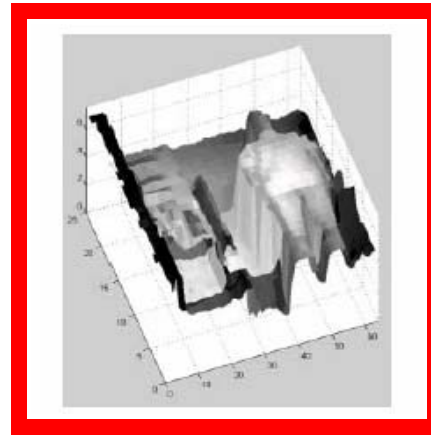
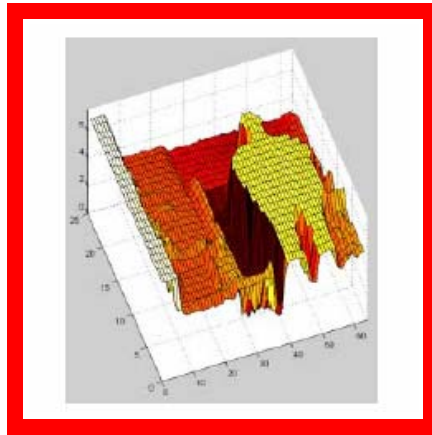


ORTHOGONALLY MODULATED CMOS READOUT INTEGRATED CIRCUIT FOR IMAGING APPLICATIONS



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December 13, 2004

Research work supported by the Army Research Laboratory



Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 13 DEC 2004		2. REPORT TYPE		3. DATES COVERED 00-00-2004 to 00-00-2004	
4. TITLE AND SUBTITLE Orthogonally Modulated CMOS Readout Integrated Circuit for Imaging Applications				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Delaware, Department of Electrical and Computer Engineering, Newark, DE, 19716				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 48	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			



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- Introduction and motivation
- Contribution Phase I: Proof of principle
 - Orthogonal encoding readout system description
 - Prototype system design and verification
 - Conclusions
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 - Readout cell improvements
 - Transimpedance amplifier integration
- Conclusion and brainstorm on further improvements



Read Out Integrated Circuit ROIC

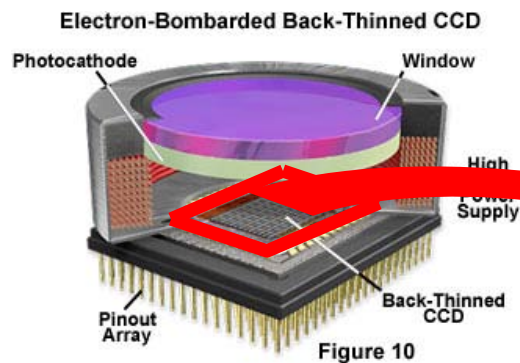
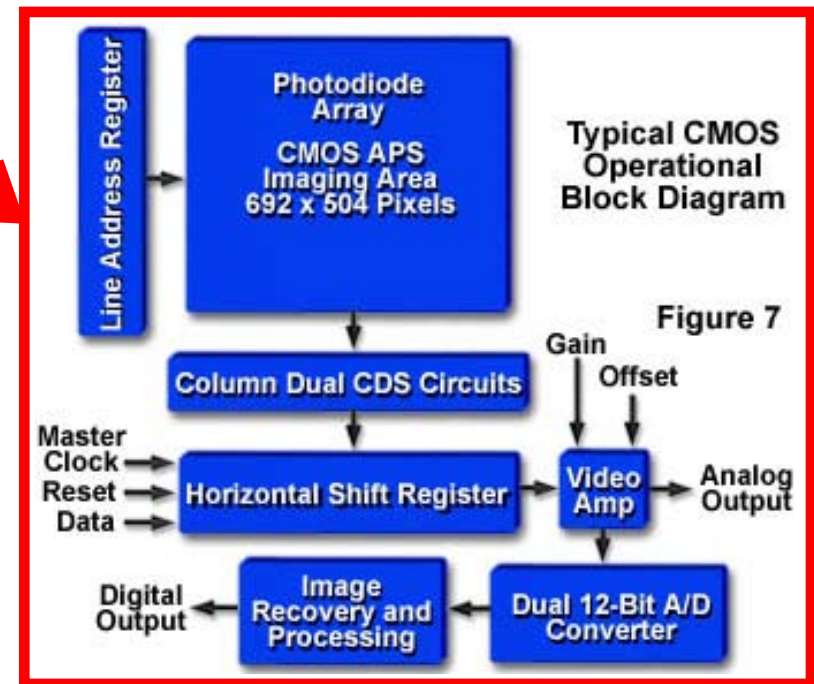


Figure 10

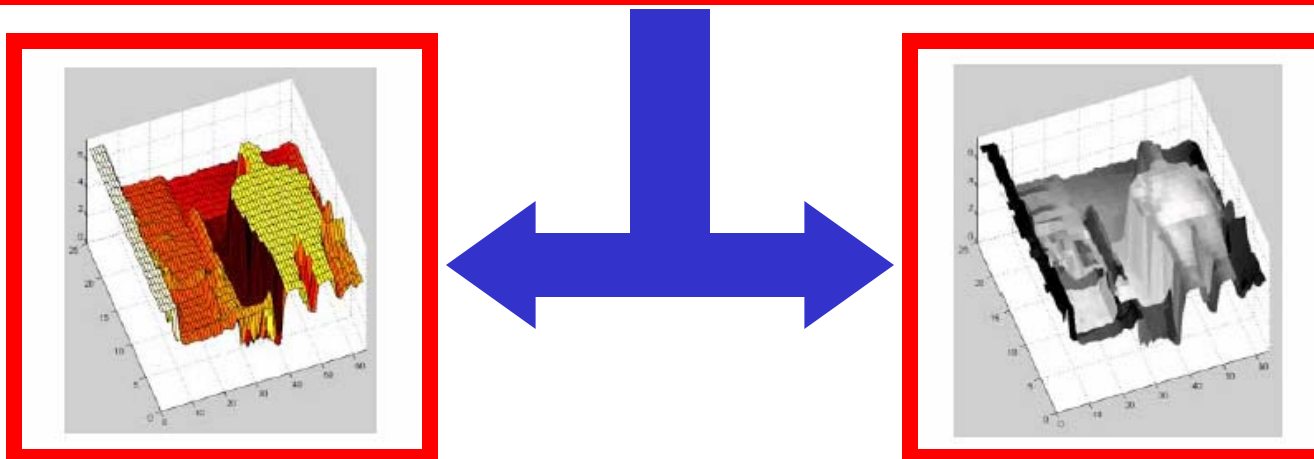
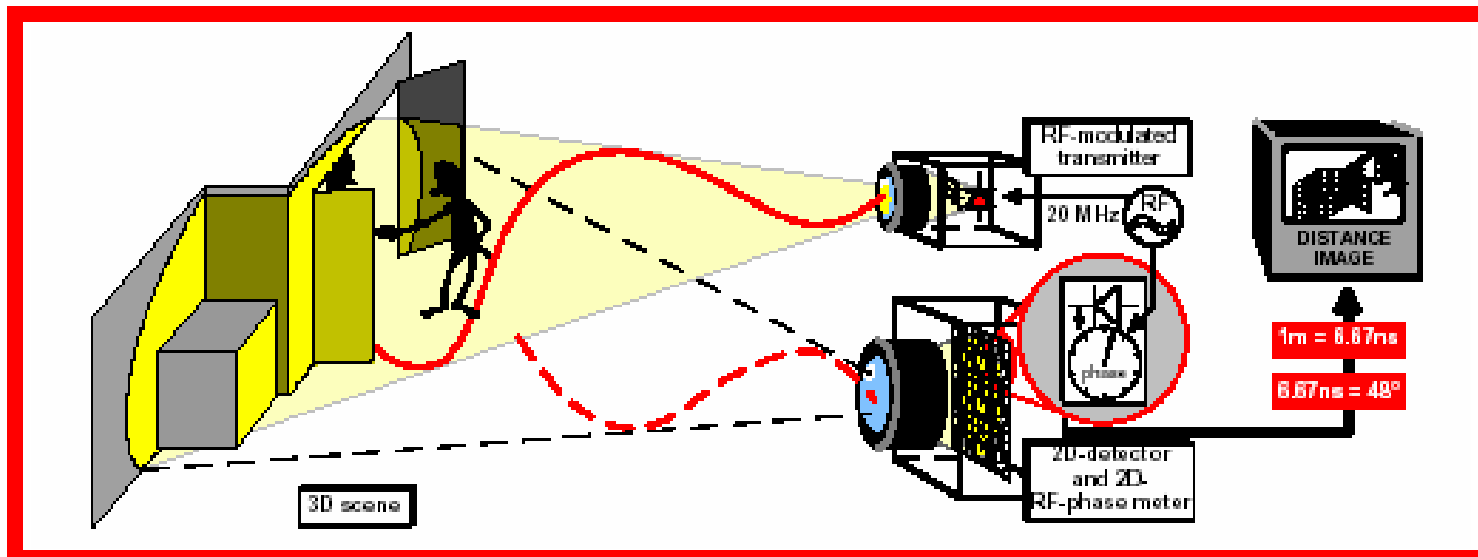
ROIC may include:

- Amplifier electronics
- Control signal generators
- Analog-Digital Conversion
- On-chip Digital Signal Processing



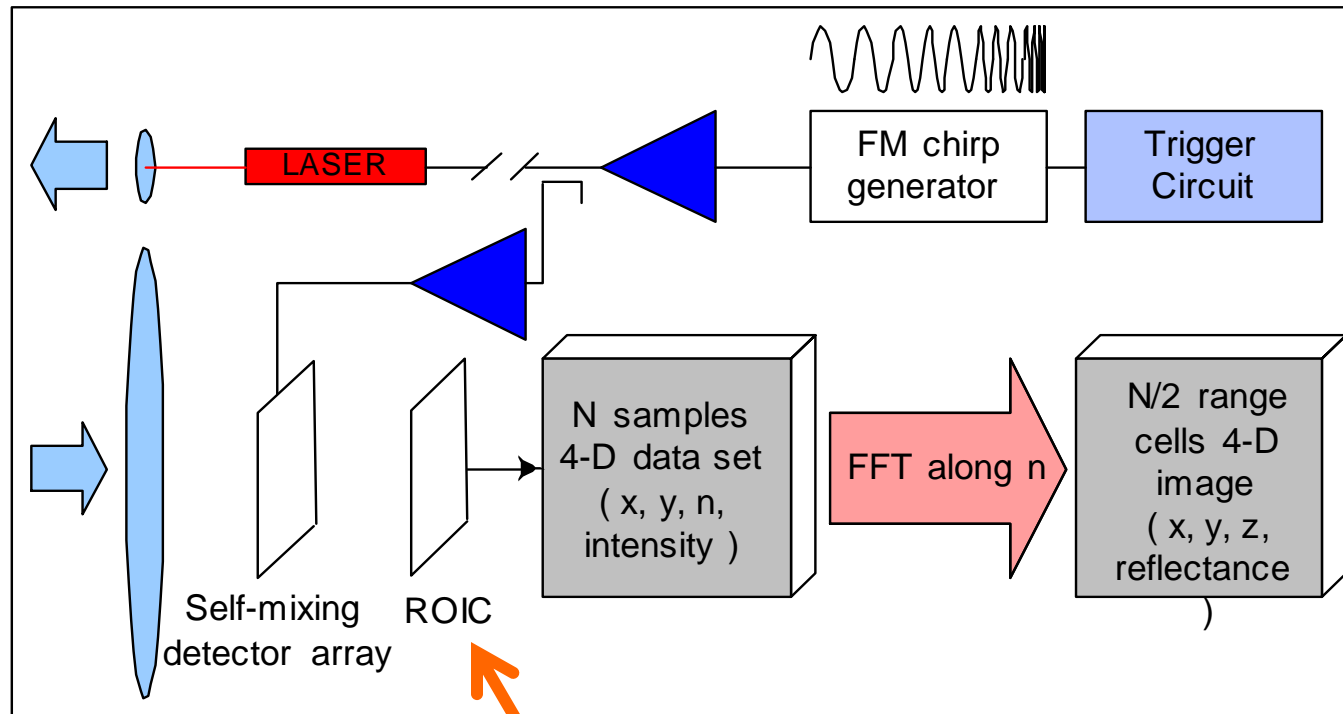


Distance information: a time of flight measurement





FM/CW LADAR system



Motivation: Readout Integrated Circuit ROIC for active/passive imaging systems

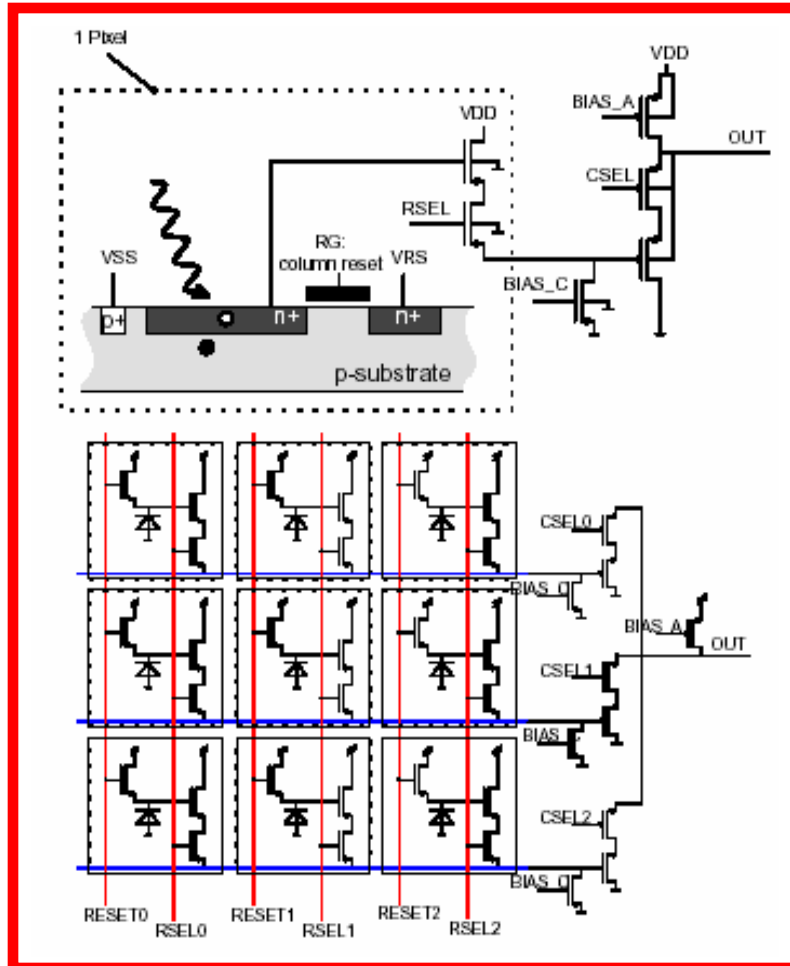


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ROIC conventional architecture



Time Domain Multiple Access

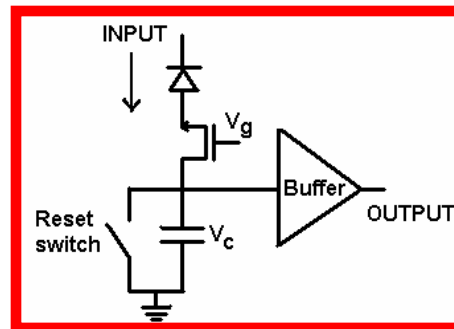
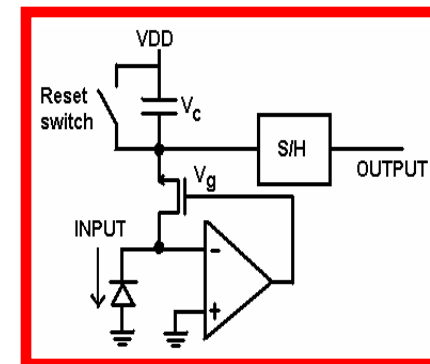
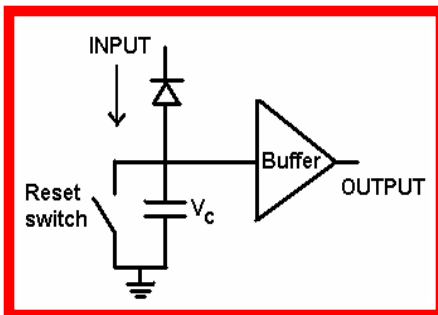
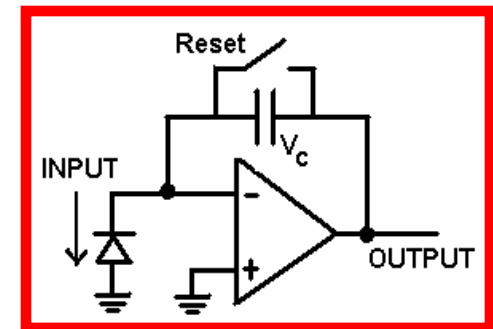
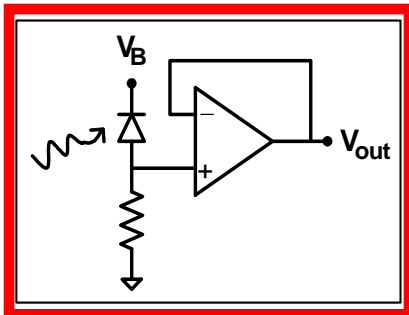
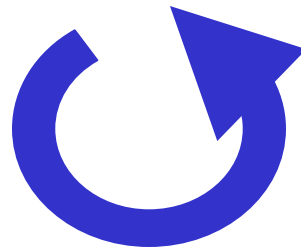
Control signals access every readout cell in a time scheduled manner, sampling the voltage signals and transferring them to the readout bus.

