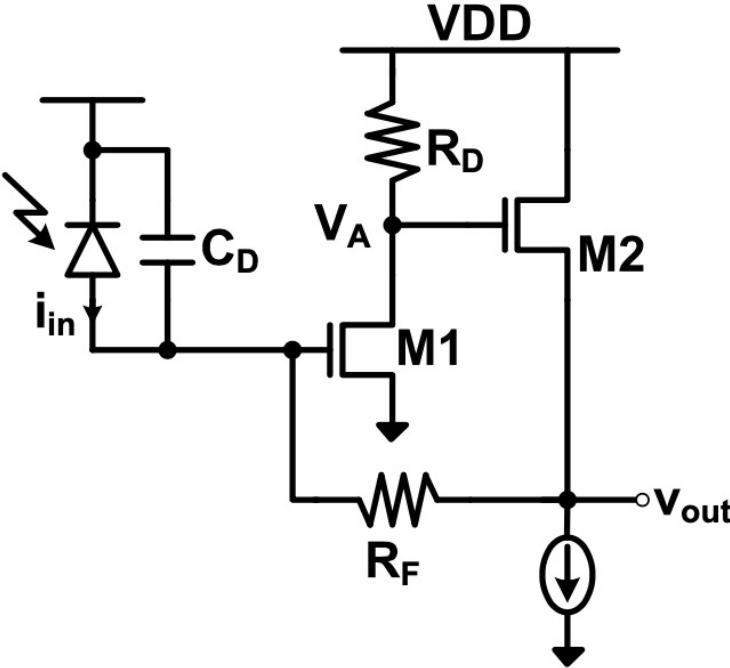
$$\boxed{\text{Maximum } R_T \leq \frac{A \omega_A}{C_T \omega_{3dB}^2}}$$

[Mohan JSSC 2000]

- Maximum R_T proportional to amp gain-bandwidth product
- If amp GBW is limited by technology f_T , then in order to increase bandwidth, R_T must decrease quadratically!

[Sam Palermo]

Feedback TIA



Assuming that the source follower has an ideal gain of 1

$$A = g_{m1}R_D$$

$$R_T = \frac{g_{m1}R_D}{1 + g_{m1}R_D} R_F$$

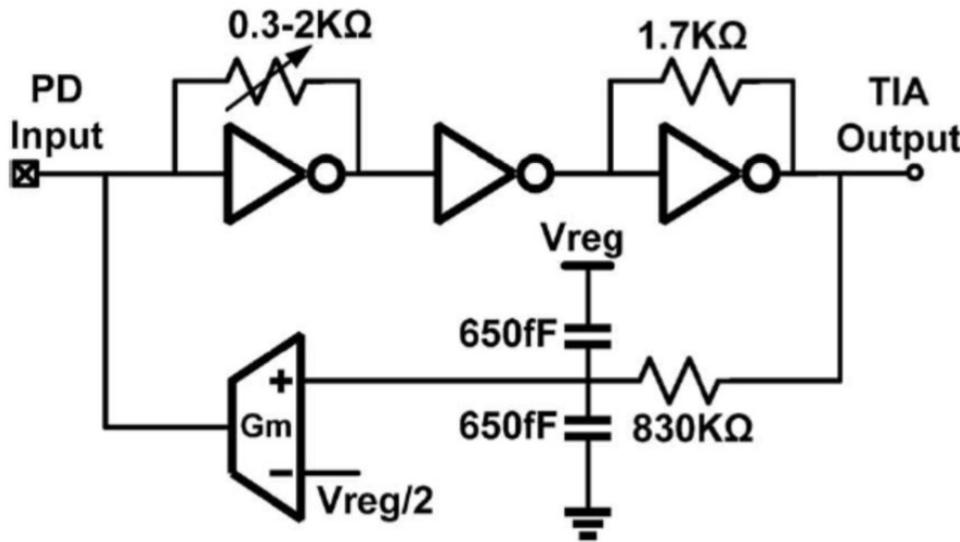
$$R_{in} = \frac{R_F}{1 + g_{m1}R_D}$$

$$R_{out} = \frac{1}{g_{m2}(1 + g_{m1}R_D)}$$

- As power supply voltages drop, there is not much headroom left for R_D and the amplifier gain degrades

[Sam Palermo]

CMOS Inverter-Based Feedback TIA



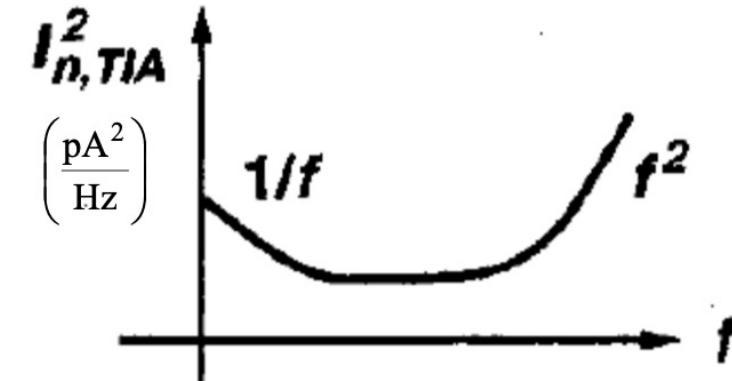
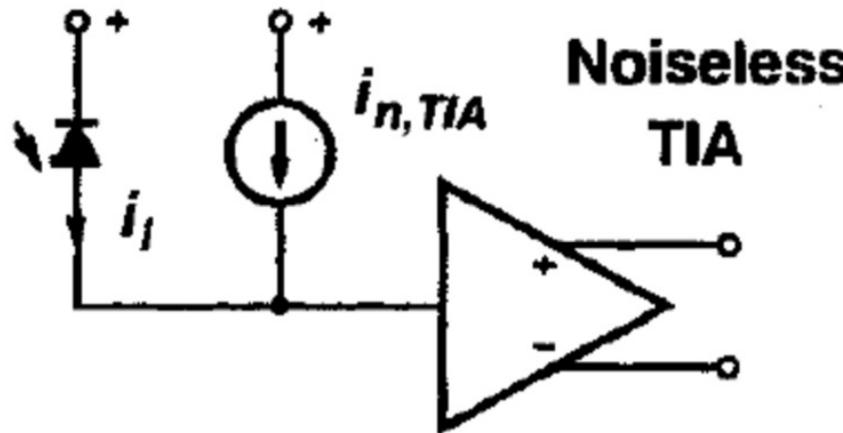
[Li JSSC 2014]

- CMOS inverter-based TIAs allow for reduced voltage headroom operation
- Cascaded inverter-gm + TIA stage provide additional voltage gain
- Low-bandwidth feedback loop sets the amplifier output common-mode level

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[Sam Palermo]

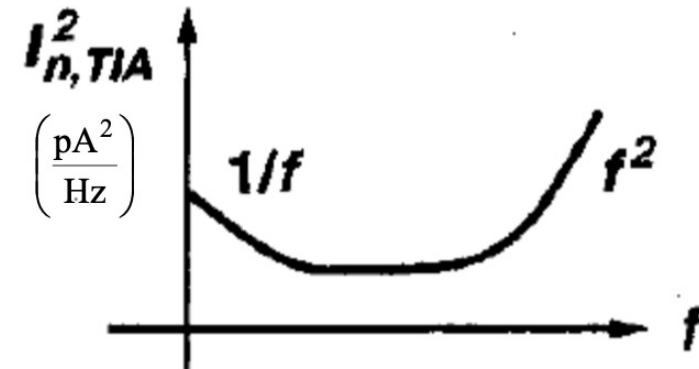
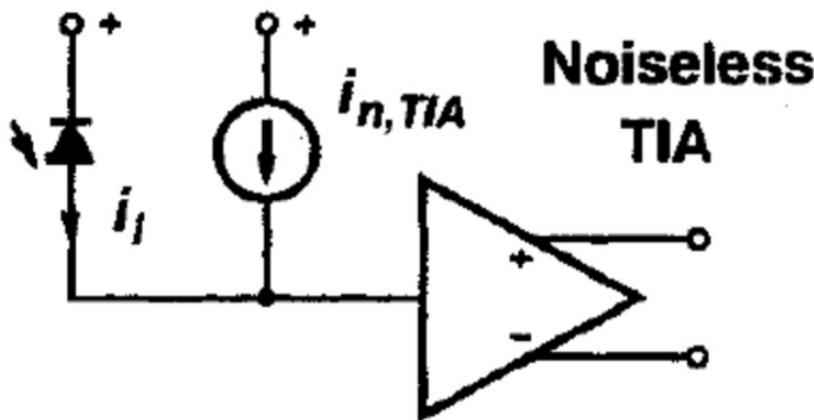
Input-Referred Noise Current



- TIA noise is modeled with an input-referred noise current source that reproduces the output TIA output noise when passed through an ideal noiseless TIA
- This noise source will depend on the source impedance, which is determined mostly by the photodetector capacitance

[Sam Palermo]

Input-Referred Noise Current Spectrum



- Input-referred noise current spectrum typically consists of uniform, high-frequency f^2 , & low-frequency $1/f$ components
- To compare TIAs, we need to see this noise graph out to $\sim 2X$ the TIA bandwidth
 - Recall the noise bandwidth tables

[Sam Palermo]

Input-Referred RMS Noise Current

- The input-referred rms noise current can be calculated by dividing the rms output noise voltage by the TIA's midband transimpedance value

$$i_{n,TIA}^{rms} = \frac{1}{R_T} \sqrt{\int_0^{>2BW} |Z_T(f)|^2 I_{n,TIA}^2(f) df}$$

- If we integrate the output noise, the upper bound isn't too critical. Often this is infinity for derivations, or 2X the TIA bandwidth in simulation
- This rms current sets the TIA's electrical sensitivity

$$i_{sens}^{pp} = 2Qi_{n,TIA}^{rms}$$

- To determine the total optical receiver sensitivity, we need to consider the detector noise and responsivity

[Sam Palermo]

Averaged Input-Referred Noise Current Density

- TIA noise performance can also be quantified by the averaged input-referred noise current density

$$i_{n,TIA}^{avg} = \frac{i_{n,TIA}^{rms}}{\sqrt{BW_{3dB}}}$$

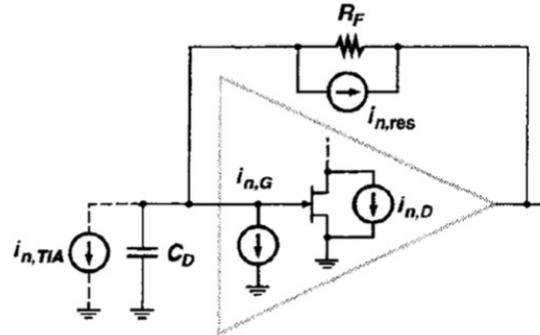
This quantity has units of $\left(\frac{\text{pA}}{\sqrt{\text{Hz}}} \right)$.

