Using Plastic Fiber for Data Communications at 5-10Gbs

- A Technology Who's Time Has Come -

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Much of this talk is based on the research of recently graduated Ph.D. Student Yunzhi Dong

What is POF

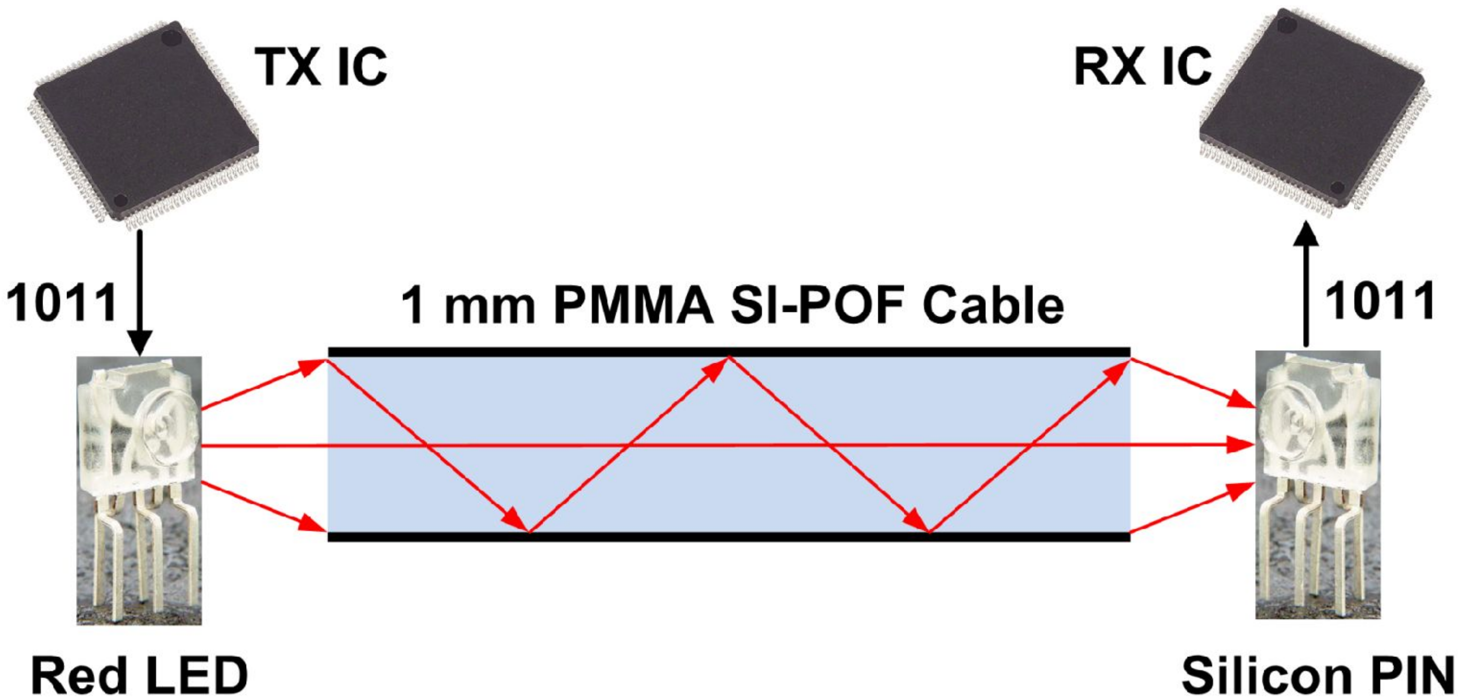
Above: terminating a duplex POF cable with OptoLock™ Connector ——Mike Jones, "Ethernet over optical fiber"

- POF = Plastic Optical Fiber
- Usually made of PMMA-based polymer
- (polymethyl methacrylate or acrylic)
- Easy home/field termination with simple tools