It requires faster electronics for bigger photodetector arrays.

Each readout cell must be capable of storing the required charge, which becomes a problem for big array sizes (1024x1024).

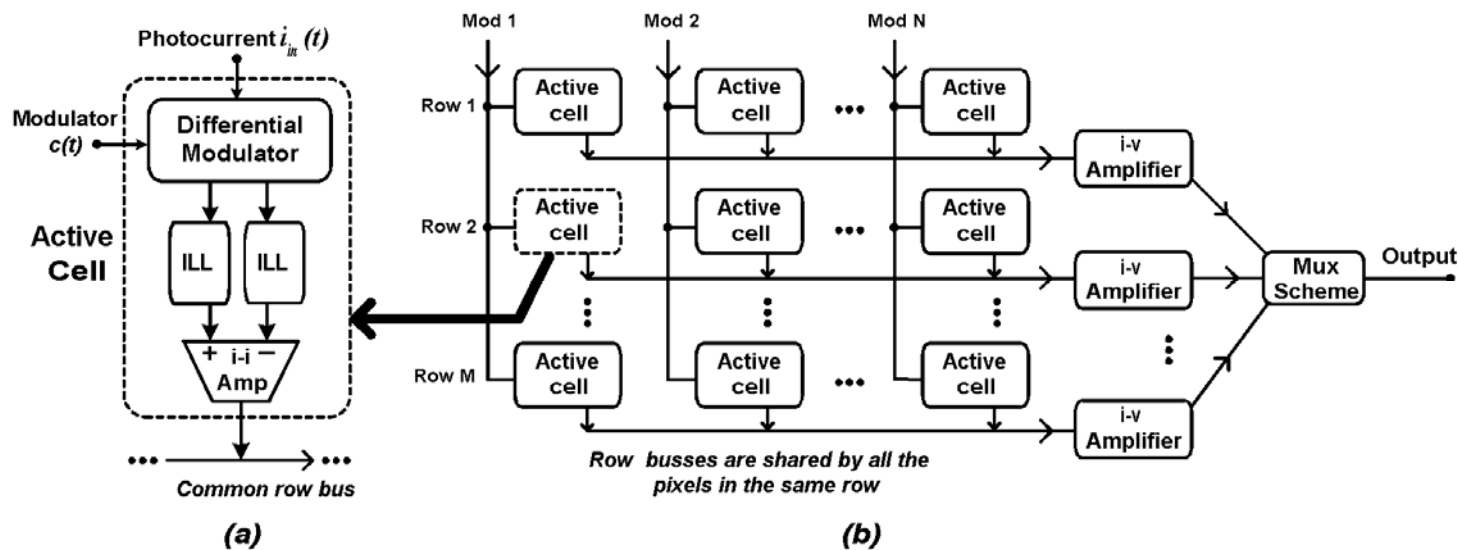
Read Out Cell Architectures

From Direct Injection to Capacitive TransImpedance Amplifier





ROIC proposed architecture



Orthogonal encoding ROIC

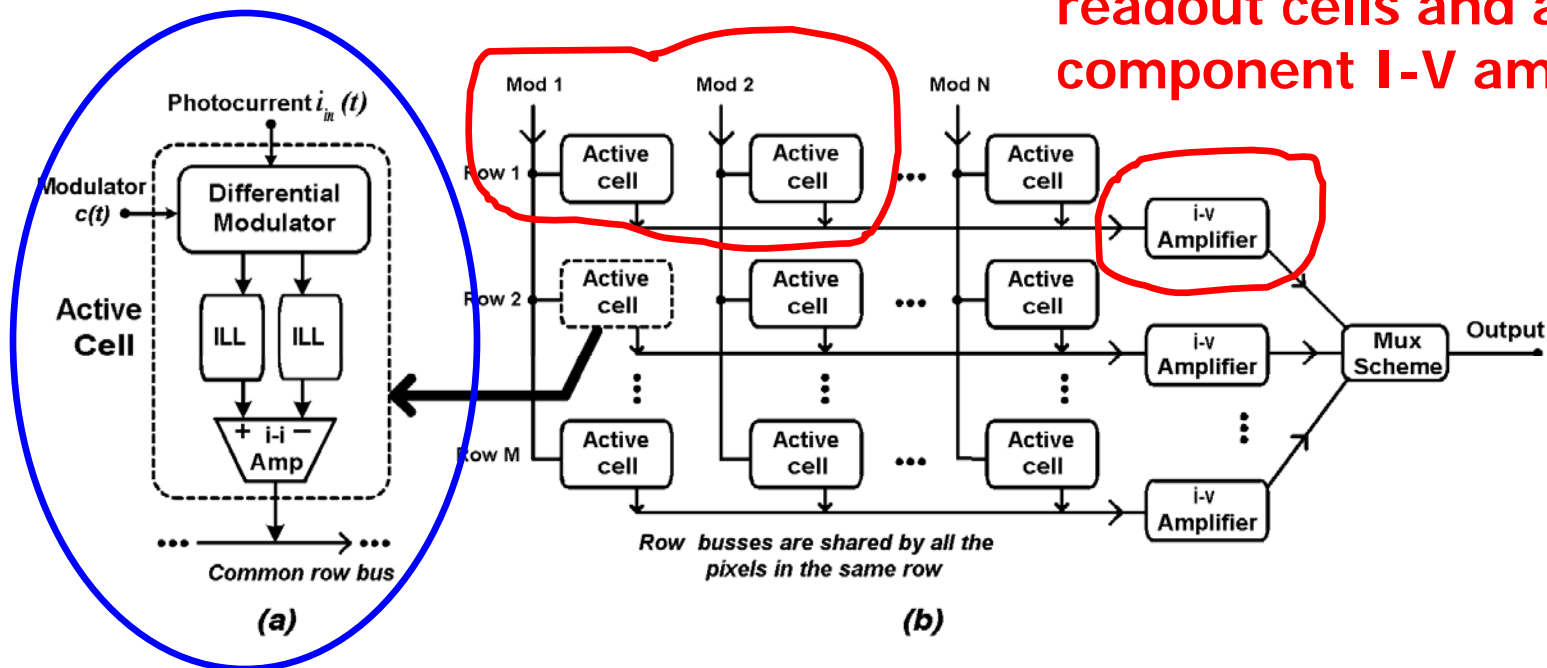
- Each column is multiplied by a unique code, and the multiplied signals are summed in the row common bus
- Codes are chosen to minimize cross talk
- Current-to-voltage amplifier per row
- Multiplexer scheme to generate single data stream



Orthogonal Encoding ROIC

First Phase Design Tasks

Test system with four readout cells and a discrete component I-V amplifier

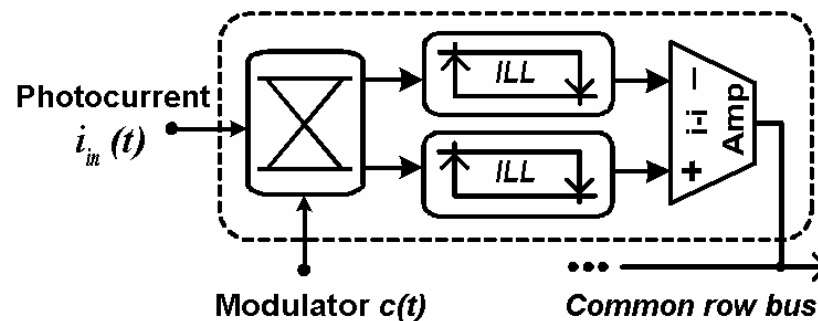


Design of the
Active Readout
Cell

To design and fabricate a test chip
for a proof of principle of the
active 2D readout technique.



Active Readout Cell: Design Requirements



Readout cell for orthogonal encoding

Multiplies the input current by the code

Provides detector virtual ground

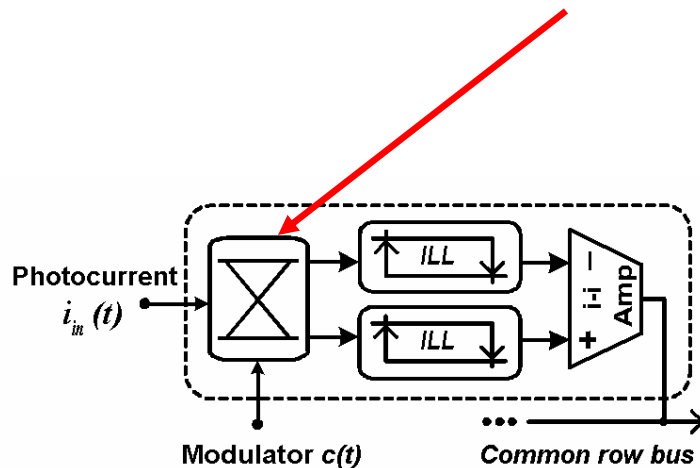
Couples the detector impedance to the bus

Reduces charge injection noise

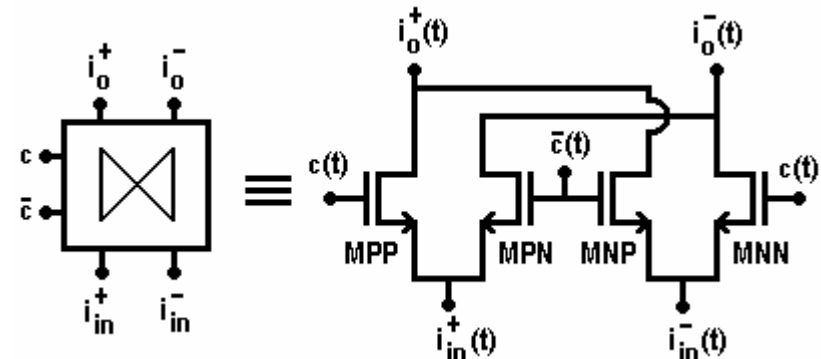


Active Readout Cell: Implementation

Differential code multiplier



Readout cell for
orthogonal encoding



$$i_o^+(t) = i_{in}^+(t) \cdot c(t) + n_c + i_{in}^-(t) \cdot \bar{c}(t) + n_{\bar{c}},$$

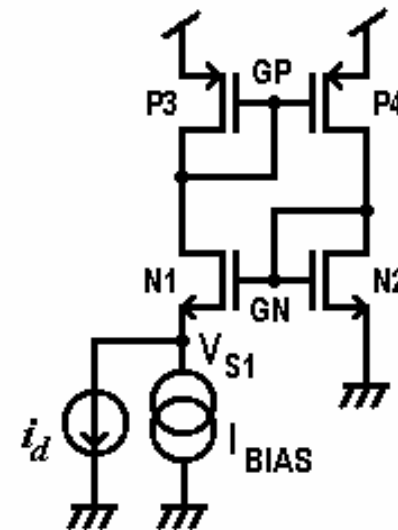
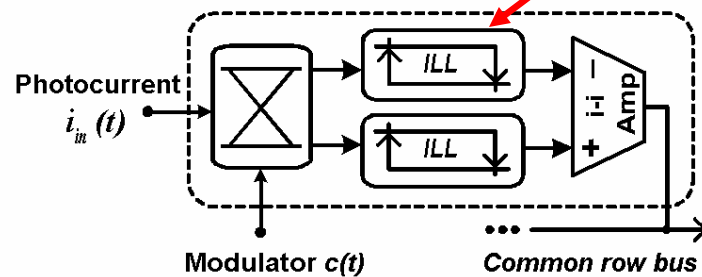
$$i_o^-(t) = i_{in}^-(t) \cdot \bar{c}(t) + n_{\bar{c}} + i_{in}^+(t) \cdot c(t) + n_c,$$

Differential output current $i_{od}(t) = i_o^+(t) - i_o^-(t) = [i_{in}^+(t) - i_{in}^-(t)] \cdot [c(t) - \bar{c}(t)],$



Active Readout Cell

Current Locked Loop ILL



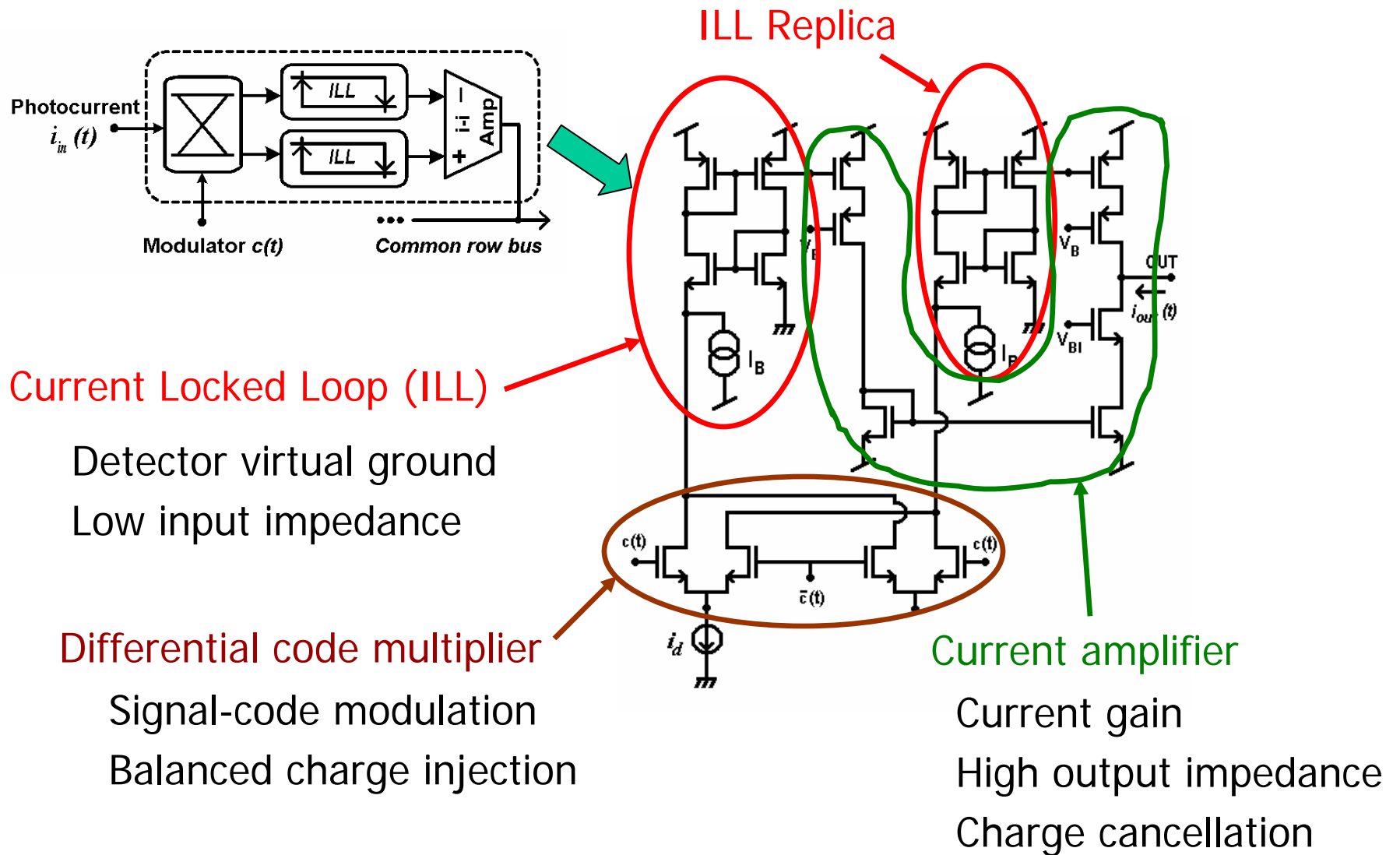
Characteristics

Detector virtual ground

$$\left. \frac{v_{g1}}{v_{s1}} \right|_{low\ freq.} = \frac{-g_1 g_4}{g_2 g_3 - g_1 g_4} = \frac{-\gamma}{1 - \gamma}, \text{ with } \gamma = \frac{g_1 g_4}{g_2 g_3}$$