Note, this is different than averaging the input - referred noise spectrum,

$I_{n,TIA}^2(f)$ over the TIA bandwidth.

[Sam Palermo]

FET Feedback TIA Input-Referred Noise Current Spectrum



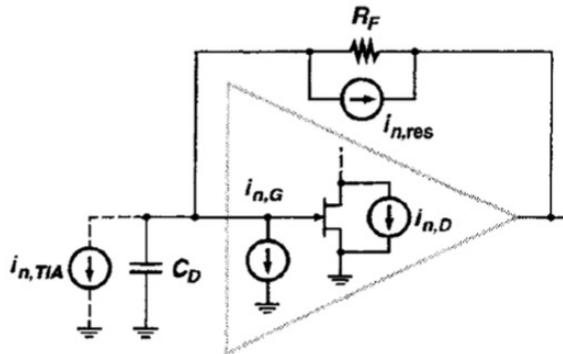
- The feedback resistor and amplifier front-end noise components determine the input-referred noise current spectrum

$$I_{n,TIA}^2(f) = I_{n,res}^2(f) + I_{n,front}^2(f)$$

- The feedback resistor component is uniform with frequency

$$I_{n,res}^2(f) = \frac{4kT}{R_F}$$

FET Feedback TIA Input-Referred Noise Current Spectrum



- Gate current-induced shot noise

$$I_{n,G}^2 = 2qI_G$$

This is typically small for CMOS designs

- FET channel noise

$$I_{n,D}^2 = 4kT\Gamma g_m$$

Γ is the channel noise factor, typically 0.7 - 3 depending on the process.

[Sam Palermo]

Input-Referring the FET Channel Noise

To do this, we could calculate $\frac{i_{n,TIA}}{i_{n,D}} = \frac{\left(\frac{v_{out}}{i_{n,D}}\right)}{Z_T}$

But it is easier (and equivalent) to ground the output and calculate

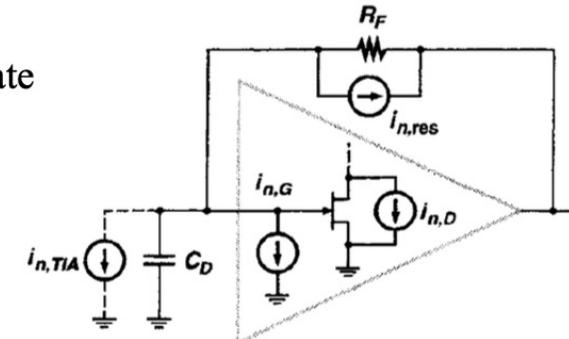
$$i_{n,D} = g_m v_{n,TIA} = \frac{g_m i_{n,TIA}}{sC_T + \frac{1}{R_F}} = \frac{g_m R_F}{1 + sR_F C_T} i_{n,TIA}$$

where $C_T = C_D + C_I$, the summation of the detector and amplifier input capacitance.

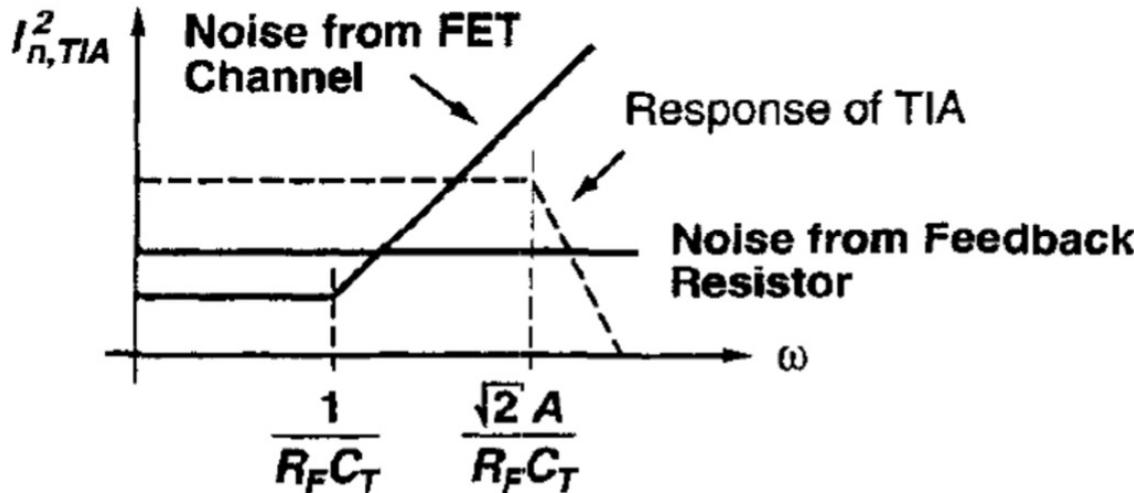
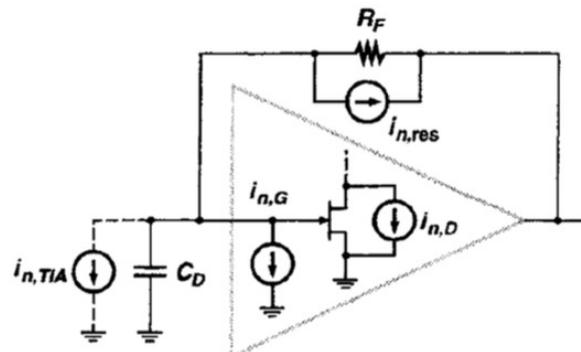
$$\left(\frac{i_{n,D}}{i_{n,TIA}}\right)^{-1} = \frac{1 + sR_F C_T}{g_m R_F}$$

Using this high - pass transfer function, the input - referred FET channel noise is

$$\begin{aligned} I_{n,front,D}^2(f) &= \frac{1 + (2\pi f R_F C_T)^2}{(g_m R_F)^2} \cdot 4kT\Gamma g_m \\ &= 4kT\Gamma \left(\frac{1}{g_m R_F^2}\right) + 4kT\Gamma \left(\frac{(2\pi C_T)^2}{g_m}\right) f^2 \end{aligned} \quad \text{Uniform and } f^2 \text{ component!}$$



Total Input-Referred FET Feedback TIA Noise



$$I_{n,TIA}^2(f) = \frac{4kT}{R_F} + 2qI_G + 4kT\Gamma\left(\frac{1}{g_m R_F^2}\right) + 4kT\Gamma\left(\frac{(2\pi C_T)^2}{g_m}\right)f^2$$

Feedback Resistor

Gate Shot Noise

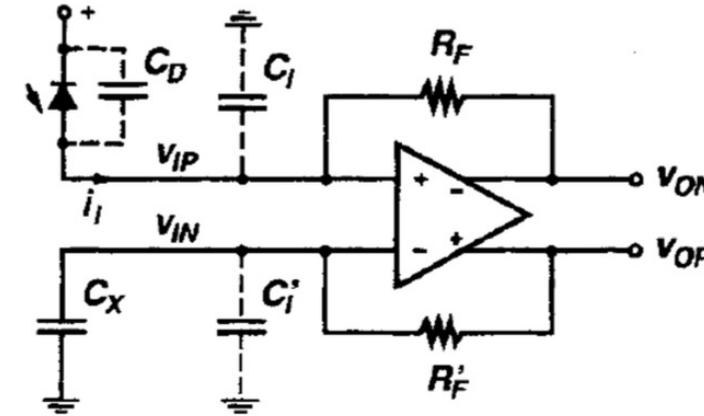
FET Channel Noise

- Note that the TIA input-referred noise current spectrum begins to rise at a frequency lower than the TIA bandwidth

[Sam Palermo]

Differential TIAs

- Differential circuits have superior immunity to power supply/substrate noise
- A differential TIA output allows easy use of common differential main/limiting amplifiers
 - This comes at the cost of higher noise and power
- How to get a differential output with a single-ended photocurrent input?
 - Two common approaches, based on the amount of capacitance applied at the negative input



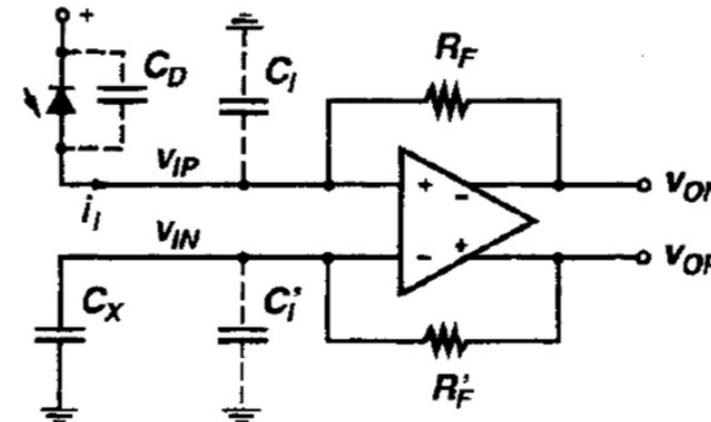
[Sam Palermo]

Balanced TIA

- A balanced TIA design attempts to match the capacitance of the two differential inputs

$$C_X \approx C_D$$

- This provides the best power supply/substrate noise immunity, as the noise transfer functions are similar
- Due to double the circuitry, the input-referred rms noise current is increased by $\sqrt{2}$