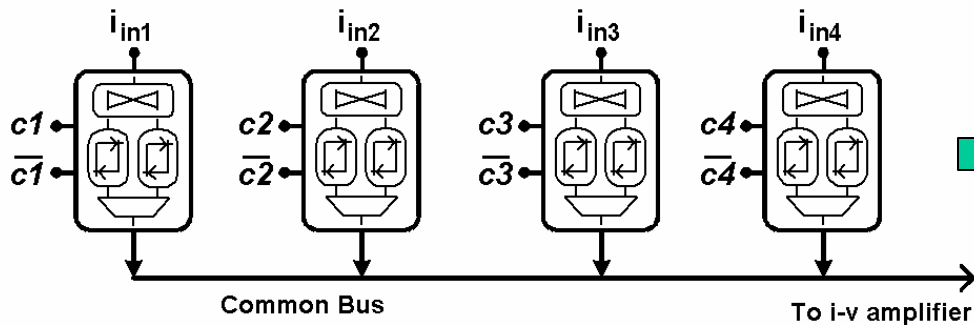
Low input impedance

$$\left. Z_{in} \right|_{low\ freq.} = \frac{1}{g_1} (1 - \gamma)$$

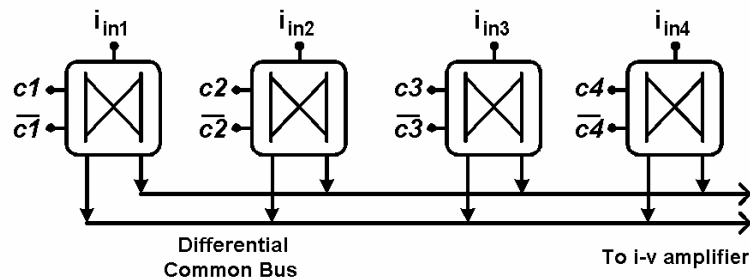




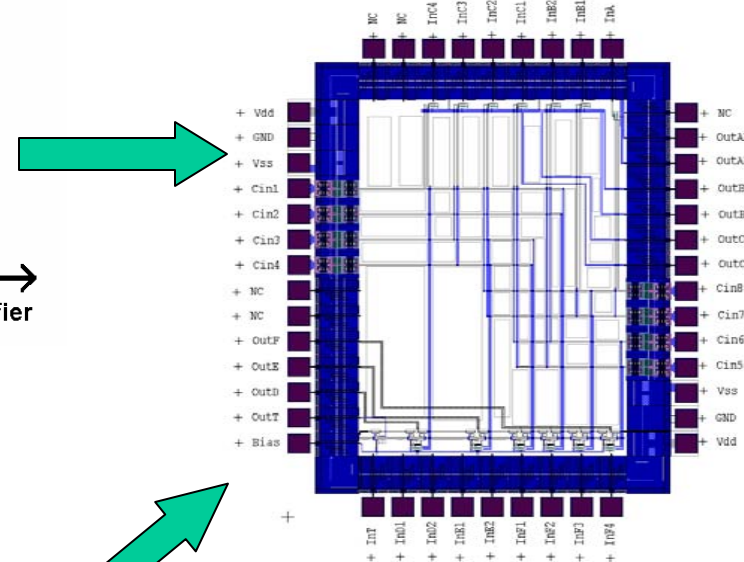
Test chip implementation



4 instances of active readout cell



4 instances of cell with input modulator only



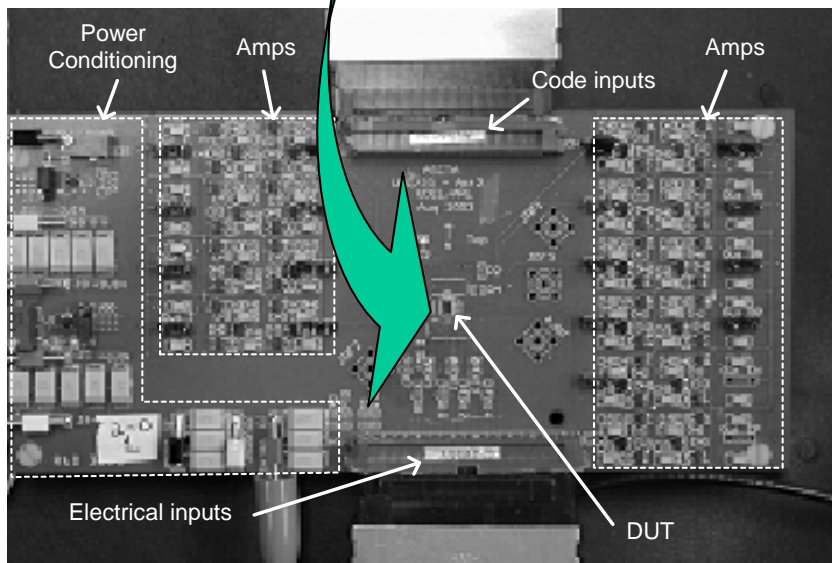
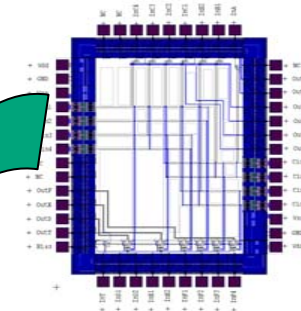
Test chip with cell prototypes



Prototype system testing

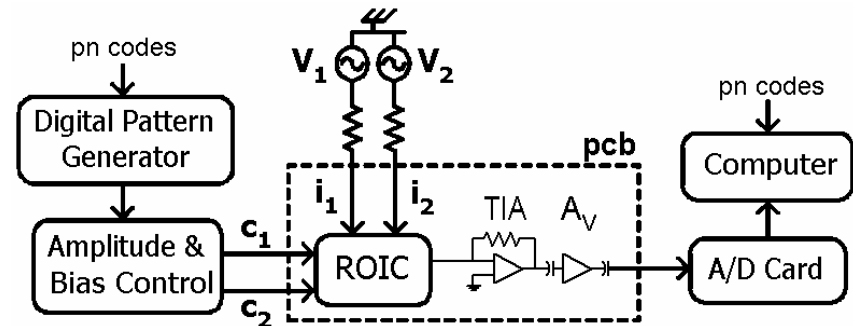


Test chip
with cell
prototypes



Custom printed circuit board
for electro-optical testing

ROIC electrical
verification set up



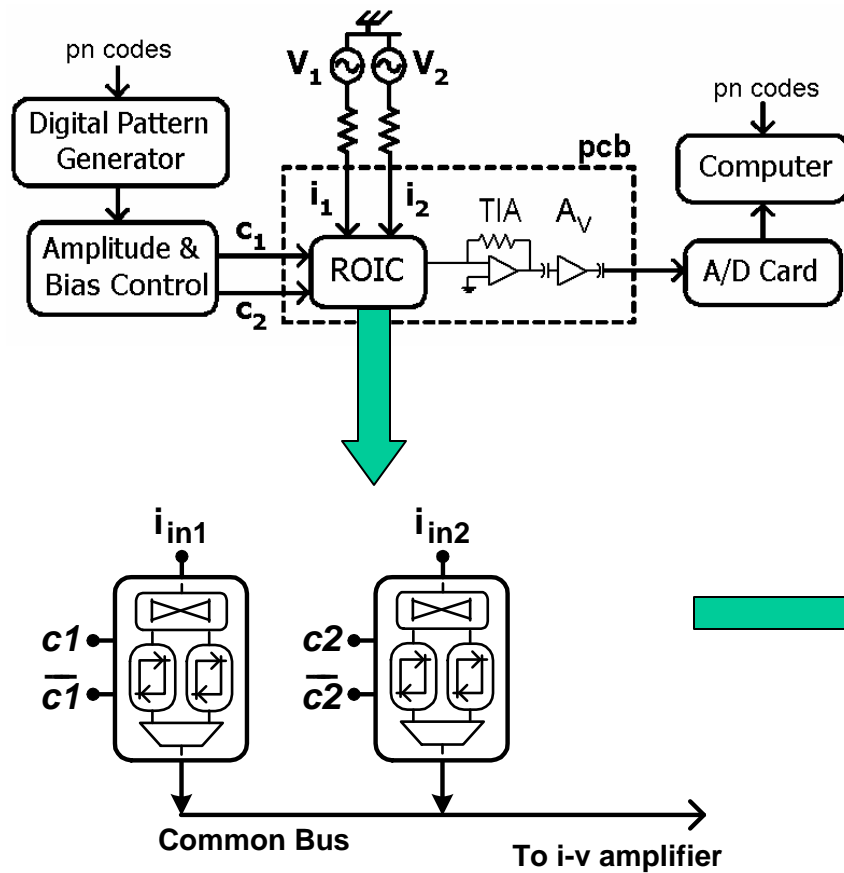
Code signals generated and
conditioned externally

Voltage sources + Resistors emulate
electrical current inputs

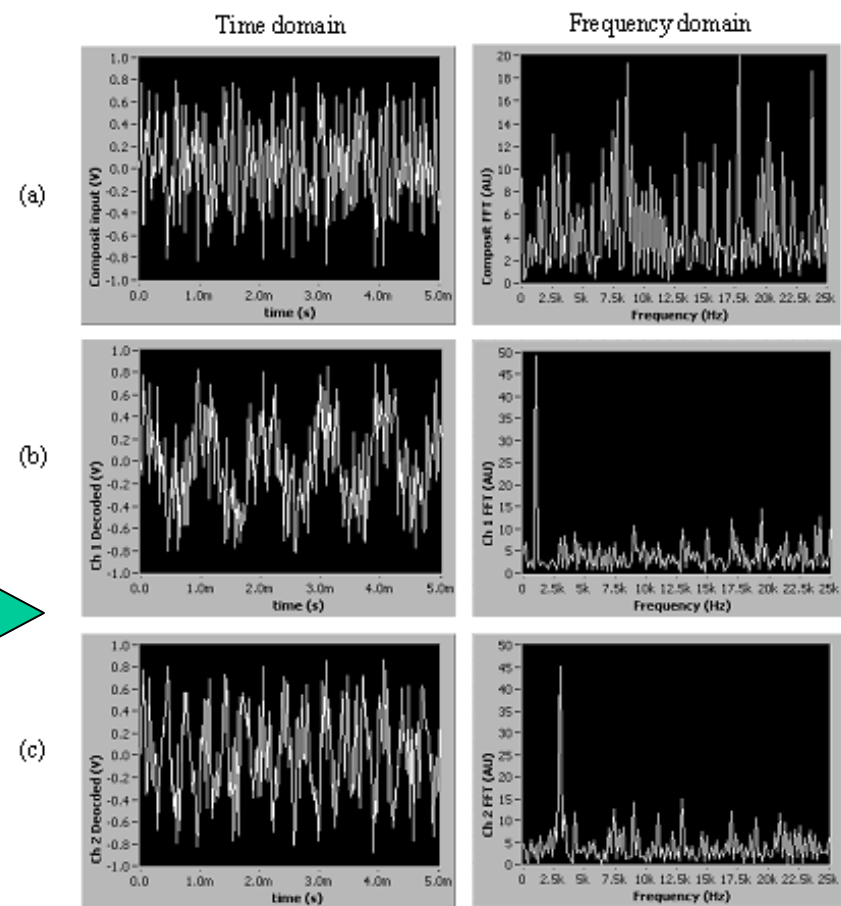
High-gain off-chip transimpedance
amplifiers on the pcb

Data is acquired and processed in
the computer

Verification Results



**Proof of principle system
with 2 encoding cells**



Test results



Prototyping phase conclusion

Satisfactory results with the 2 encoding cells experiment confirm validity of the orthogonal encoding scheme for readout circuits

Applicability extends to passive imaging systems

Depending on the system conditions, the orthogonal encoding architecture is advantageous with respect to the conventional time-multiplexed scheme

Integrating the transimpedance amplifiers with improved versions of readout cells should enhance noise performance of the overall system



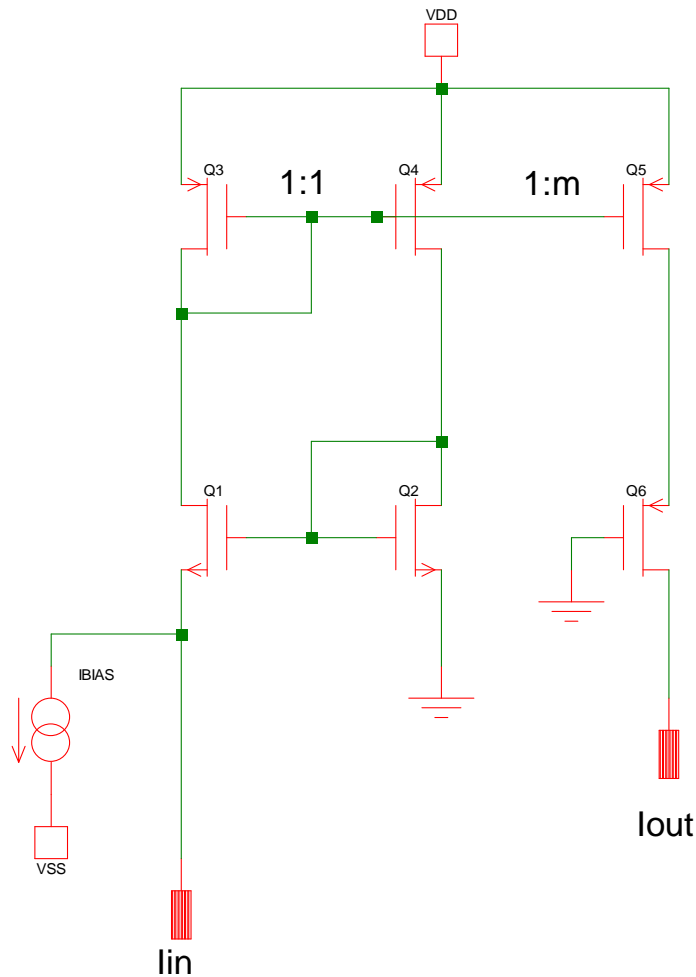
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Active Readout Cell Improvements

ILL current gain and noise performance



$$\overline{i_{Q3}^2} = 4kT\gamma g_3$$

$$\overline{i_{out}^2} = 4kT\gamma g_5 \left(1 + \frac{g_5}{g_3} \right) = 4kT\gamma g_3 m (1 + m)$$

Input referred noise

$$\overline{i_{ieq}^2} = \frac{\overline{i_{out}^2}}{m^2} = 4kT\gamma g_3 \frac{(1 + m)}{m}.$$

Minimize g_3

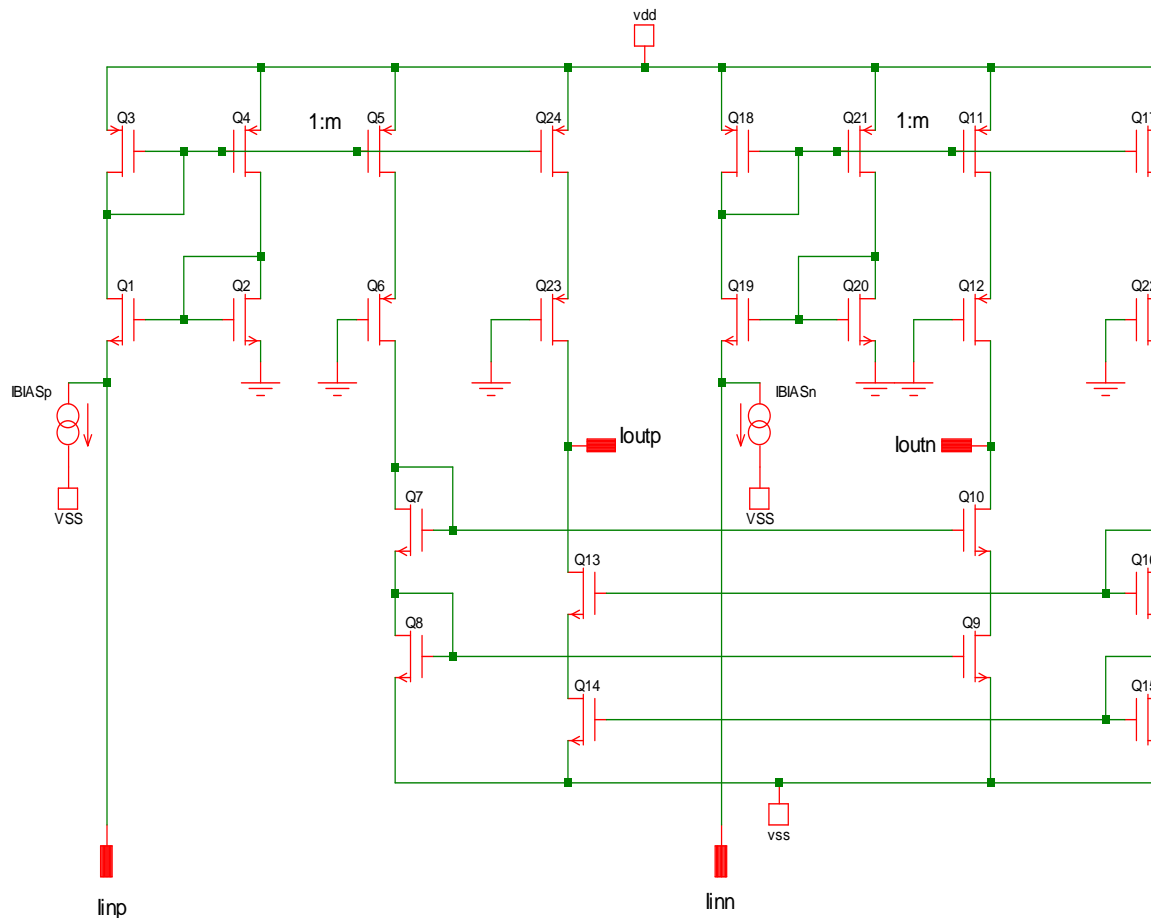
Maximize current gain m



Active Readout Cell Improvements



Fully differential architecture



Additional current mirror
for complementary
output

Improved charge injection
cancellation and offset

Noise from cascode
mirrors is minimized



Active Readout Cell Improvements

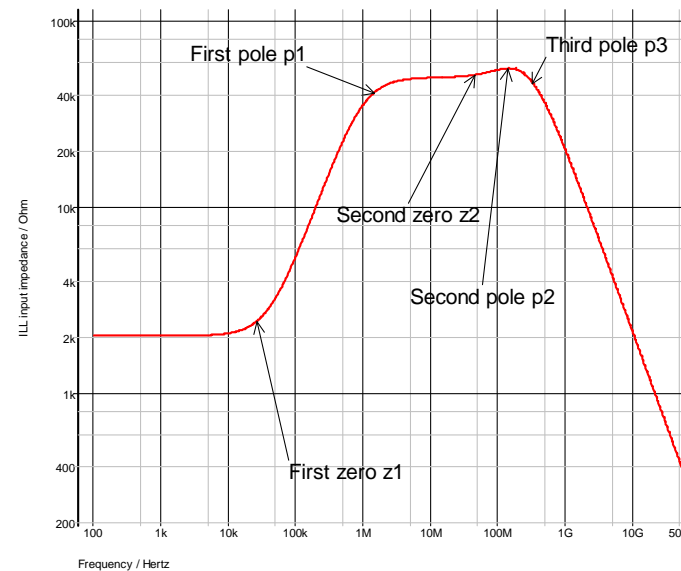
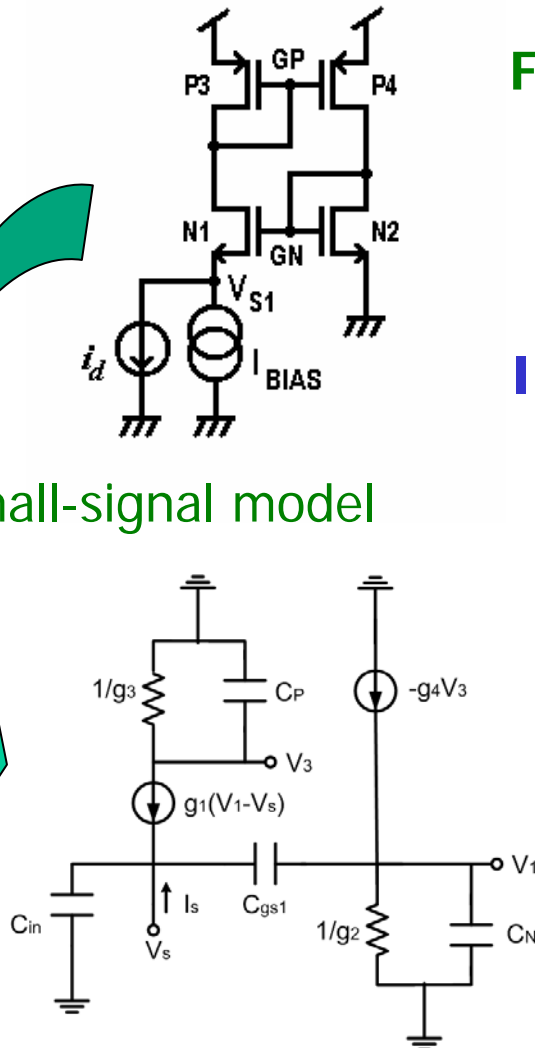
Input impedance engineering

From small-signal model, solve for Z_{in}

$$Z_{in} = \frac{V_s(s)}{I_s(s)} = \left(\frac{1}{sC_{in}} \right) // \frac{(g_3 + sC_P)(g_2 + s(C_{gs1} + C_N)) - g_1g_4}{(g_1 + sC_{gs1})(g_3 + sC_P)(g_2 + sC_N)}$$

Input impedance without C_{in}

Small-signal model

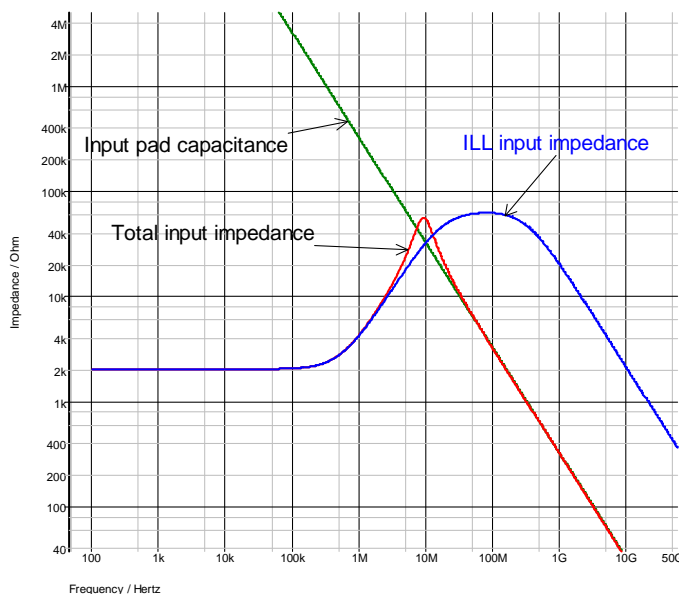




Active Readout Cell Improvements

Input impedance engineering (cont'd)

Input impedance with C_{in}



ILL pole-zero analysis

$$z_1 = \frac{K_z - C_{gs1}g_3 - C_Ng_3 - C_Pg_2}{2C_P(C_{gs1} + C_N)}$$

$$z_2 = \frac{-K_z - C_{gs1}g_3 - C_Ng_3 - C_Pg_2}{2C_P(C_{gs1} + C_N)}$$

$$p_1 = -\frac{g_3}{C_P}$$

$$p_2 = -\frac{g_2}{C_N}$$

$$p_3 = -\frac{g_1}{C_{gs1}}$$

$$K_z = \sqrt{C_{gs1}^2 g_3^2 + 2C_{gs1}(C_N g_3^2 + C_P(2g_1 g_4 - g_2 g_3)) + C_N^2 g_3^2 + 2C_N C_P(2g_1 g_4 - g_2 g_3) + C_P^2 g_2^2}$$

C_P controls p_1 and z_1 , but also moves z_2 to the left

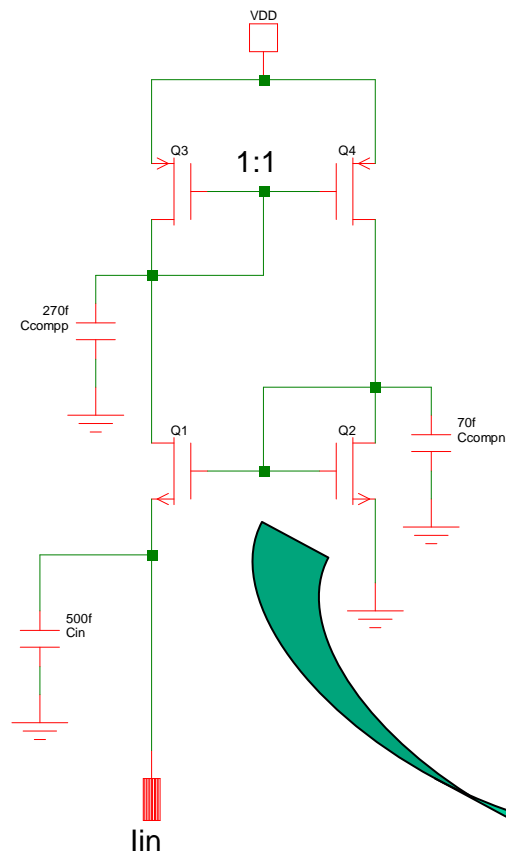
C_N moves p_2 close to z_2 , canceling its effect

p_3 determines overall gain-bandwidth

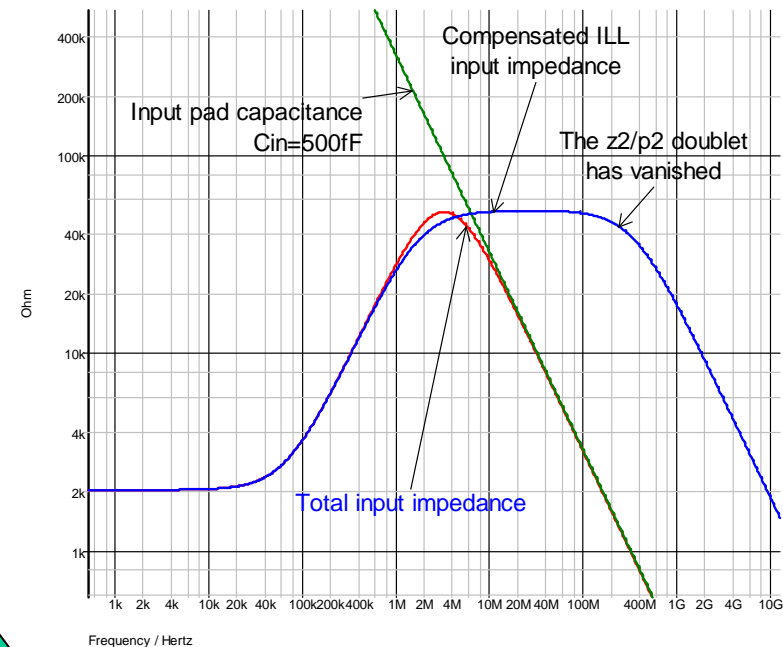


Active Readout Cell Improvements

Input impedance engineering (cont'd)



Compensated input impedance with C_{in}



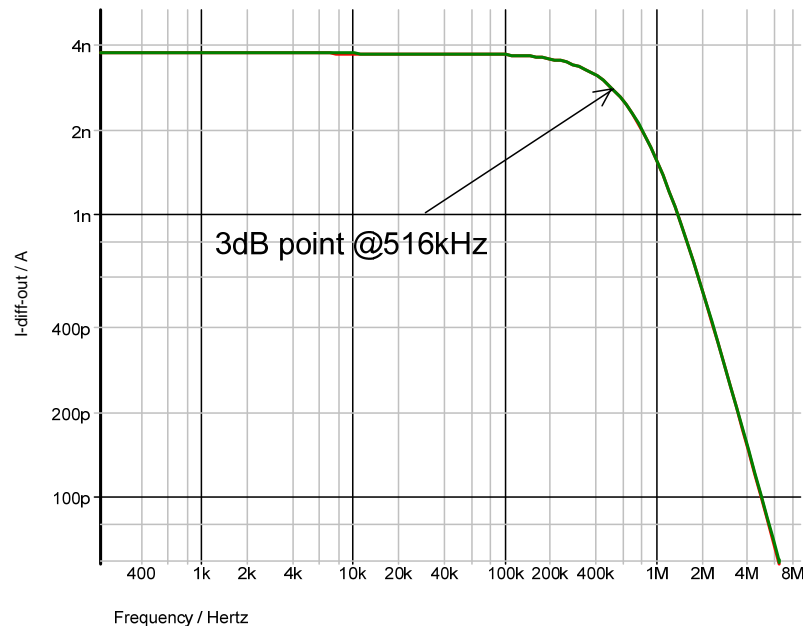
$C_p = 270\text{fF}$ and $C_n = 70\text{fF}$ compensate the input impedance for $C_{in} = 500\text{fF}$



Improved Active Readout Cell Performance

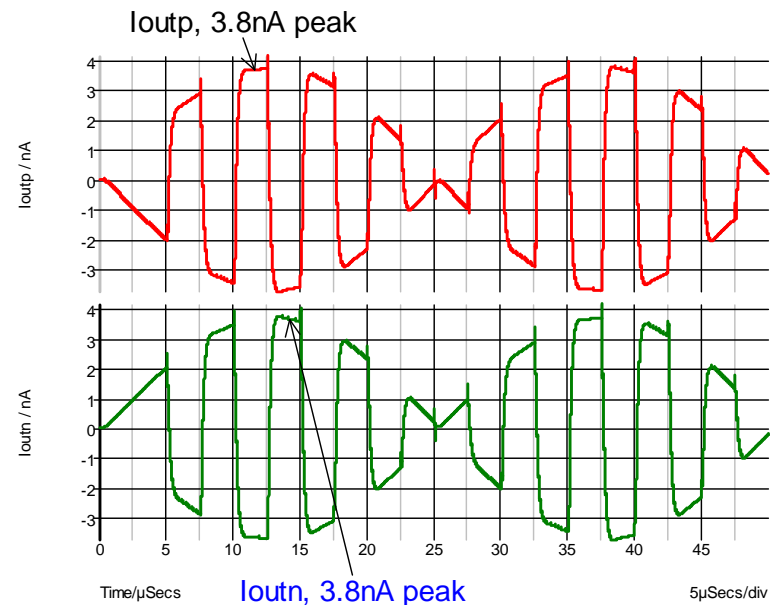


Frequency response



Designed for 500kHz code bandwidth (16 cells)