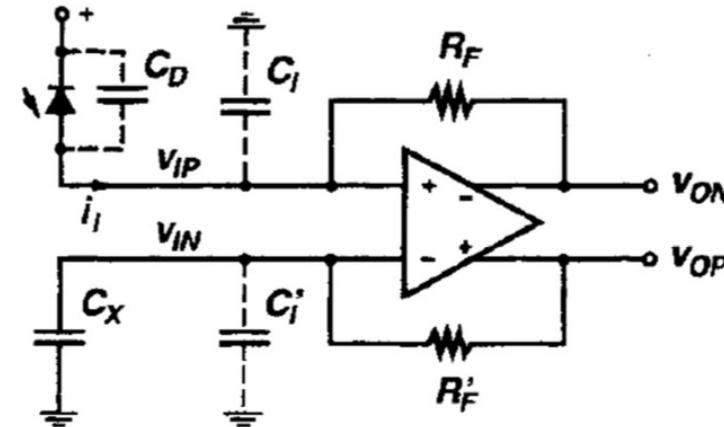
Assuming an high BW amplifier
and $C_T = C_D + C_I$

$$Z_T(s) = \frac{v_{OP} - v_{ON}}{i_i} = \frac{\left(\frac{A}{A+1}\right)R_F}{1 + \frac{sC_T R_F}{A+1}}$$

Same transfer function as the single - ended design [Sam Palermo]

Pseudo-Differential TIA

- A pseudo-differential TIA design uses a very large capacitor at the negative input, such that it can be approximated as an AC ground $C_X \rightarrow \infty$
- While not good to reject power supply/substrate noise, it does provide significant filtering of the R_F' noise
- The differential transimpedance is approximately doubled relative to the single-ended case

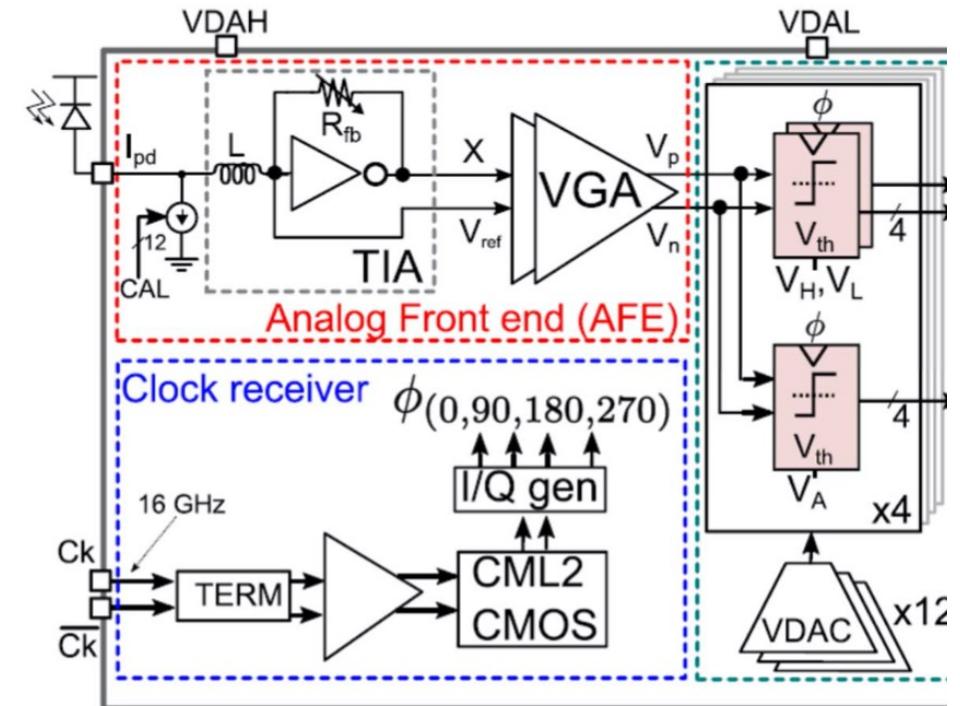


Assuming an high BW amplifier
and $C_T = C_D + C_I$

$$Z_T(s) = \frac{v_{OP} - v_{ON}}{i_i} = \frac{\left(\frac{2A}{A+2}\right)R_F}{1 + \frac{sC_T R_F}{\frac{A}{2} + 1}}$$

Single-ended TIA to Differential Output

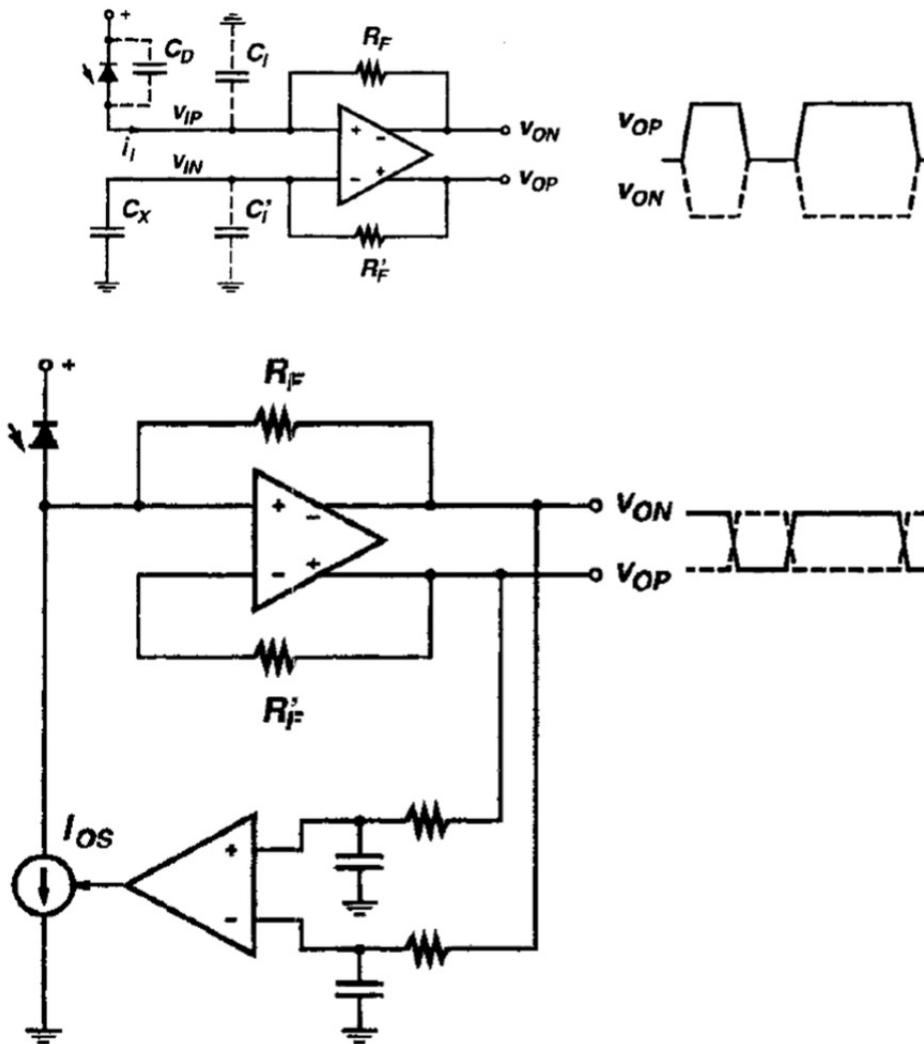
Need for a Pre-Amp



[IBM, JSSC 2017]

Offset Control

- Due to the single-ended photodetector signal, the differential output signal swings from 0 to V_{ppd} , which can limit the dynamic range
- Adding offset control circuitry can allow for an output swing of $\pm V_{ppd}/2$



[Sam Palermo]

Optical RX Scaling Issues

- 😊 Traditionally, TIA has high R_T and low R_{in}

$$R_T = R_F \left(\frac{A}{1+A} \right)$$

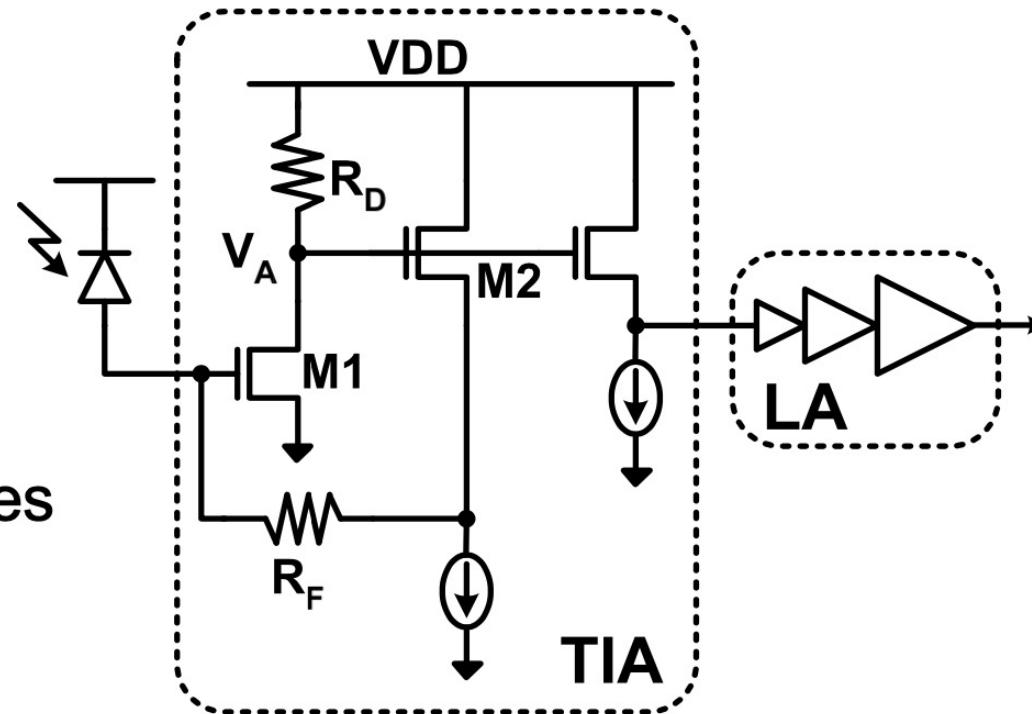
$$\omega_{3dB} \approx \frac{1+A}{R_F C_{IN}}$$