Transient response



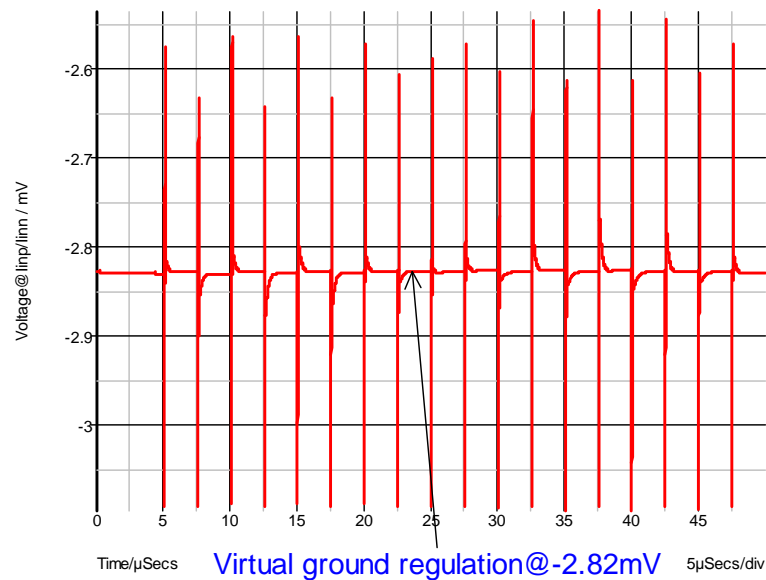
Current gain of 3.8A/A



Improved Active Readout Cell Performance

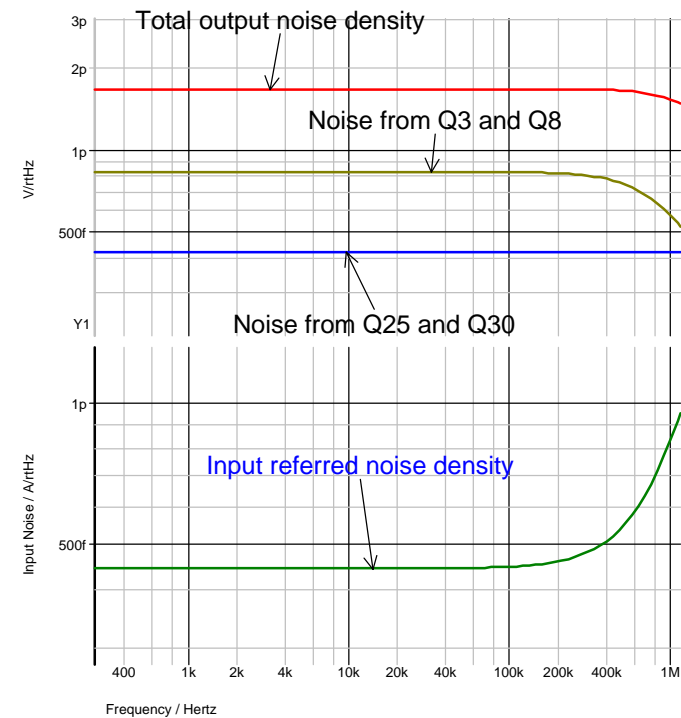


Virtual ground regulation



Between -3.1mV and -2.6mV

Noise performance



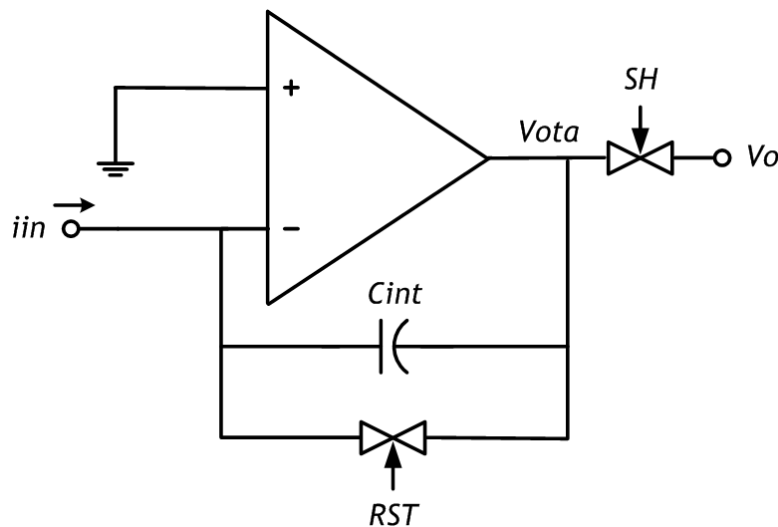
Input referred noise 400fA/rtHz



Transimpedance amplifier implementation

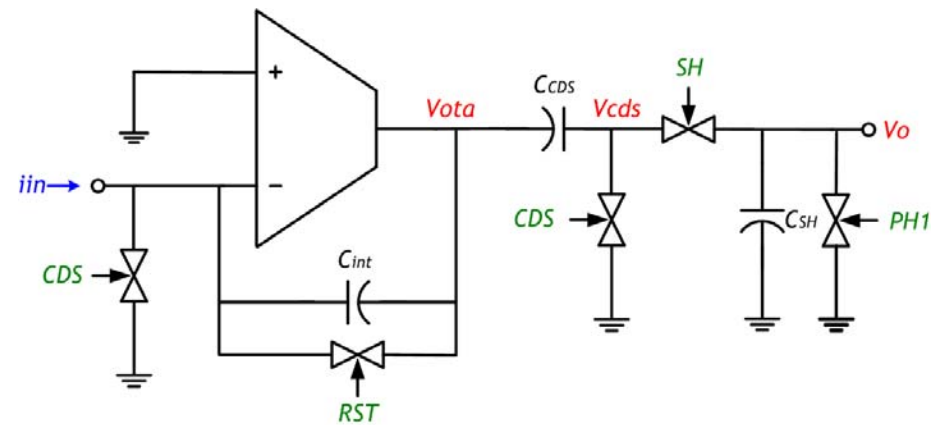


Capacitive TIA (CTIA)



RST switch injects charge and produces sampling (kT/C) noise

CTIA with correlated double sampling (cds)



CDS structure removes sampling noise

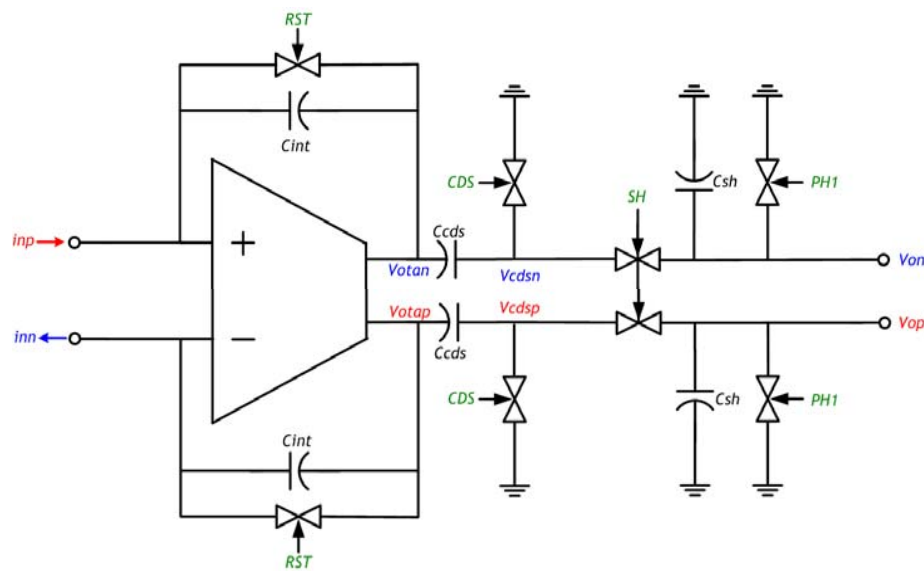
SH capacitor produces voltage divider



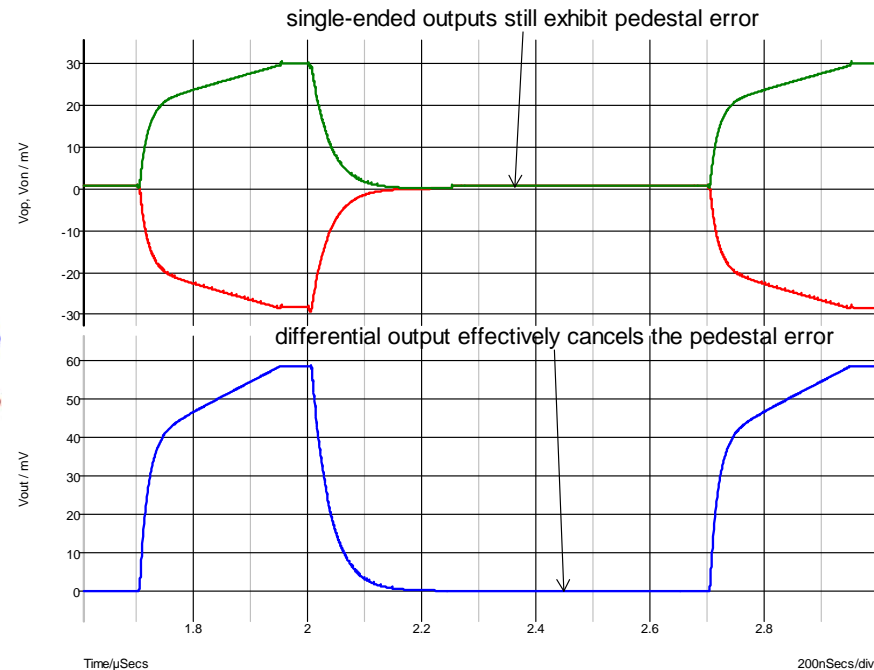
CTIA system-level implementation



Advantages of fully differential CTIA system



Fully differential
CTIA system



Transient response of
Single-ended vs. Differential output



Input stabilization switches

$C_{CDS} = 5\text{pF}$, $C_{SH} = 1\text{pF}$, $C_{comp}=3\text{pF}$, $C_{int} = 50\text{fF}$

Switches designed for worst-case scenario $R_{SW} \sim 1\text{k}\Omega$



- $G_m > 250 \text{ mS}$
- a_{vo} (2% settling accuracy) $> 40k$
- Input referred noise $< 5 \text{ nV}/\sqrt{\text{Hz}}$
- Dominant pole and non-dominant pole more than three decades apart
- Output common-mode $< 10 \text{ mV}$
- $\text{CMRR} > 60 \text{ dB}$
- Input differential capacitance not to exceed 15 pF
- Output swing of $2.4 \text{ V}_{\text{pk-pk}}$
- Dual power supplies of $\pm 2.5 \text{ V}$
- Best effort on power consumption and layout area



OTA design methodology

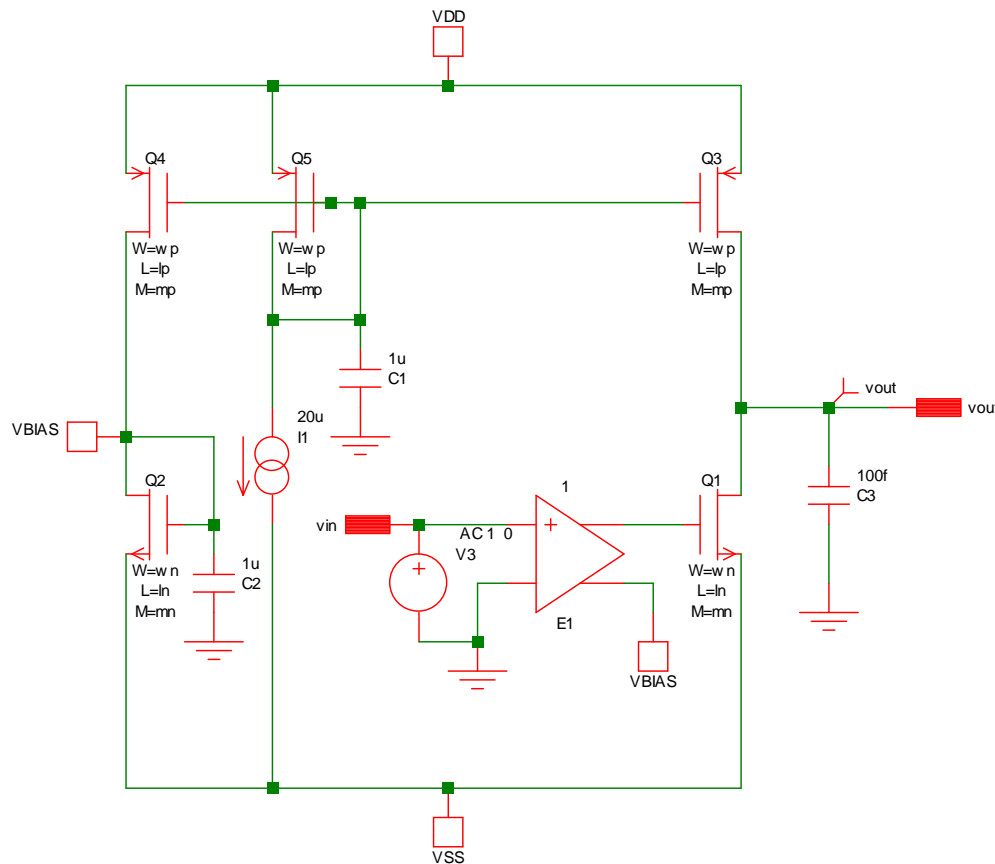


<div>FIRST PHASE OF DESIGN: FROM SPECS TO CIRCUIT PARAMETERS</div> <table><tr><th colspan="3">Specifications</th></tr><tr><td>Settling accuracy:= E</td><td>2.00%</td><td></td></tr><tr><td>Settling time:= ts</td><td>5.00E-08 sec</td><td></td></tr><tr><td>Dynamic Range:= DR(dB)</td><td>40.00 dB</td><td></td></tr><tr><td>Closed Loop Gain:= c</td><td>V/V</td><td></td></tr><tr><td>Vin step:= Vstep</td><td>V</td><td></td></tr><tr><td>Supplies:= VDD= -VSS</td><td>2.50 V</td><td></td></tr></table> <table><tr><th colspan="3">Initial design knobs</th></tr><tr><td>C feedback (Cf)</td><td>2.00E-14 F</td><td></td></tr><tr><td>C series (Cs)</td><td>F</td><td></td></tr><tr><td>C input (Cp) (assumed)</td><td>1.50E-11 F</td><td></td></tr><tr><td>CCDS (CDS cap)</td><td>5.00E-12 F</td><td></td></tr><tr><td>CSH (SH cap)</td><td>1.00E-12 F</td><td></td></tr><tr><td>Delta Vod (Vpk-pk)¹</td><td>3.00 V</td><td></td></tr><tr><td>Static error%:= St.err%</td><td>0.80</td><td></td></tr></table> <table><tr><th colspan="3">Preliminary calculations</th></tr><tr><td>$F = Cf / (Cf + Cp)$</td><td>1.33E-03 V/V</td><td></td></tr><tr><td>$Ao \sim 1 / F$</td><td>7.51E+02 V/V</td><td></td></tr></table> <table><tr><th colspan="3">Constants</th></tr><tr><td>Boltzmann</td><td>1.38E-23</td><td>S#%</td></tr><tr><td>Temperature</td><td>300</td><td>K</td></tr><tr><td>q</td><td>1.60E-19</td><td>C</td></tr><tr><td colspan="3">Transistor parameters</td></tr><tr><td>NMOS</td><td>PMOS</td><td></td></tr><tr><td>Cox</td><td>2.46E-15</td><td>2.38E-15 F/um²</td></tr><tr><td>Col_factor</td><td>2.01E-16</td><td>2.61E-16 F/um²</td></tr><tr><td>uCox</td><td>1.14E-04</td><td>3.78E-05 A/V²</td></tr></table>	Specifications			Settling accuracy:= E	2.00%		Settling time:= ts	5.00E-08 sec		Dynamic Range:= DR(dB)	40.00 dB		Closed Loop Gain:= c	V/V		Vin step:= Vstep	V		Supplies:= VDD= -VSS	2.50 V		Initial design knobs			C feedback (Cf)	2.00E-14 F		C series (Cs)	F		C input (Cp) (assumed)	1.50E-11 F		CCDS (CDS cap)	5.00E-12 F		CSH (SH cap)	1.00E-12 F		Delta Vod (Vpk-pk) ¹	3.00 V		Static error%:= St.err%	0.80		Preliminary calculations			$F = Cf / (Cf + Cp)$	1.33E-03 V/V		$Ao \sim 1 / F$	7.51E+02 V/V		Constants			Boltzmann	1.38E-23	S#%	Temperature	300	K	q	1.60E-19	C	Transistor parameters			NMOS	PMOS		Cox	2.46E-15	2.38E-15 F/um ²	Col_factor	2.01E-16	2.61E-16 F/um ²	uCox	1.14E-04	3.78E-05 A/V ²	<div>1. 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Load (P) Vov:= V3*</td><td>450 mV</td><td></td></tr></table> <table><tr><td>R1 (achieved) = ro1 // ro3</td><td>180 kOhm</td><td></td></tr><tr><td>and gm3 = gm1. 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Dynamic Accuracy</div> <table><tr><td colspan="2">Dynamic error:= E_dyn</td></tr><tr><td>$E_dyn = E - E_st$</td><td>0.400%</td></tr></table> <div>Slewing (N/A for CTIA)</div> <table><tr><td>Slew time (t_slew)</td><td>0.00E+00 sec</td></tr><tr><td>SR_ext = (B-1).IBIAS / Co</td><td>V/us</td></tr><tr><td>SR_int = IBIAS / C</td><td>V/us</td></tr><tr><td>SR_ext = SR_int</td><td></td></tr><tr><td colspan="2">then IBIAS-slew:</td></tr><tr><td>$(DeltaVod/2)^*C / t_slew$</td><td>A</td></tr><tr><td colspan="2">B(2nd:1st BIAS ratio) = 1 + Co/C</td></tr><tr><td>Linear</td><td></td></tr><tr><td>Linear time:= t_lin = ts-t_slew</td><td>5.00E-08 sec</td></tr><tr><td>Linear accuracy:= E_lin</td><td></td></tr><tr><td>$E_lin = E_dyn (NO SLEW)$</td><td>0.400%</td></tr></table> <div>minimum OTA's transconductance:</div> <table><tr><td>$Gm_s = -(Co/F)^*(ln(E_lin)/T_lin)$</td><td>7.08E-02 Sie</td></tr><tr><td>or desired Gm</td><td>4.00E-01 Sie</td></tr><tr><td>$Gm = max(Gm_s, desired Gm)$</td><td>4.00E-01 Sie</td></tr></table> <table><tr><td colspan="2">Then IBIAS becomes</td></tr><tr><td>$max(IBIAS-slew, IBIAS-linear)$</td><td>241.40 uA</td></tr></table>	Static error:= E_st		$E_st = E * St.err\%$	1.600%	a0 (minimum)		$a0 = 1 / (F.E_st)$	46.94 k	a0 (dB)	33.43 dB	Gain of second stage, a2 (minimum)		$a2=a0 / a1$	160.74 V/V	Dynamic error:= E_dyn		$E_dyn = E - E_st$	0.400%	Slew time (t_slew)	0.00E+00 sec	SR_ext = (B-1).IBIAS / Co	V/us	SR_int = IBIAS / C	V/us	SR_ext = SR_int		then IBIAS-slew:		$(DeltaVod/2)^*C / t_slew$	A	B(2nd:1st BIAS ratio) = 1 + Co/C		Linear		Linear time:= t_lin = ts-t_slew	5.00E-08 sec	Linear accuracy:= E_lin		$E_lin = E_dyn (NO SLEW)$	0.400%	$Gm_s = -(Co/F)^*(ln(E_lin)/T_lin)$	7.08E-02 Sie	or desired Gm	4.00E-01 Sie	$Gm = max(Gm_s, desired Gm)$	4.00E-01 Sie	Then IBIAS becomes		$max(IBIAS-slew, IBIAS-linear)$	241.40 uA	<div>3. From total Gm and a2 to second stage design</div> <div>Requirements for second stage (minimum)</div> <table><tr><td>a2 (minimum)</td><td>160.74</td></tr><tr><td>$gm8 = Gm / a1$ (minimum)</td><td>1.37E-03 Sie</td></tr><tr><td>$R2 = a2 / gm8$ (minimum)</td><td>1.17E+05 Ohm</td></tr></table> <div>SECOND STAGE DESIGN</div> <div>From simulations and iteration:</div> <table><tr><td>Gain of second stage a2</td><td>150 V/V</td></tr><tr><td>2nd st. transconduct gm8</td><td>3.60E-04 Sie</td></tr><tr><td>R2 = a2 / gm8 (required)</td><td>4.17E+05</td></tr><tr><td>Com. src. ro8 (from sims) =</td><td>1.48E+05</td></tr><tr><td>Load CS, ro7 (from sims) =</td><td>2.89E+05</td></tr><tr><td>Com src. (P) Vov:= V8* (from sims)</td><td>4.45E-01 V</td></tr><tr><td>Load CS (N) Vov:= V7* (from sims)</td><td>3.11E-01 V</td></tr></table> <table><tr><td>R2 (achieved) = ro7 // ro8</td><td>9.79E+04</td></tr><tr><td>and gm7 = gm8. 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$Gm_s = -(Co/F)^*(ln(E_lin)/T_lin)$	7.08E-02 Sie																																																																																																																																																																																																																																																				
or desired Gm	4.00E-01 Sie																																																																																																																																																																																																																																																				
$Gm = max(Gm_s, desired Gm)$	4.00E-01 Sie																																																																																																																																																																																																																																																				
Then IBIAS becomes																																																																																																																																																																																																																																																					
$max(IBIAS-slew, IBIAS-linear)$	241.40 uA																																																																																																																																																																																																																																																				
a2 (minimum)	160.74																																																																																																																																																																																																																																																				
$gm8 = Gm / a1$ (minimum)	1.37E-03 Sie																																																																																																																																																																																																																																																				
$R2 = a2 / gm8$ (minimum)	1.17E+05 Ohm																																																																																																																																																																																																																																																				
Gain of second stage a2	150 V/V																																																																																																																																																																																																																																																				
2nd st. transconduct gm8	3.60E-04 Sie																																																																																																																																																																																																																																																				
R2 = a2 / gm8 (required)	4.17E+05																																																																																																																																																																																																																																																				
Com. src. ro8 (from sims) =	1.48E+05																																																																																																																																																																																																																																																				
Load CS, ro7 (from sims) =	2.89E+05																																																																																																																																																																																																																																																				
Com src. (P) Vov:= V8* (from sims)	4.45E-01 V																																																																																																																																																																																																																																																				
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R2 (achieved) = ro7 // ro8	9.79E+04																																																																																																																																																																																																																																																				
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M8,M10 (common source)	8.56E+01	4.000																																																																																																																																																																																																																																																			
M7,M9 (active loads)	7.29E+01	5.000																																																																																																																																																																																																																																																			
$(1/a1)(B/3)(KT/gm8)(1+gm7/gm8)$	6.71E-20 V2/Hz																																																																																																																																																																																																																																																				
<div>SECOND PHASE OF DESIGN: TRANSISTOR SIZES and VERIFICATION</div> <table><tr><th colspan="3">4. 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OTA design methodology