- 🙁 Headroom/Gain issues in 1V CMOS
 - $A \approx 2 - 3$

- 🙁 Power/Area Costs

$$\text{TIA } I_D \propto (R_T C_{IN})^2 f_{3dB}^4$$

$$\text{LA } I_D \propto f_{3dB}^2$$



$$V_A = V_{GS1} + V_{GS2} \approx 0.8 * VDD$$

$$A \approx g_m R_D = \frac{\alpha(VDD - V_A)}{VOD} \approx \frac{\alpha(0.2 * VDD)}{VOD}$$

[Sam Palermo]

State-of-the-art TIAs

Ref: “A 128 Gb/s, 11.2 mW Single-Ended PAM4 Linear TIA With 2.7 μ Arms Input Noise in 22 nm FinFET CMOS”, Intel JSSC 2022

- Multi-stage Inv. Based
- Series vs. shunt inductive peaking

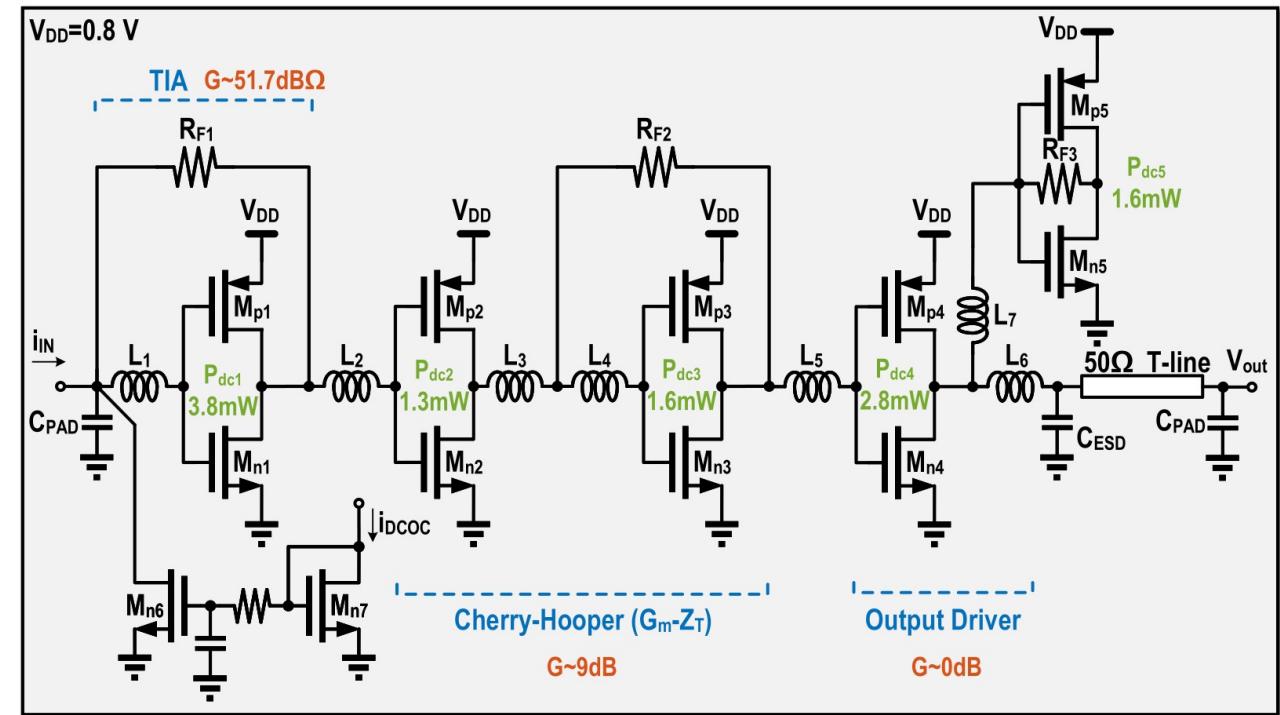
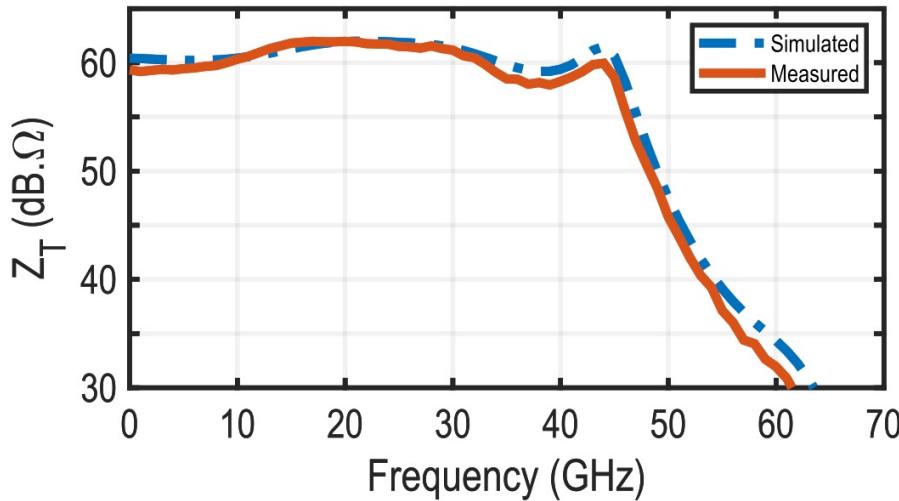


Fig. 9. Schematic of the single-ended four-stage TIA with series and shunt inductive peaking for bandwidth enhancement.

TABLE II
COMPARISON TO STATE-OF-THE-ART LINEAR TIAs

Ref.	This Work	[5] BCTM 2015	[9] TCASI 2018	[26] SOCC 2019	[6] CSICS 2016	[8] JSSC 2018	[46] ESSCIRC 2018	[43] JSSC 2019	[17] JSSC 2019	[47] SSCL 2020
Technology	22 nm FinFET	55 nm SiGe BiCMOS	130 nm SiGe BiCMOS	65 nm CMOS	130 nm SiGe BiCMOS	130 nm SiGe BiCMOS	28 nm CMOS	28 nm CMOS	16 nm FinFET	28 nm CMOS
Interface	SE	SE	SE	SE	Diff.	Diff.	S2D	S2D	S2D	Diff.
Application	IM [†]	IM	IM	IM	CD ^{††}	CD	IM	IM	IM	CD
Supply Voltage (V)	0.8	2.3	2.0	1.0	3.3	3.3	0.9	1.2	1.8	2.4
S ₂₁ (dB)	26	13	—	—	—	27	24.5	—	33	39**
BW _{3dB-S₂₁} (GHz)	48.7	92	—	—	—	50	62	—	17	10**
PD Cap. (fF)	70	—	100	60	60	—	70	80	10	—
Z _T (dB.Ω)	59.3	—	41	49	77	65	65	74	78	78
BW _{3dB-Z_T} (GHz)	45.5	—	50	29.9	34	66	60	27	27	42
Data Rate (Gb/s)	128	120	50	45	45	100	112	54	106.25	—
TDECQ	1.80	—	—	—	—	—	—	—	1.78	—
Input Ref. Noise Density (pA/ $\sqrt{\text{Hz}}$)	12.6	—	39.8	30	20	7.6	19.3	—	16.7	18
P _{dc} (mW)	11.2	48	24	16.4	285	150	107	34.6	60.8	319
FoM* ($\Omega \cdot \text{GHz}/\text{mW}$)	3797 [§]	428 [‡]	234	513	845	782	997	145	3527.4	1046

[†] Intensity Modulation

^{††} Coherent Detection

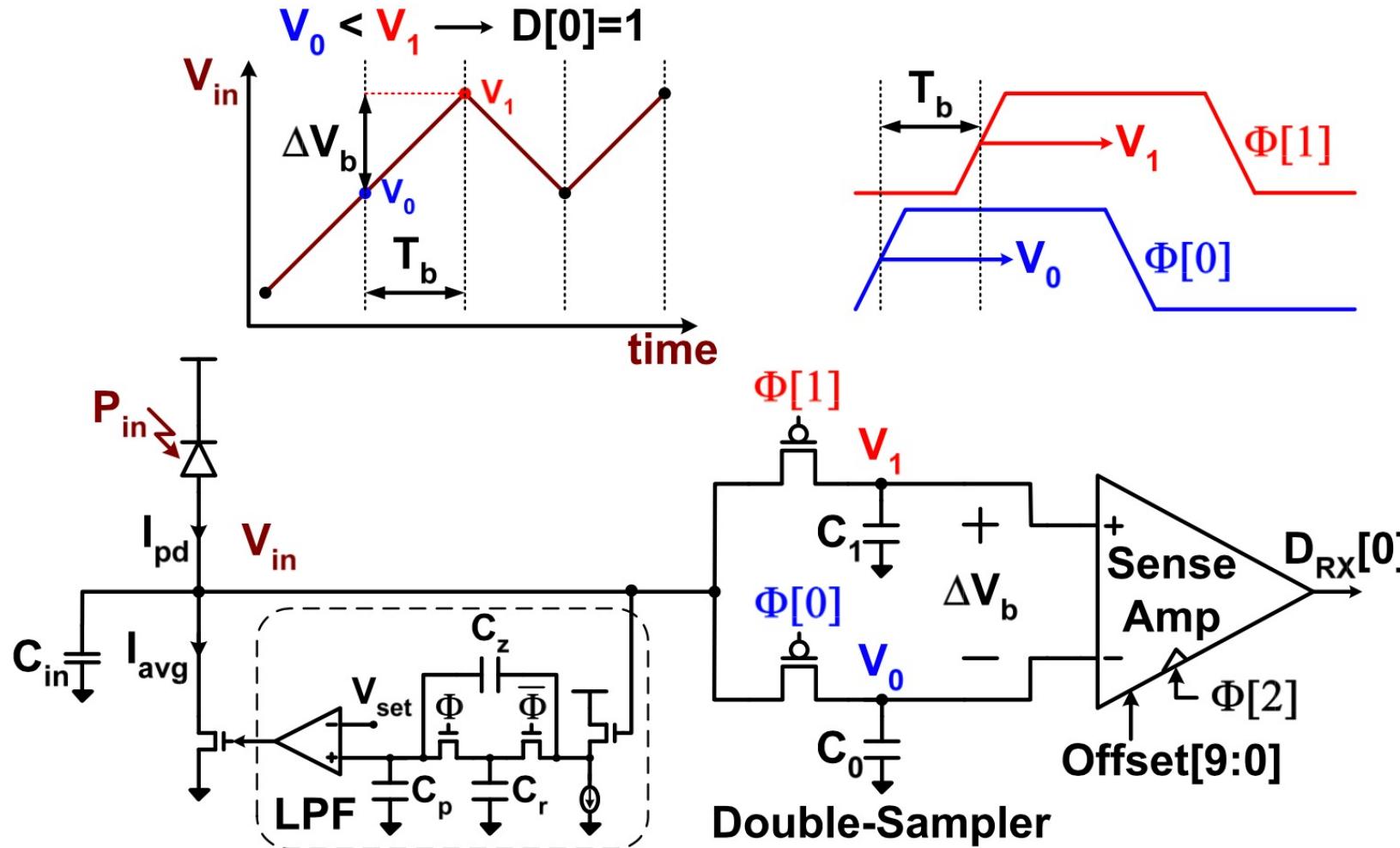
^{**} Estimated from the plots

$$* \text{FoM} = \frac{Z_T[\Omega] \times \text{BW}_{3dB-Z_T}[\text{GHz}]}{P_{dc}[\text{mW}]}$$

[§] Does not include the impact of LDO

[‡] Z_T is estimated from $50 \times S_{21}$ and BW_{3dB-S₂₁} is used for BW_{3dB-Z_T}.

Integrating Receiver Block Diagram

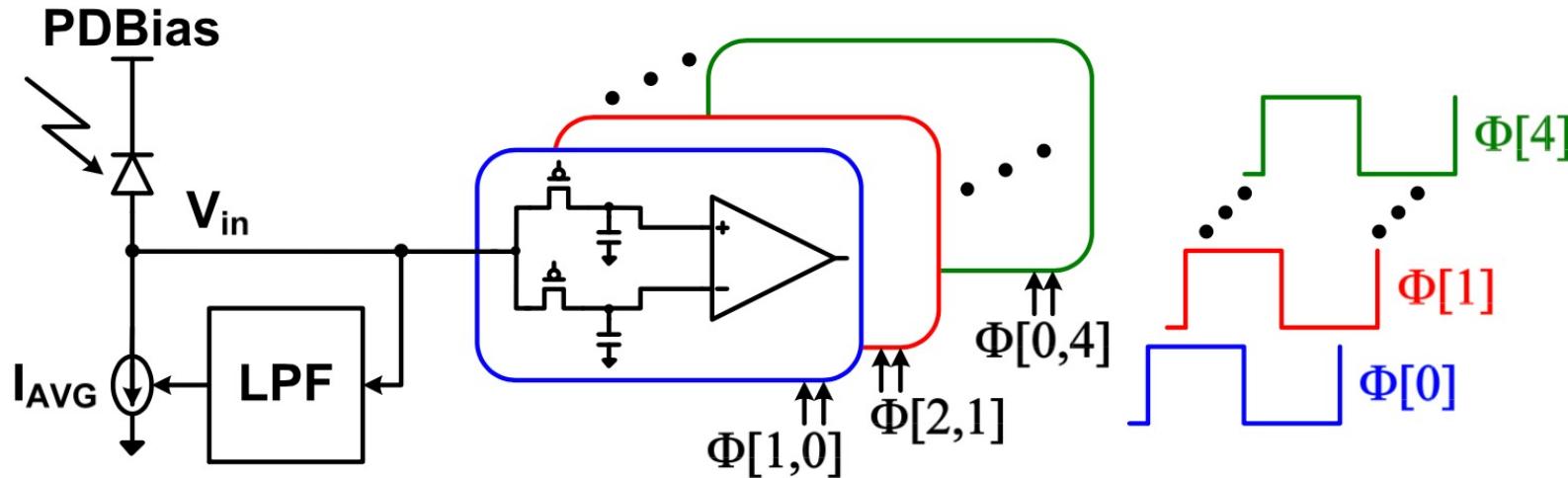


[Emami VLSI 2002]

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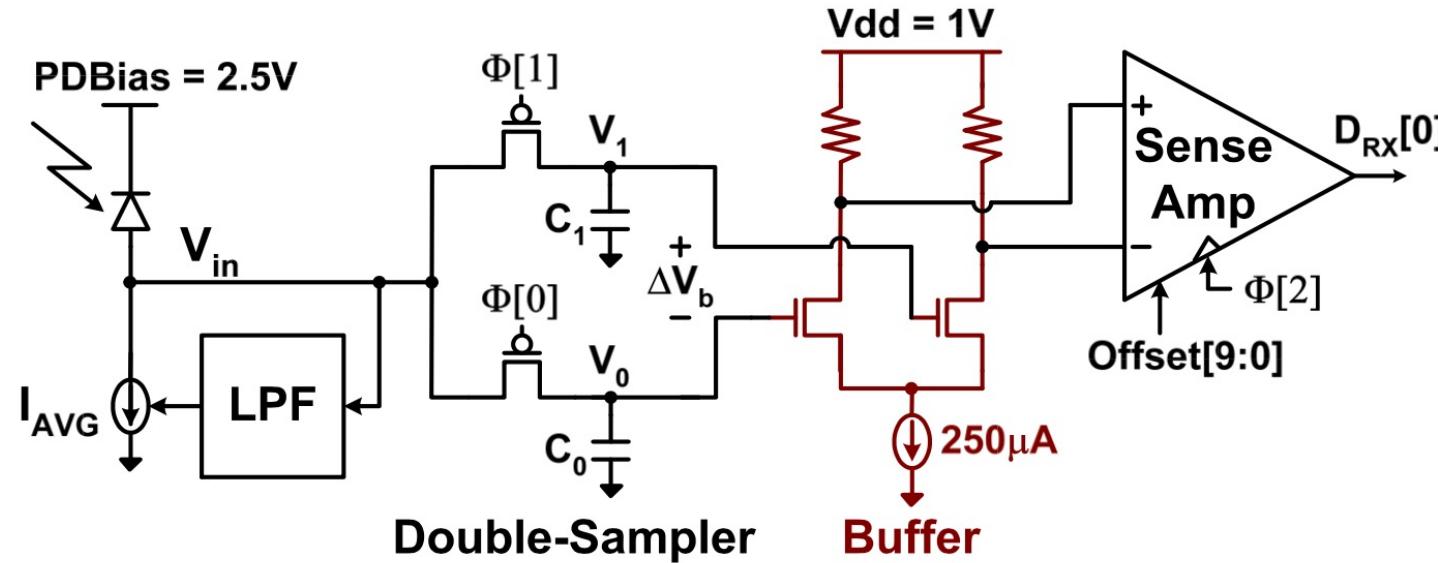
[Sam Palermo]

Demultiplexing Receiver



- Demultiplexing with multiple clock phases allows higher data rate
 - Data Rate = #Clock Phases x Clock Frequency
 - Gives sense-amp time to resolve data
 - Allows continuous data resolution

1V Modified Integrating Receiver



Differential Buffer

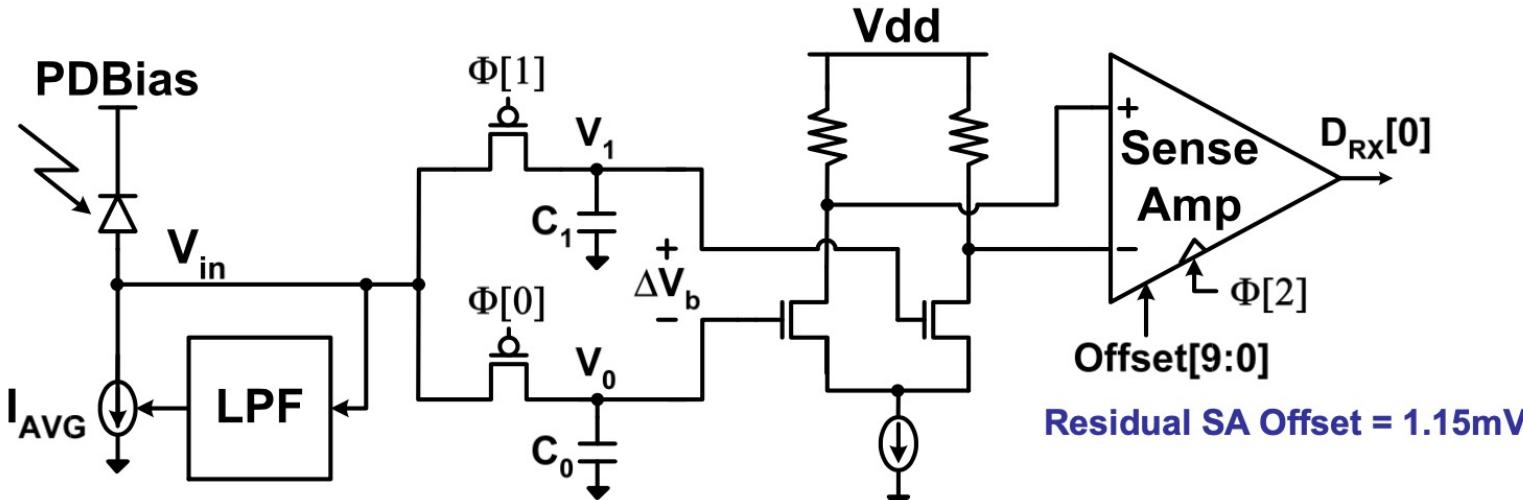
- 😊 Fixes sense-amp common-mode input for improved speed and offset performance
- 😊 Reduces kickback charge
- 😢 Cost of extra power and noise

Input Range = 0.6 – 1.1V

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[Sam Palermo]

Receiver Sensitivity Analysis



$$\text{Max } \Delta V_{in}(\Delta I_{AVG}) = 0.6\text{mV}$$

$$\sigma_{samp} = \sqrt{\frac{2kT}{C_{samp}}} = 0.92\text{mV} \quad \sigma_{buffer} = 1.03\text{mV} \quad \sigma_{SA} = 0.45\text{mV}$$

$$\text{Clock Jitter Noise } \sigma_{clk} = \left(\frac{\sigma_j}{T_b} \right) \Delta v_b \approx 0.65\text{mV at 16Gb/s}$$

$$\text{Total Input Noise } \sigma_{tot} = \sqrt{\sigma_{samp}^2 + \sigma_{buffer}^2 + \sigma_{SA}^2 + \sigma_{clk}^2} = 1.59\text{mV}$$

$$\Delta V_b \text{ for BER} = 10^{-10} = 6.4\sigma_{tot} + \text{Offset} = 11.9\text{mV}$$