First and second stage design strategy



Circuit for design of amplification stage

Transistor models from vendor are used to optimize the design of a single stage of amplification with active loading

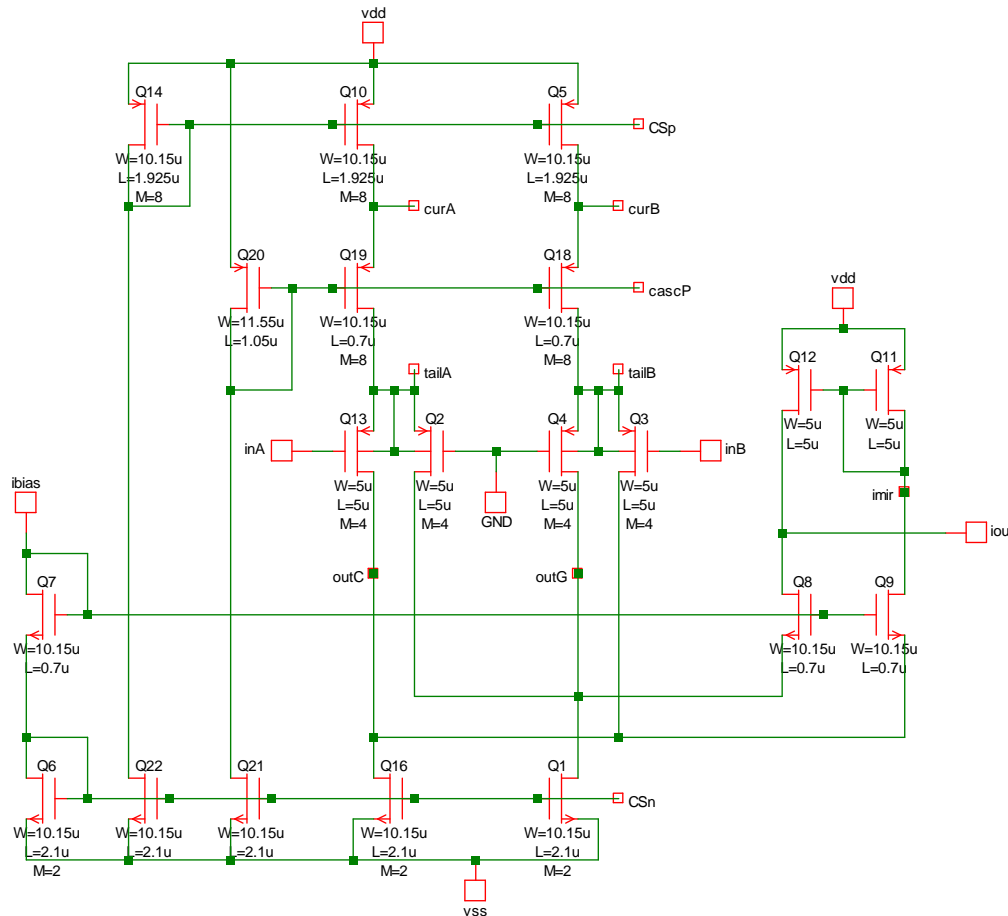
Bias conditions are replicated, and noise from biasing strategy is properly filtered out

Design results are back-annotated in work sheet



OTA design methodology

Common-Mode amplifier design



Q13 and Q3 compute common-mode voltage from the OTA output and “compare” it to the desired value (GND)

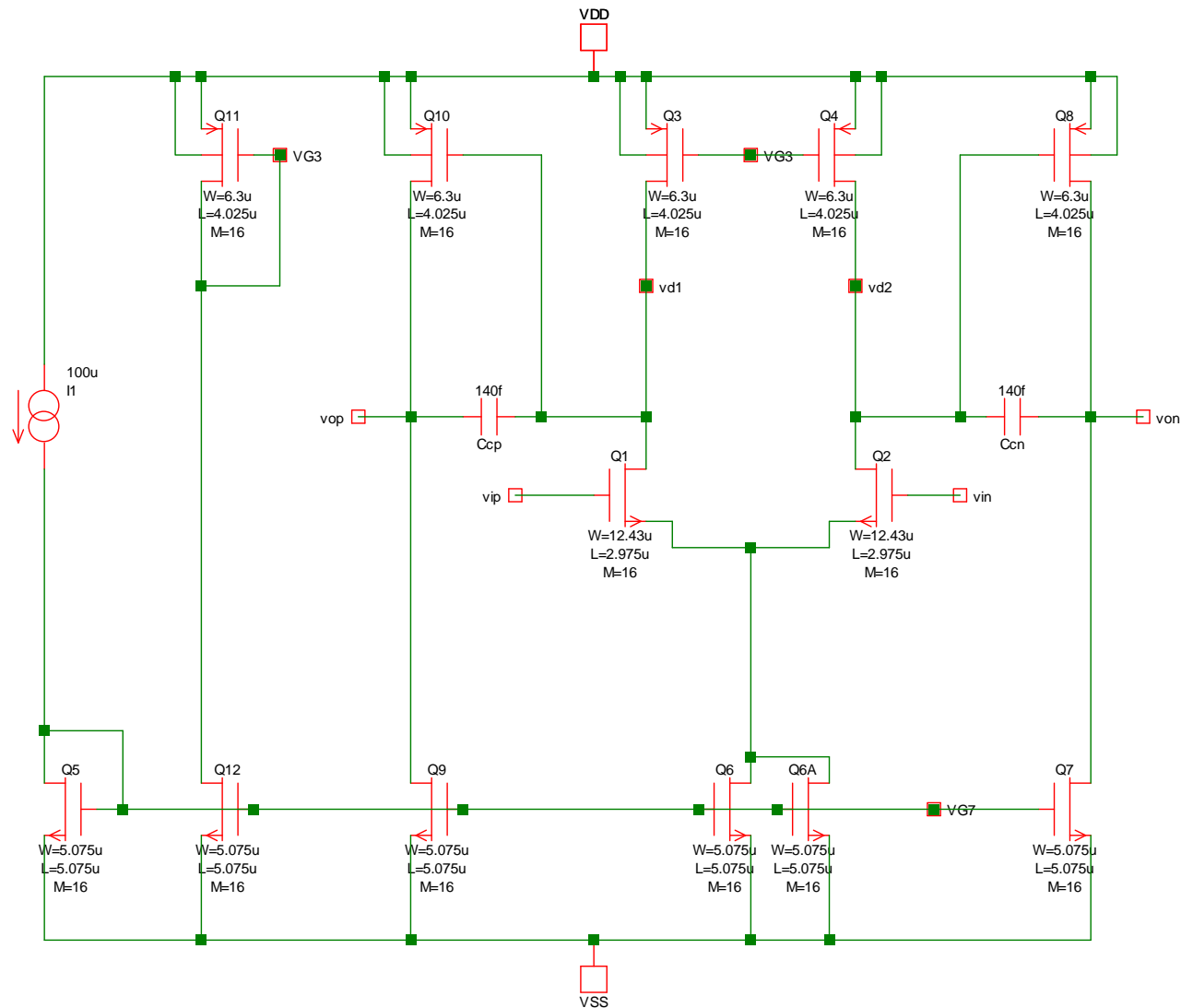
The amplifier produces a current output that regulates the common-mode voltage in the differential amplifier

Common-mode amplifier circuit



OTA design methodology

Final schematic for differential OTA

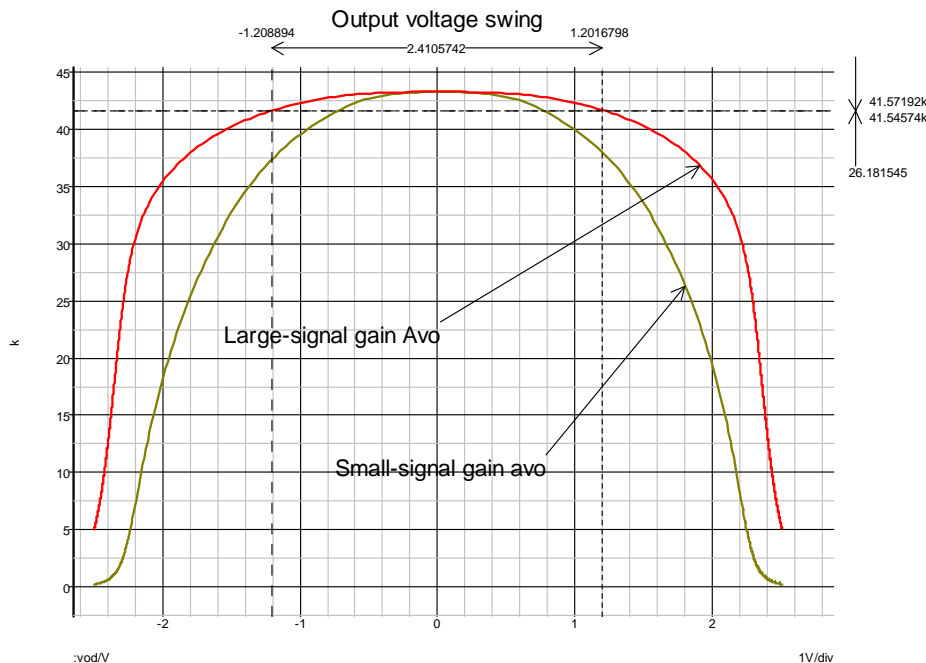




OTA Performance

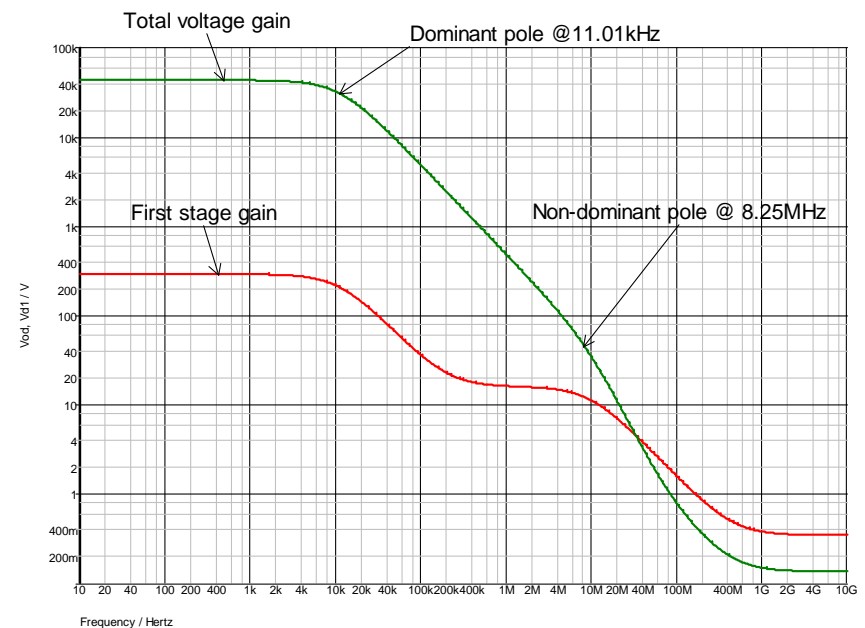


Open-loop gain



Open-loop gain exceeds 40,000 for the operation range (2.4Vpk-pk)

Frequency response



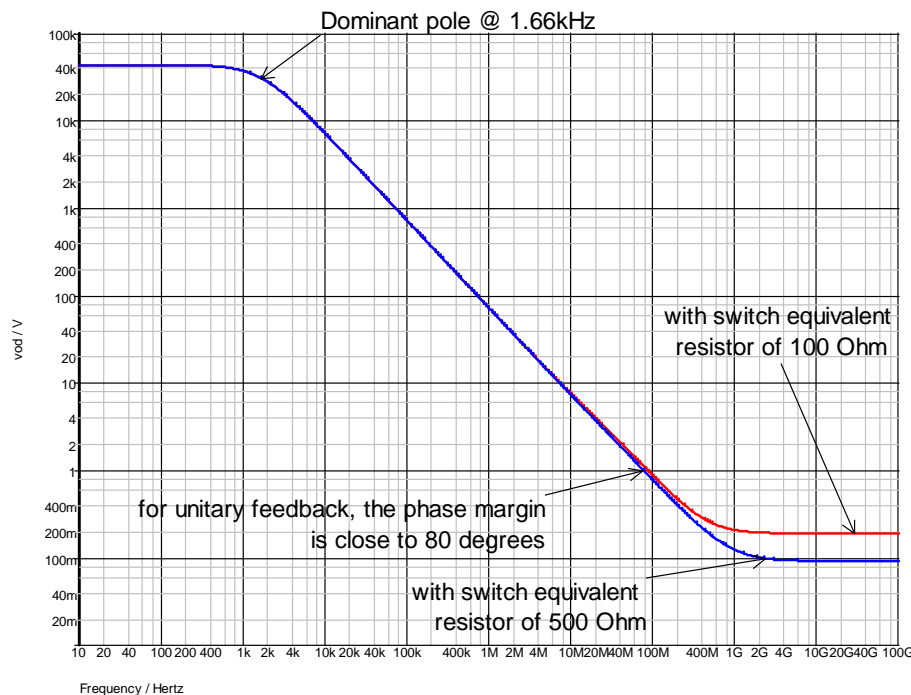
Dominant and non-dominant pole about three decade apart