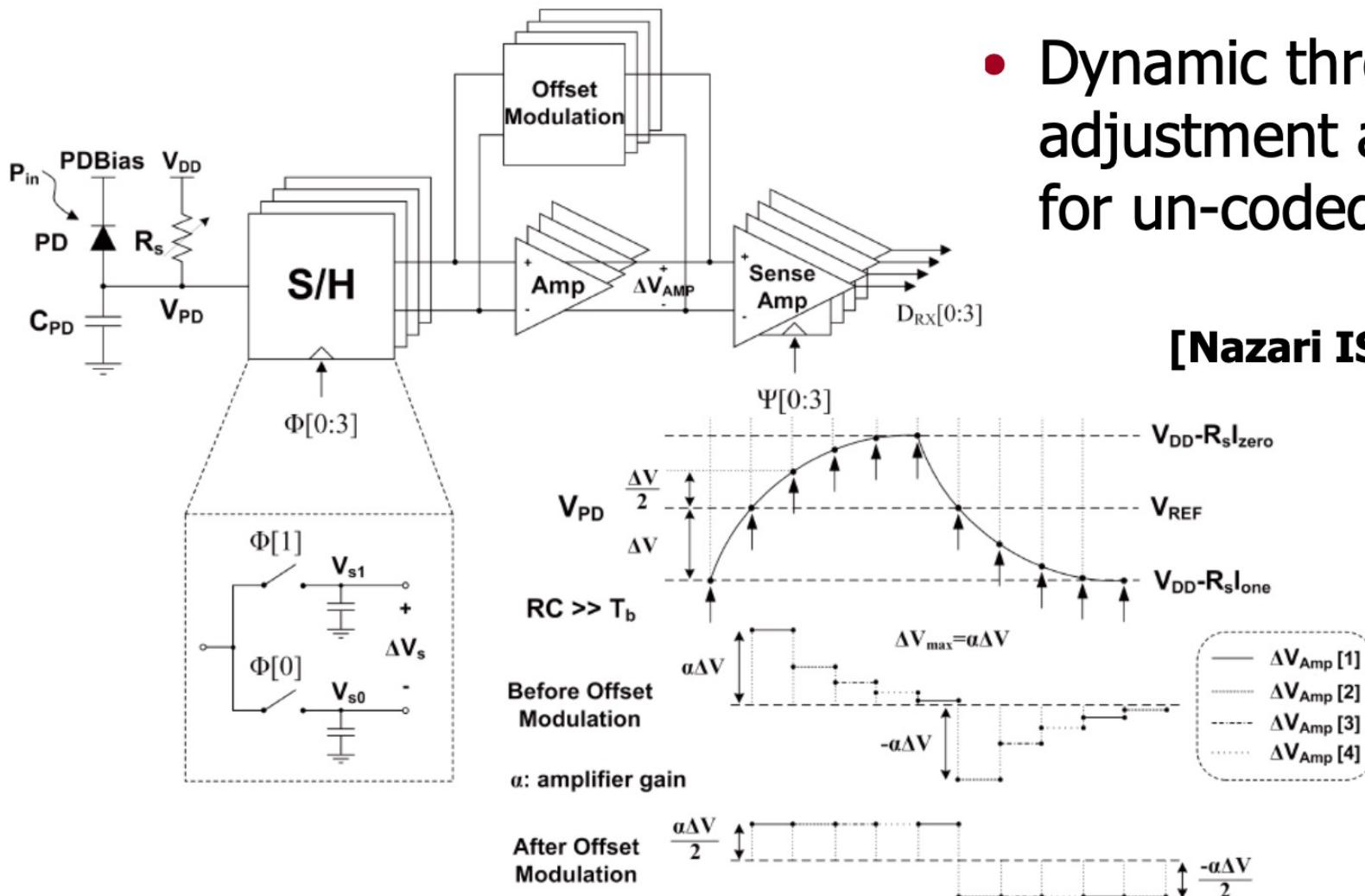
$$P_{avg} = \frac{\Delta V_b (C_{pd} + C_{in})}{\rho T_b}$$

Gb/s	P_{avg} (dBm)
10	-9.8
16	-7.8

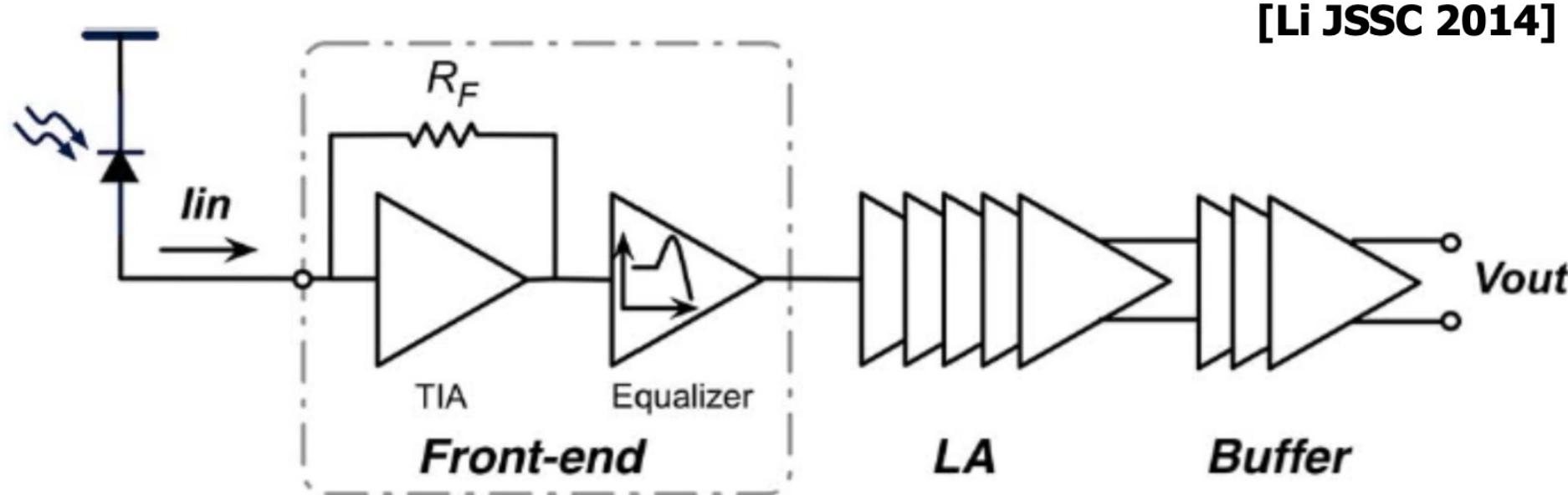
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[Sam Palermo]

Integrating RX with Dynamic Threshold



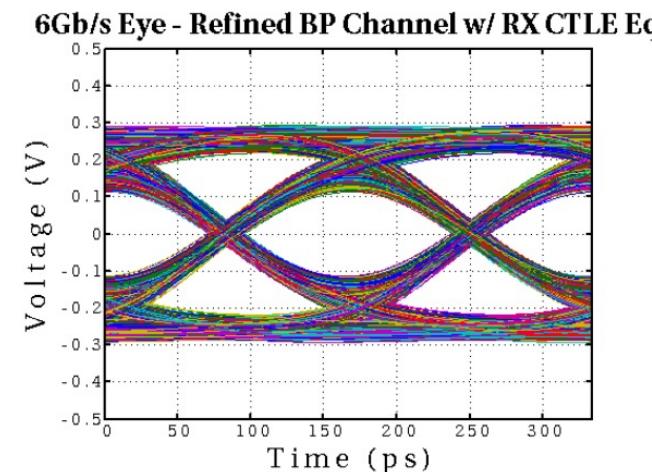
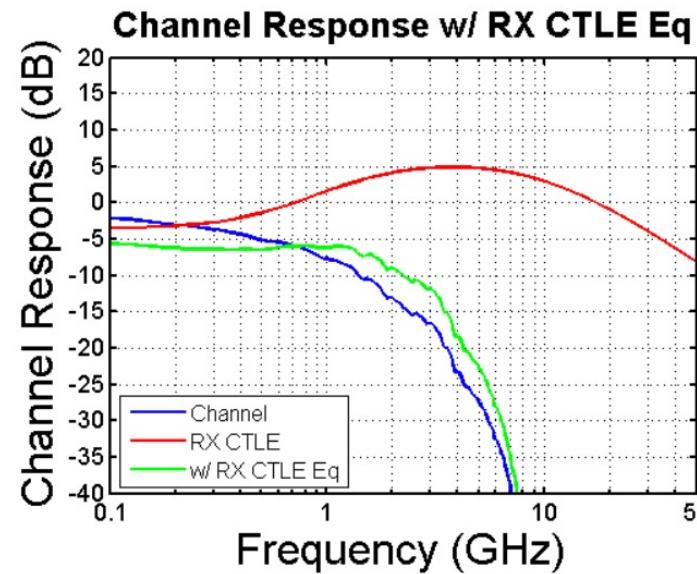
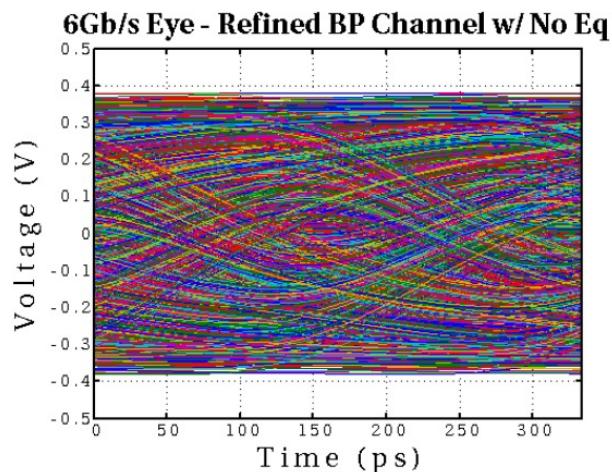
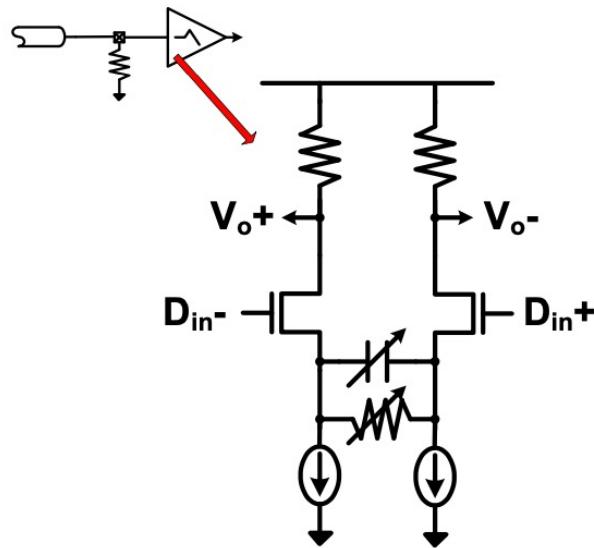
Low-BW TIA & CTLE Front-End



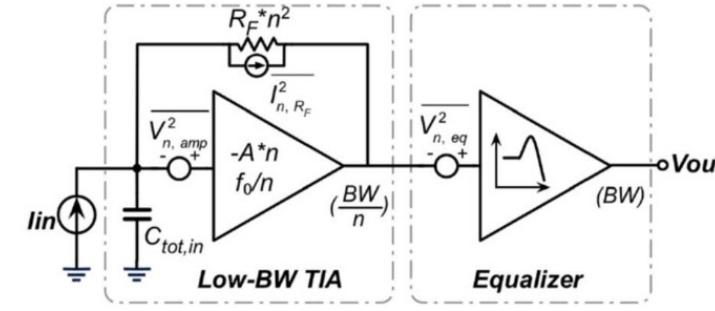
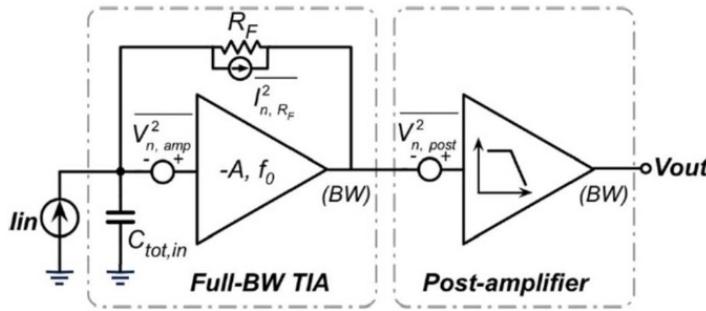
- Improved sensitivity is possible by increasing the first stage feedback resistor, resulting in a high-gain low-bandwidth TIA
- The resultant ISI is cancelled by a subsequent CTLE

[Sam Palermo]

Active CTLE Example



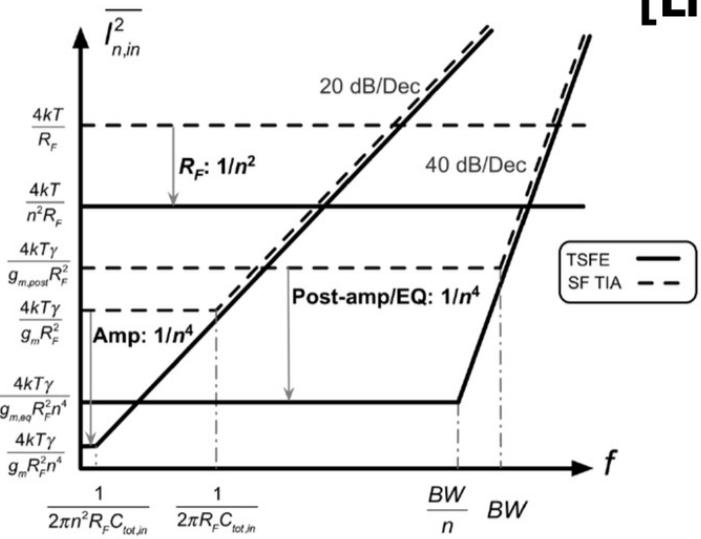
Low-BW TIA & CTLE Front-End



$$\overline{I_{n,in,SF}^2(f)} = \frac{4kT}{R_F} + \frac{4kT\gamma}{g_m R_F^2} + 4kT\gamma \frac{(2\pi C_{tot,in})^2}{g_m} f^2 + \frac{4kT\gamma}{g_{m,post} R_F^2} + \frac{4kT\gamma}{g_{m,post} R_F^2} \left(\frac{f}{BW} \right)^4$$

$$\begin{aligned} \overline{I_{n,in,TSFE}^2(f)} &= \frac{4kT}{R_F n^2} + \frac{4kT\gamma}{g_m R_F^2 n^4} \\ &\quad + 4kT\gamma \frac{(2\pi R_F n^2 C_{tot,in})^2}{g_m R_F^2 n^4} f^2 \\ &\quad + \frac{4kT\gamma}{g_{m,eq} R_F^2 n^4} + \frac{4kT\gamma}{g_{m,eq} R_F^2 n^4} \left(\frac{f}{BW/n} \right)^4 \\ &= \frac{4kT}{R_F n^2} + \frac{4kT\gamma}{g_m R_F^2 n^4} + 4kT\gamma \frac{(2\pi C_{tot,in})^2}{g_m} f^2 \\ &\quad + \frac{4kT\gamma}{g_{m,eq} R_F^2 n^4} + \frac{4kT\gamma}{g_{m,eq} R_F^2} \left(\frac{f}{BW} \right)^4 \quad (5) \end{aligned}$$

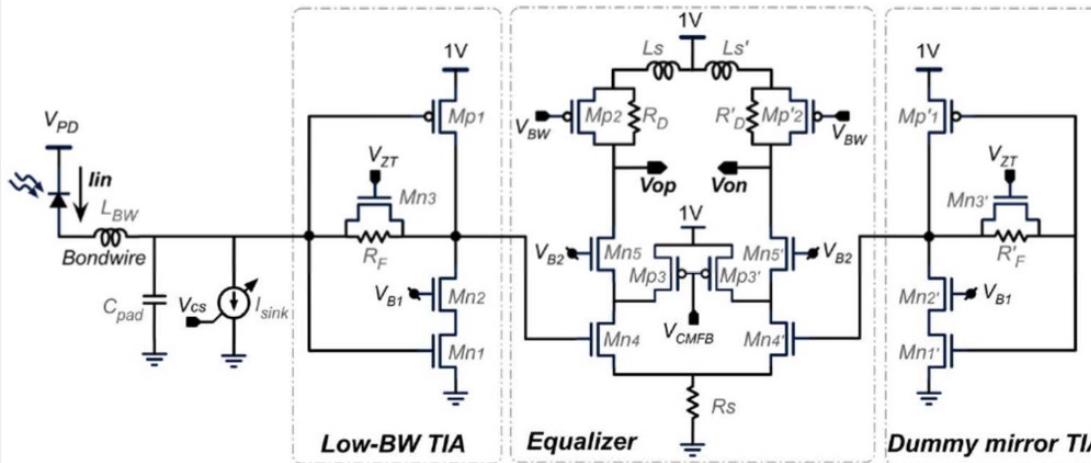
[Li JSSC 2014]



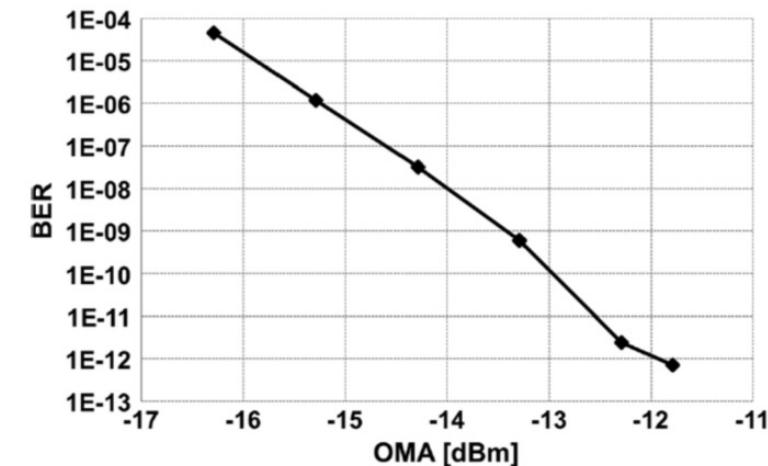
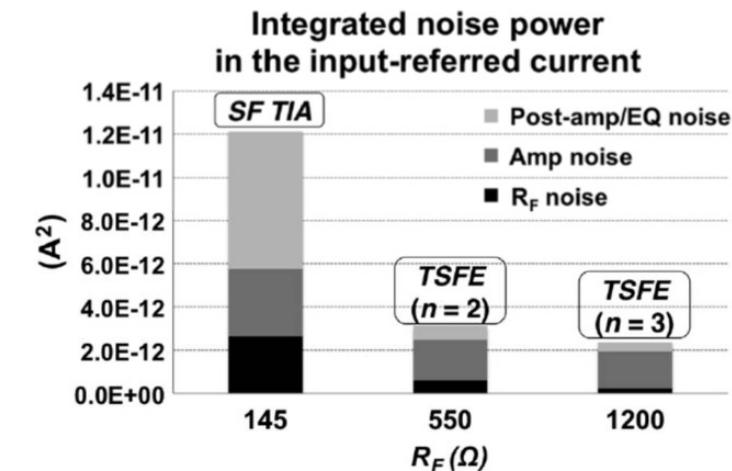
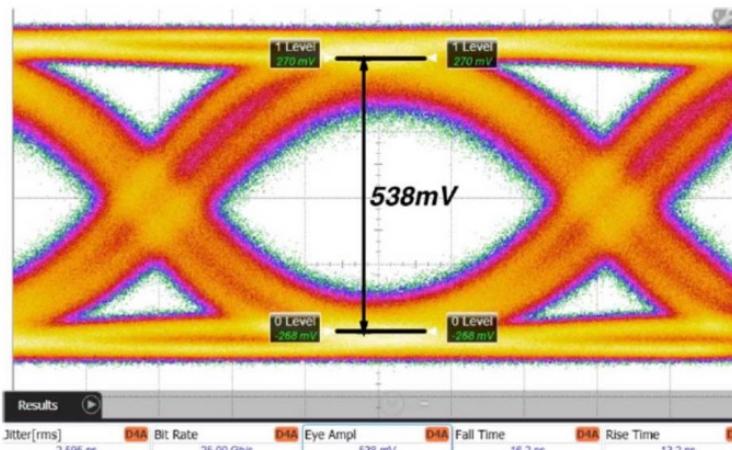
- Significant reduction in feedback resistor noise
- Low-frequency input and post amplifier noise is also reduced