OTA Performance



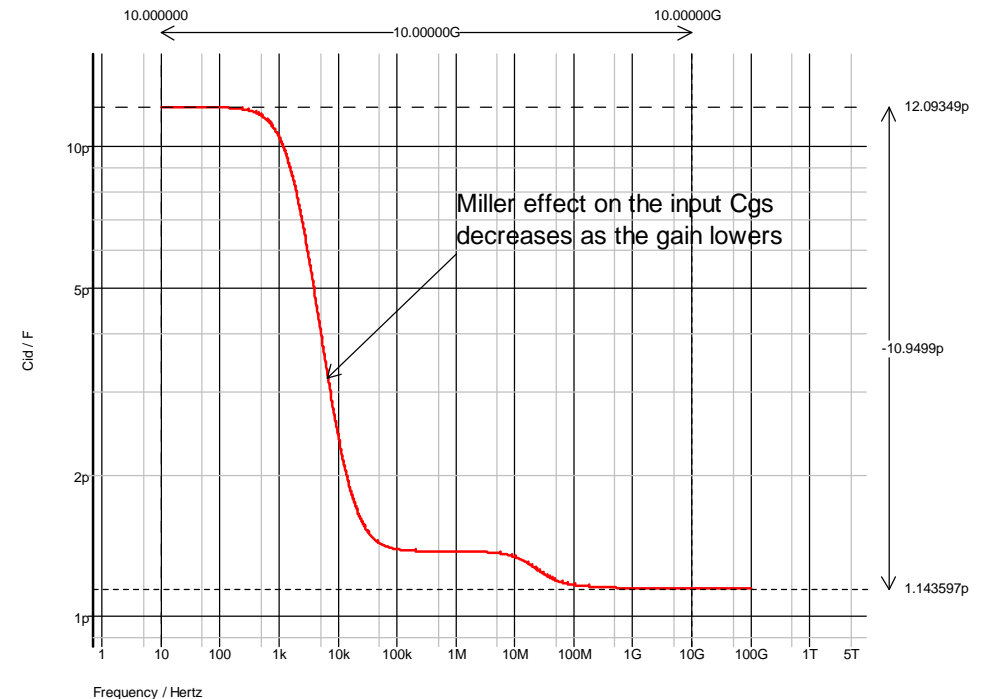
Frequency response with external compensation



External compensation of 3pF yields phase margin of about 80 degrees

Compensation switch optimally sized for zero-nulling

Input differential capacitance



$C_{in} \sim 12\text{pF}$ at low frequencies

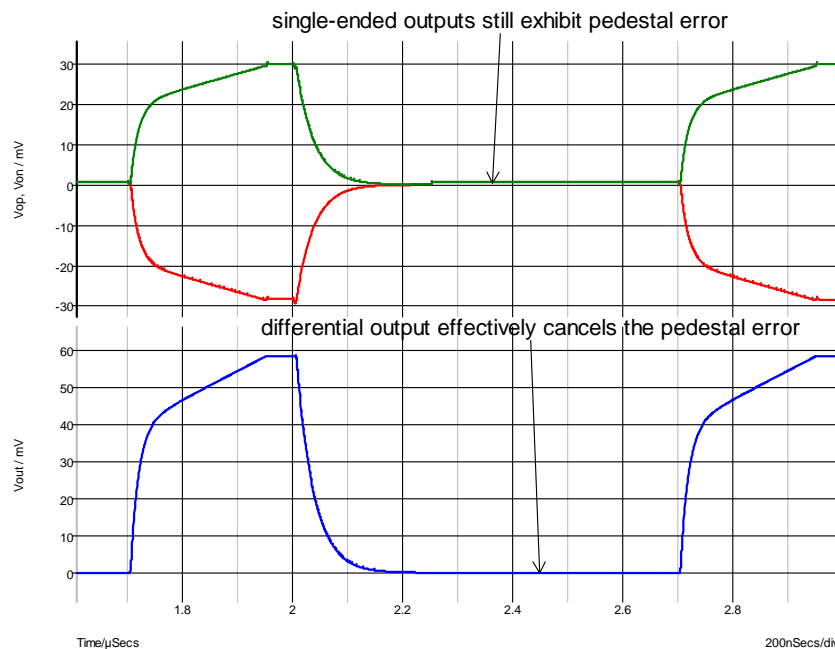
Decays for high frequencies because of absence of Miller effect



OTA Performance



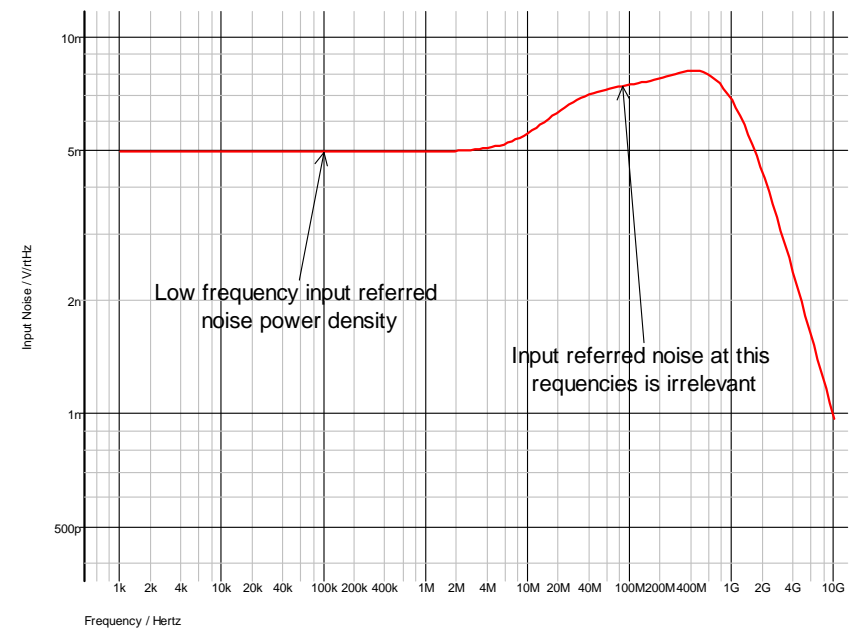
Transient response with external compensation



External compensation of 3pF effectively reduces differential transient ringing

CMFB amplifier is also compensated (1pF) to reduce common-mode voltage transient ringing

Input referred noise density



Low frequency input referred noise around 5nV/rtHz

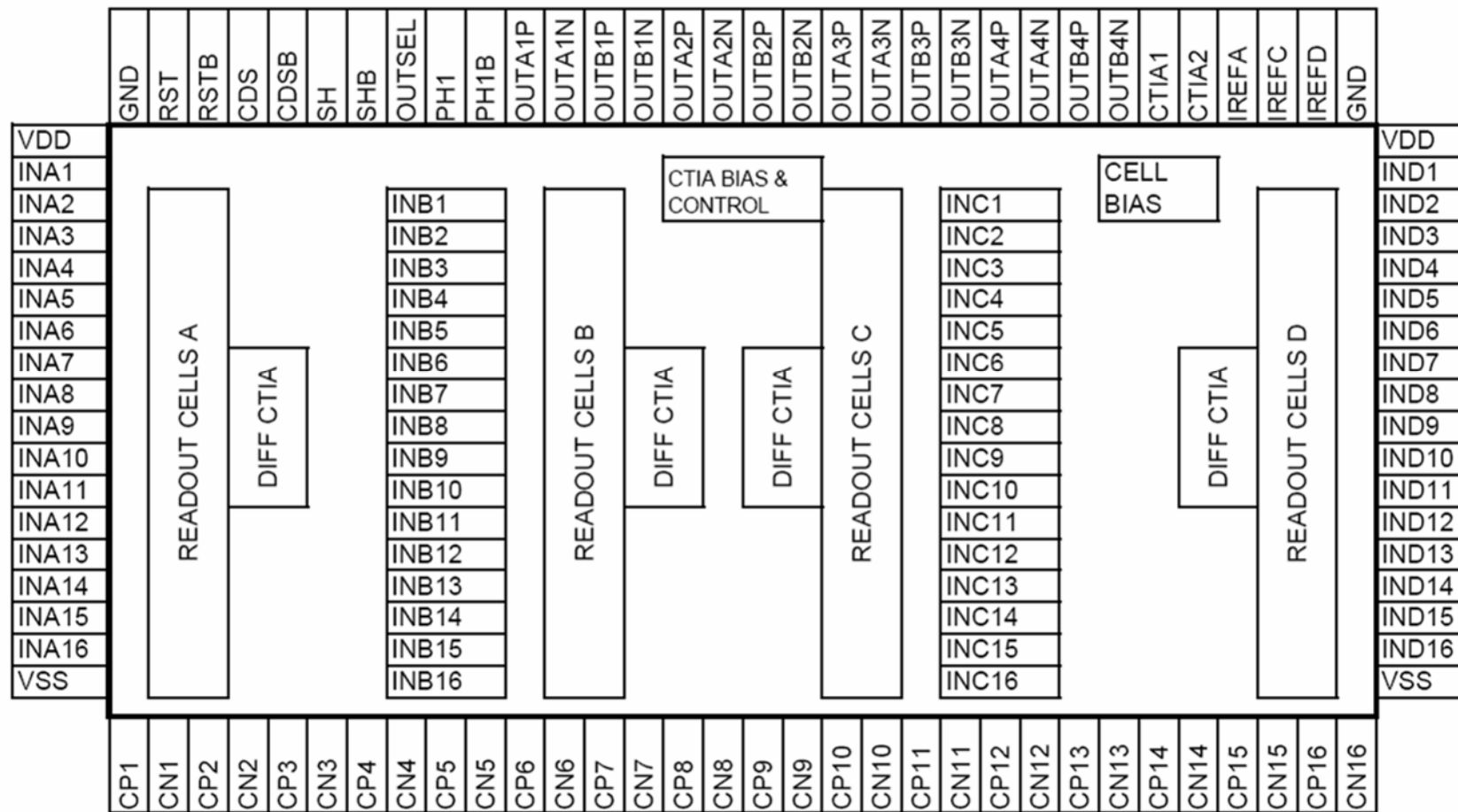
High frequency noise density is not relevant in this case



Second generation ROIC

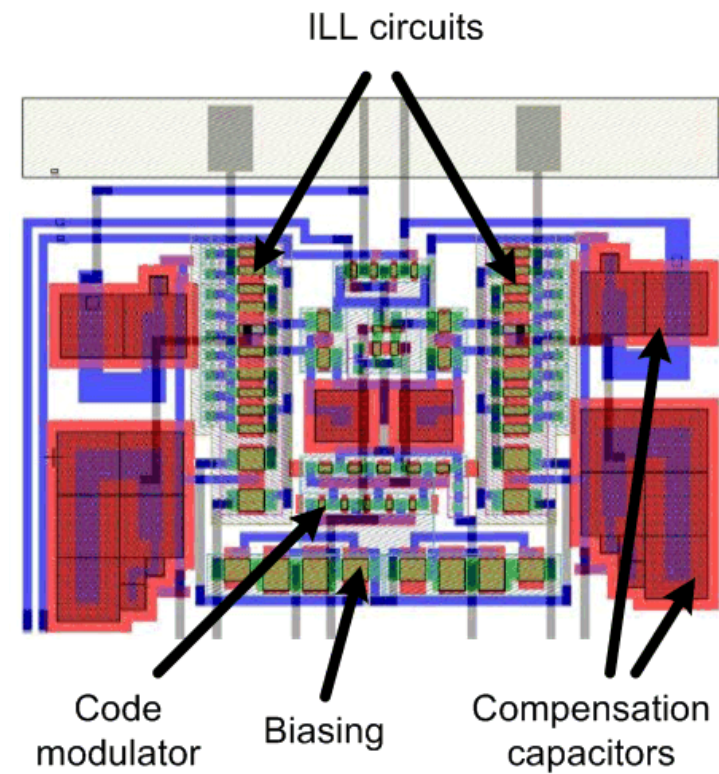
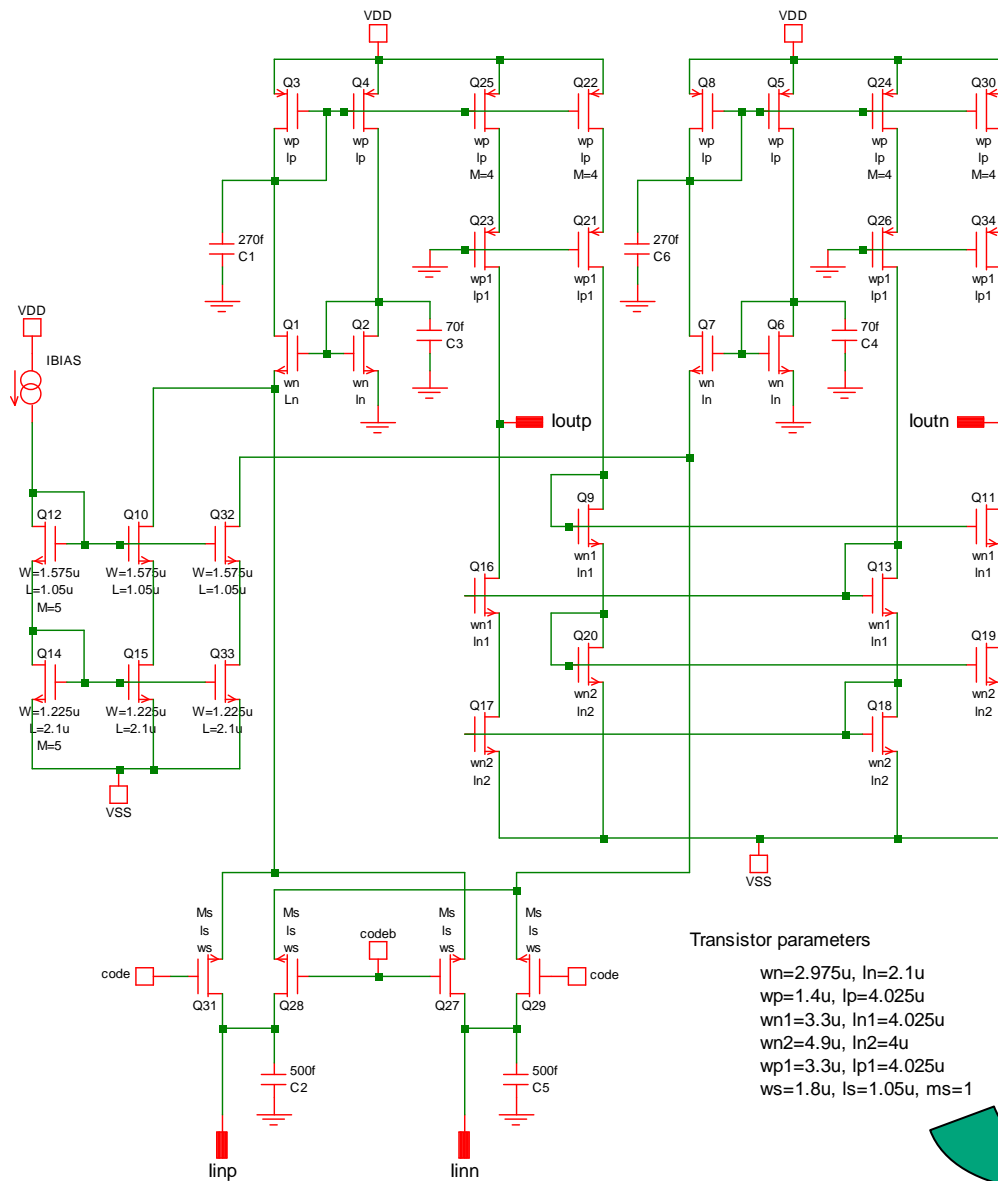
Four 1x16 arrays + Fully differential CTIA