Low-BW TIA & CTLE Front-End

[Li JSSC 2014]



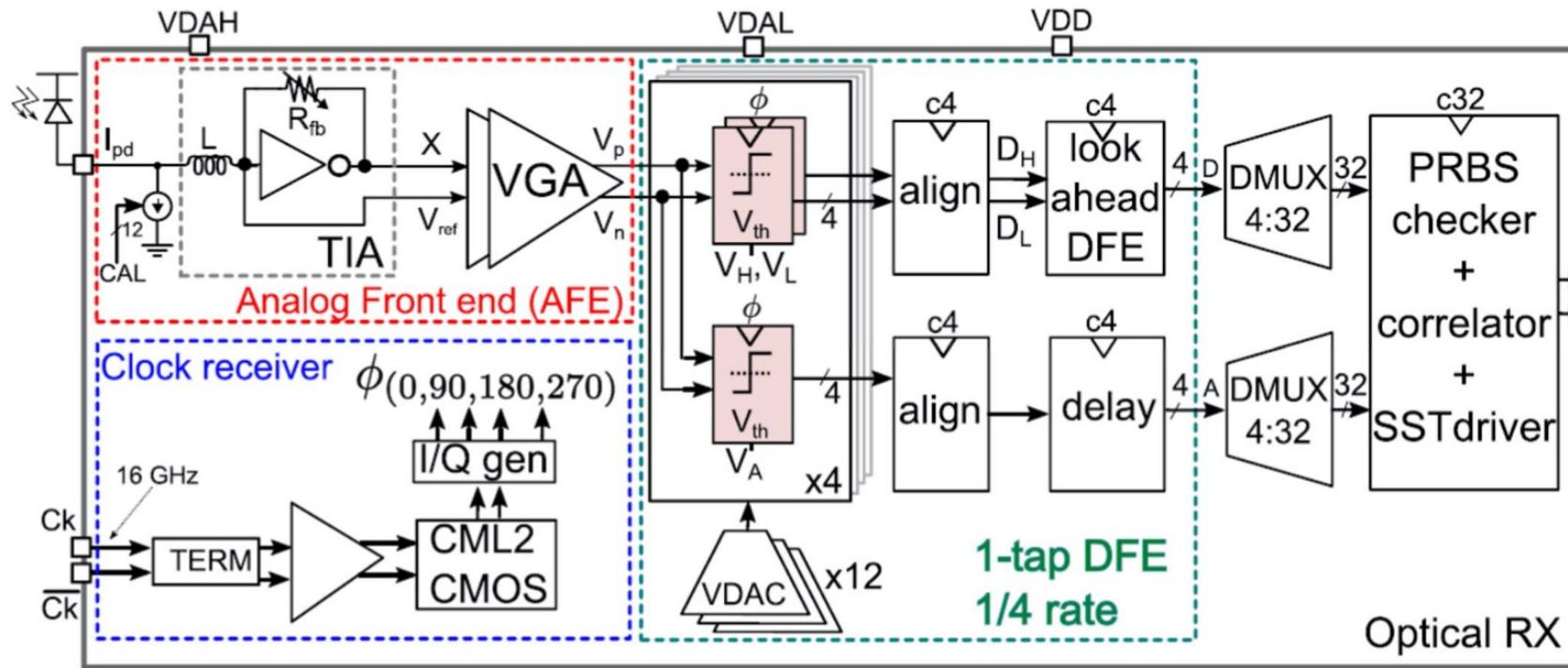
25Gb/s Eye Diagram



[Sam Palermo]

Low-BW TIA & DFE RX

[Ozkaya JSSC 2017]



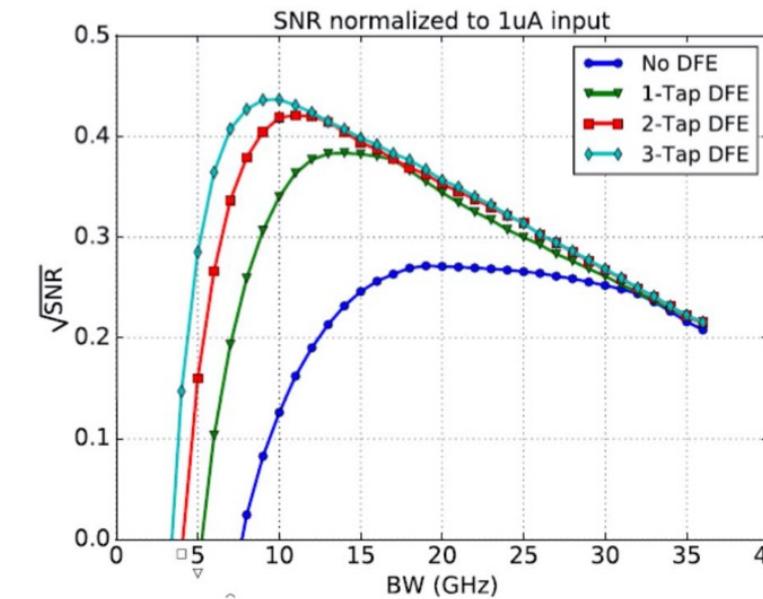
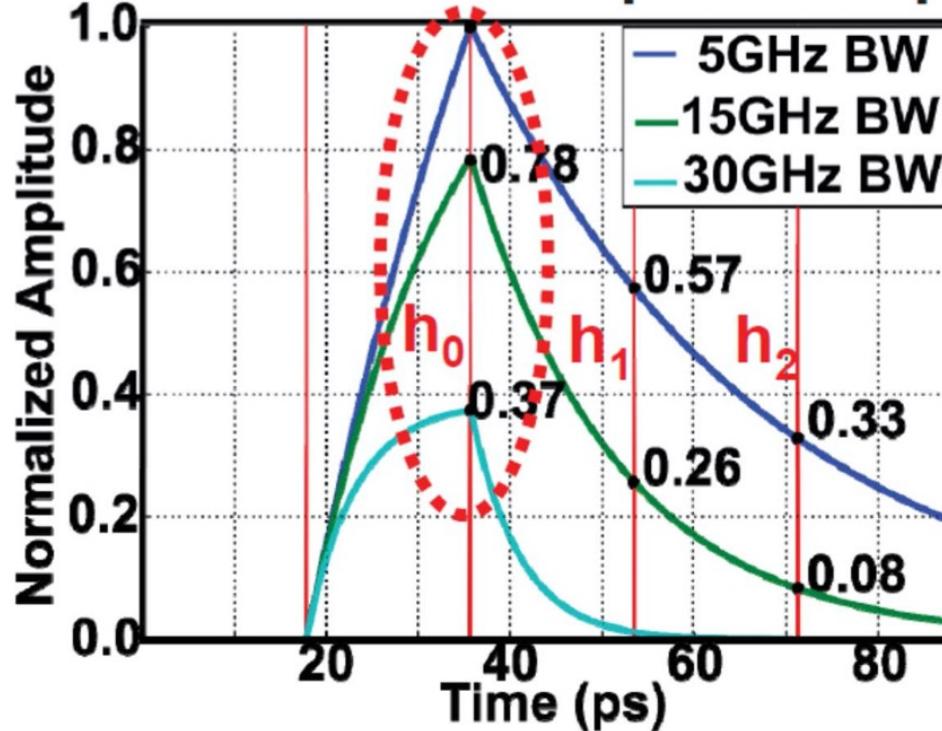
- In a similar manner, a high-gain low-bandwidth TIA is utilized
- The resultant ISI is cancelled by a subsequent 1-tap loop-unrolled DFE

[Sam Palermo]

Low-BW TIA & DFE RX

[Ozkaya JSSC 2017]

1st order TIA model pulse response (56Gb/s)

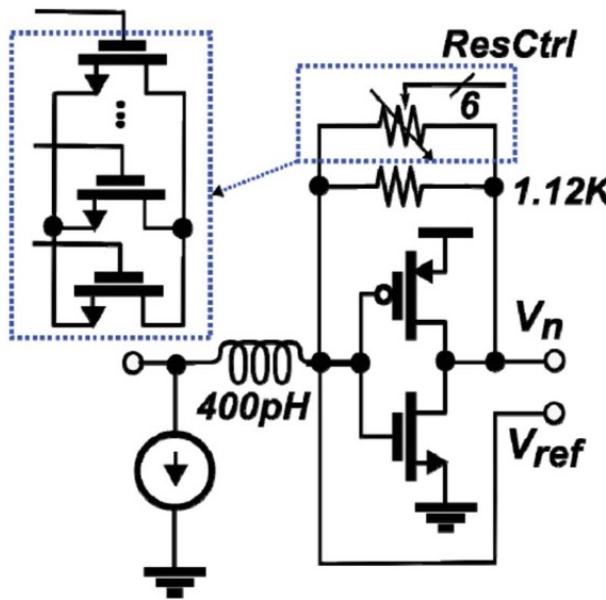


- As RF is increased, the main cursor increases and the SNR improves as ISI is cancelled by a DFE
- Large performance benefit with a low-complexity 1-tap DFE

[Sam Palermo]

Low-BW TIA & DFE RX

[Ozkaya JSSC 2017]



- Self-referenced TIA is used for differential generation
- Actual 64Gb/s pulse response has a significant pre-cursor ISI tap, which requires a 2-tap TX FFE

64Gb/s Pulse Response & Timing Margin