TOP OF THE CHIP





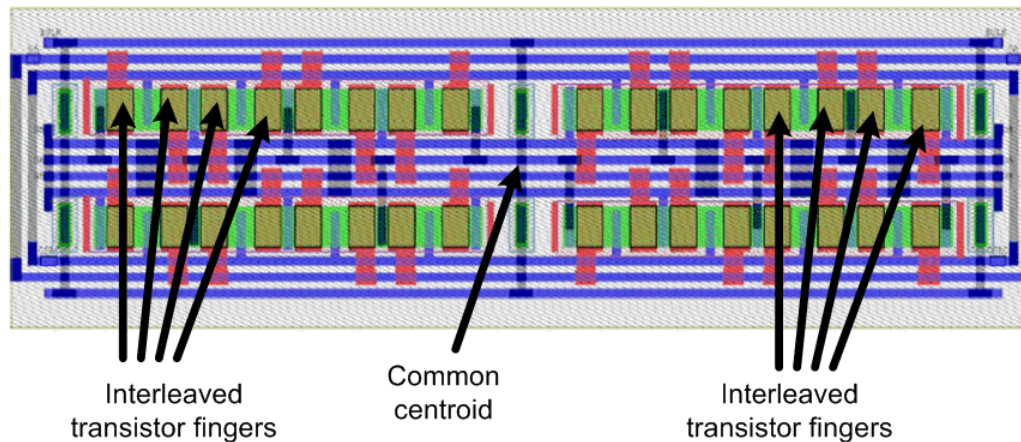
Readout cell physical design





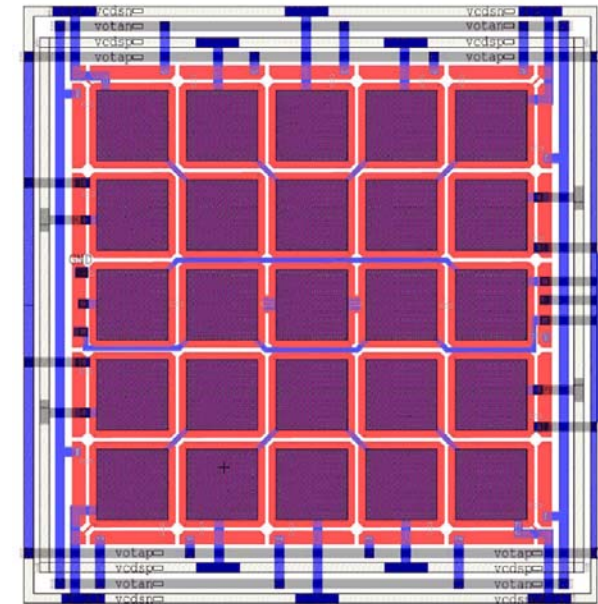
CTIA physical design

Matching transistors and capacitors



All differential pairs are designed with multi-finger, common-centroid structure

The differential OTA is divided into differential pair sections



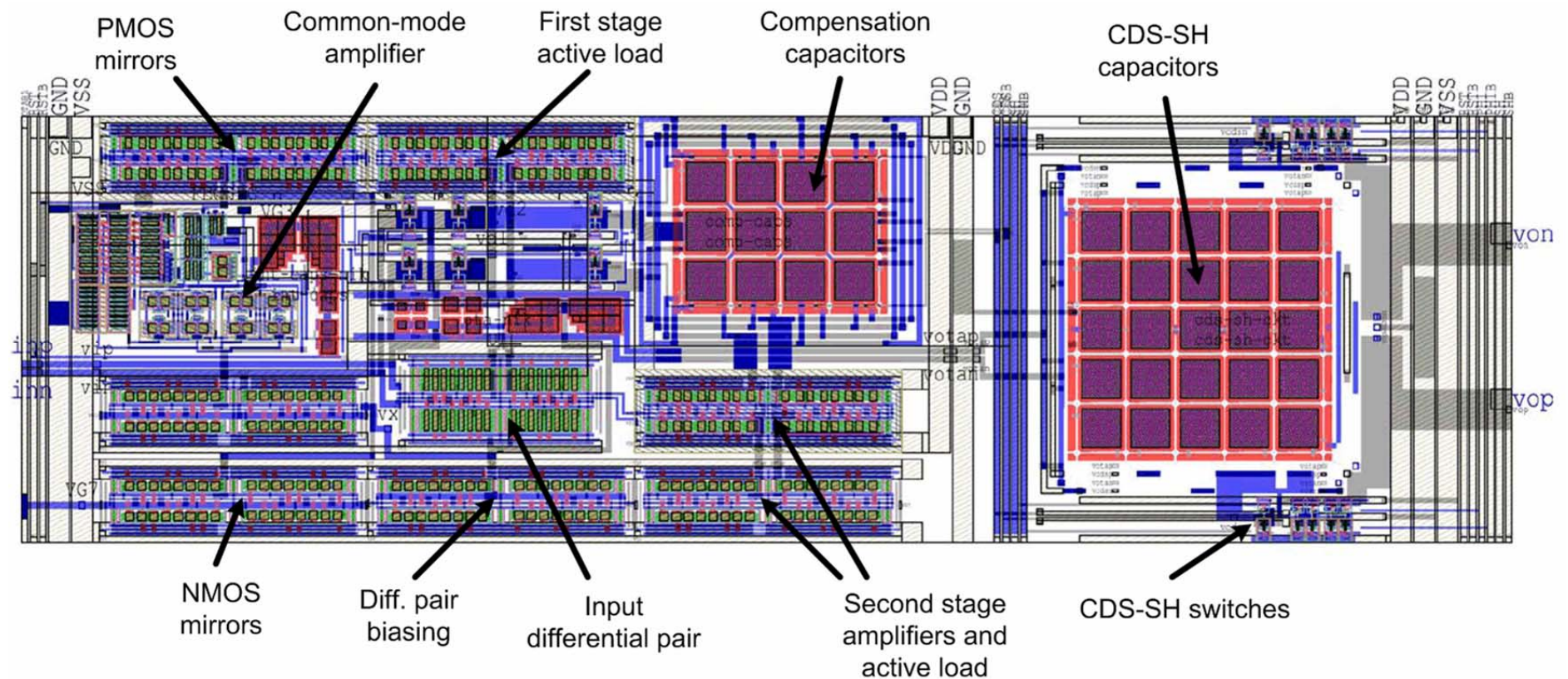
Four-capacitor layout using common-centroid techniques

Dummy cap in the middle shorted to ground



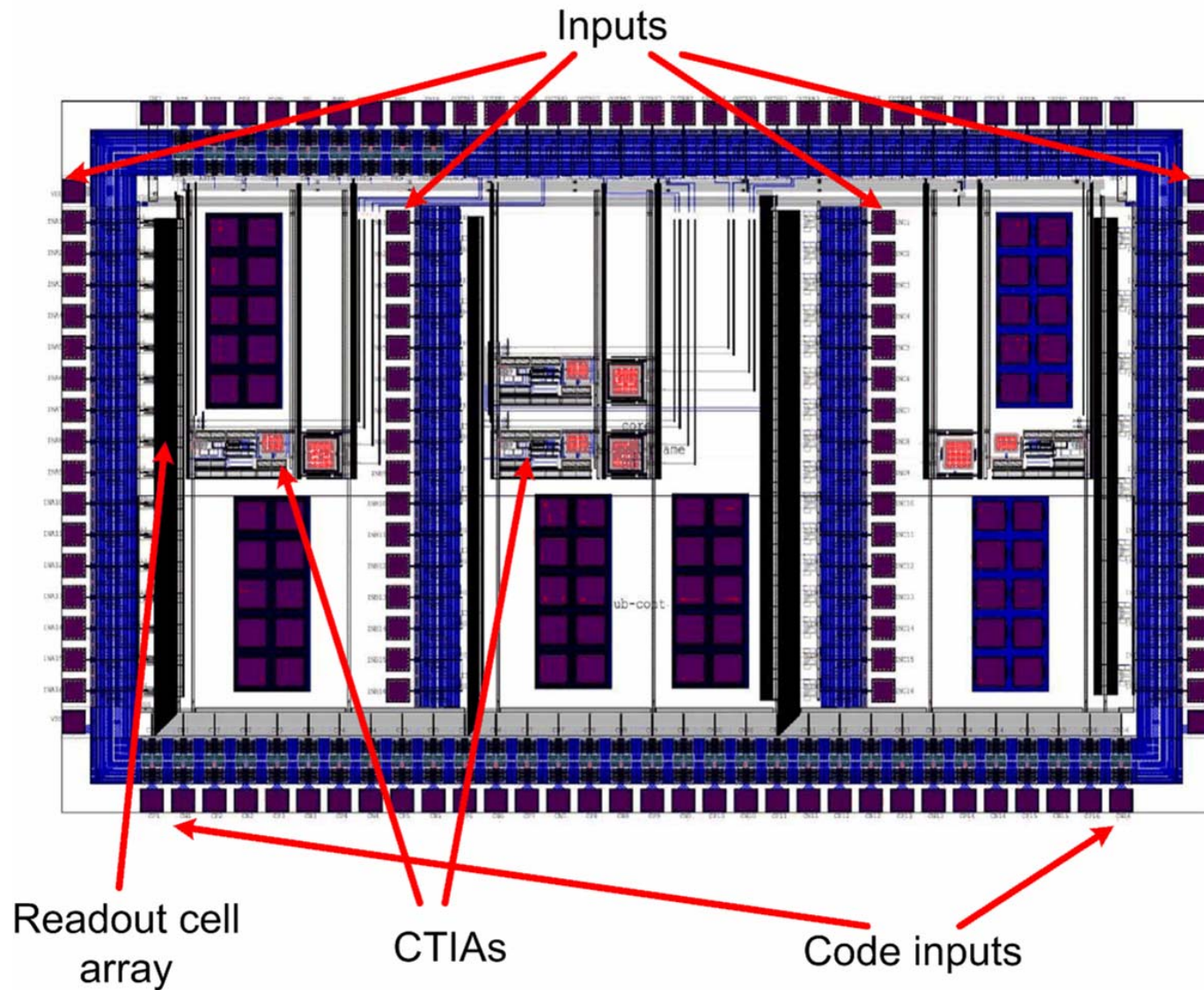
ROIC physical design

Fully differential CTIA amplifier





ROIC physical design





ORTHOGONALLY MODULATED CMOS READOUT INTEGRATED CIRCUIT FOR IMAGING APPLICATIONS

- Introduction and motivation
- Contribution Phase I: Proof of principle
 - Orthogonal encoding readout system description
 - Prototype system design and verification
 - Conclusions
- Contribution Phase II: Improving the system performance
 - Readout cell improvements
 - Transimpedance amplifier integration
- **Conclusion and brainstorm on further improvements**

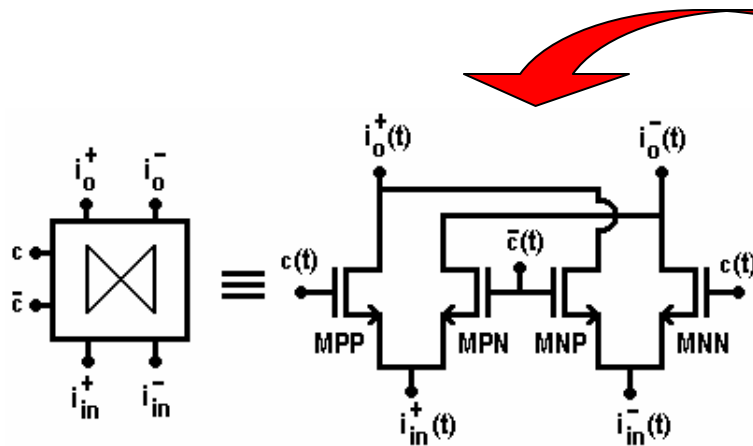


Conclusion



Satisfactory results with the prototype experiment confirm validity of the orthogonal encoding scheme for readout circuits

Expect system performance improvement with the design optimization of the readout cell and the integration of the fully differential CTIA



The readout cell with the code-modulator only is an outstanding candidate for highly-scalable imaging systems. Its characteristics: only four transistors, zero noise, no power consumption, no band width limitations.

Further improvement is accomplished if differential photodetector devices are used

$$i_o^+(t) = i_{in}^+(t) \cdot c(t) + n_c + i_{in}^-(t) \cdot \bar{c}(t) + n_{\bar{c}},$$

$$i_o^-(t) = i_{in}^+(t) \cdot \bar{c}(t) + n_{\bar{c}} + i_{in}^-(t) \cdot c(t) + n_c,$$

$$i_{od}(t) = i_o^+(t) - i_o^-(t) = [i_{in}^+(t) - i_{in}^-(t)] \cdot [c(t) - \bar{c}(t)],$$

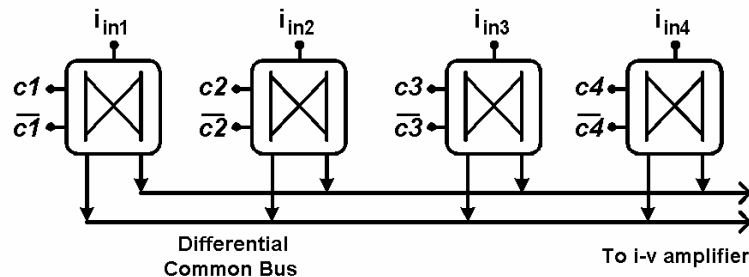


Conclusion (cont'd)

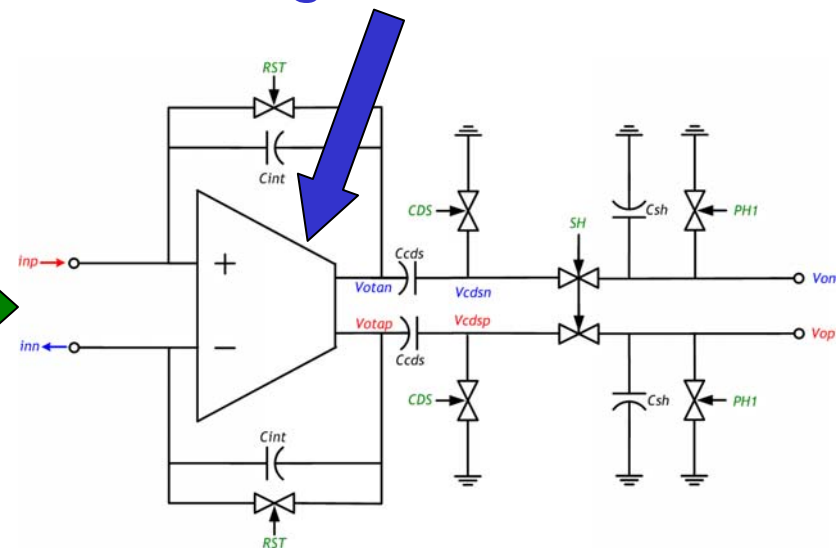


Take advantage of switched nature of the system to cancel charge injection peaks from readout cells.

With code-modulator-only cells the system becomes highly-scalable but the noise performance of the OTA amplifier needs to be improved by one order of magnitude



Code-modulator-only
readout cell array



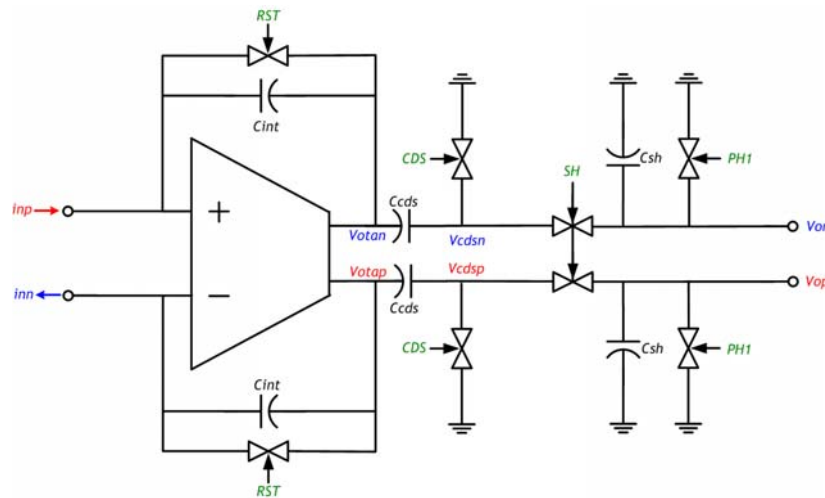
Capacitive Transimpedance
amplifier per row



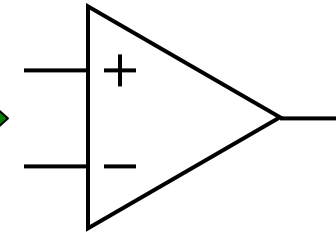
Conclusion (cont'd)



Integrating an amplifier to perform differential to single-ended conversion inside the chip would improve the system performance (pedestal voltages and vestigial voltage spikes would be cancelled inside the integrated circuit)



Capacitive Transimpedance amplifier per row



Single-ended output

Differential amplifier per row



Acknowledgements



Thanks to everybody who has been involved in the dissertation process in one way or another

Fouad, Bill, Mayra

LADAR group, thanks so much for the support