Communication over POF

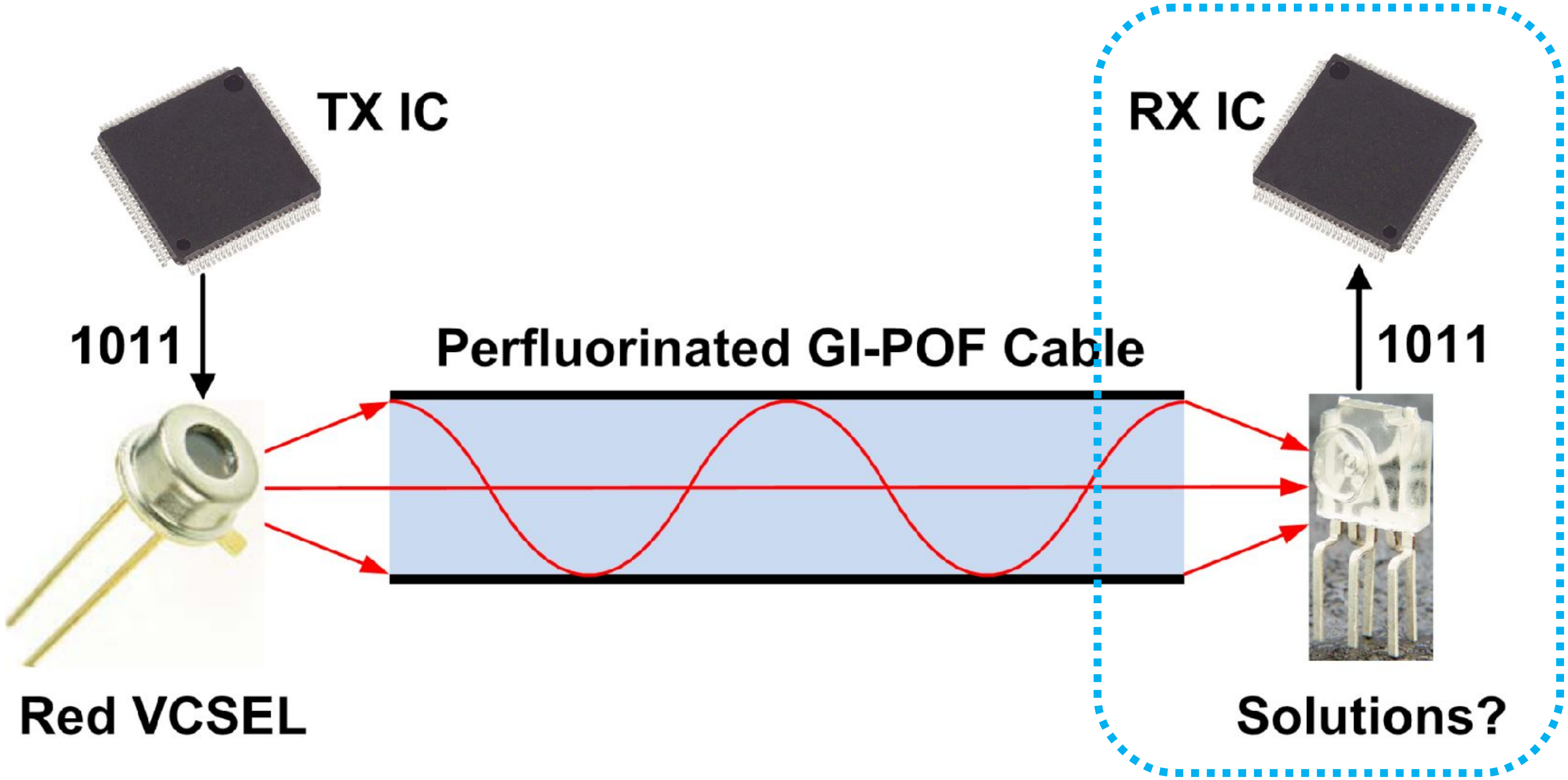
- Not only can POFs be easily terminated and installed in the field, they can be bent through very small radii (r < 1mm), and also they are easily hidden under painted tape or wood moulding.
- All of these result in low system-level costs
- POF systems are currently widely used for automotive (MOST) and industrial (PROFIBUS and PROFINET) applications at data rates up to 150Mbs; recent advances have demonstrated 1Gbs, and at much higher rates in the near future using currently available technology are predicted.

A Typical POF System



- Red LEDs' limited BW: < 300 Mbps
- SI-POF suffers from multimode dispersion: 5 MHz•km
- PMMA has low-frequency attenuation: 0.185 dB/m

Advances in POF Technology



- Red VCSELs exhibit bandwidth: 2.5 to 3.0 GHz
- GI-POF solves multimode dispersion: > 150 MHz•km
- Perfluorinated-PMMA reduces low-frequency loss: < 0.08 dB/m

Perfluorinated Graded Index Fibre

- **Partially chlorinated polymethylmethacrylate (PMMA) graded-index plastic fibers that have effective cores of 120um equal multi-mode fibers (MMF) at 650nm. Newer GI-POF based on amorphous perfluorinated polymer (such as polyperfluorobutenylvinylether), are even faster than glass MMF.**
- **The parabolic profile of the graded refraction index (from the core center out) results in continual refocusing of the rays in the core, and minimizes modal dispersion.**

What are theEnabling Technologies?

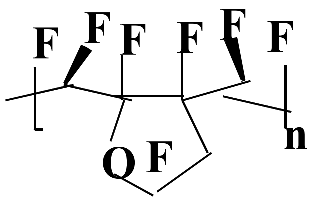
- Plastic fiber whose core has a refractive index that decreases with increasing radial distance from the fiber axis (such as polyperfluorobutenylvinylether) allow for near infrared wavelengths (850nm or 1300nm) and surpass glass MMF
- Sub-Micron CMOS receivers with low-input-impedance have bandwidths close to 10GHz
- Copper-pillar flip-chip allows lasers and detectors directly above sub-micron CMOS chips
- Precision injection-molded plastic enable cheap connectors

GINOVER GI POF lineup

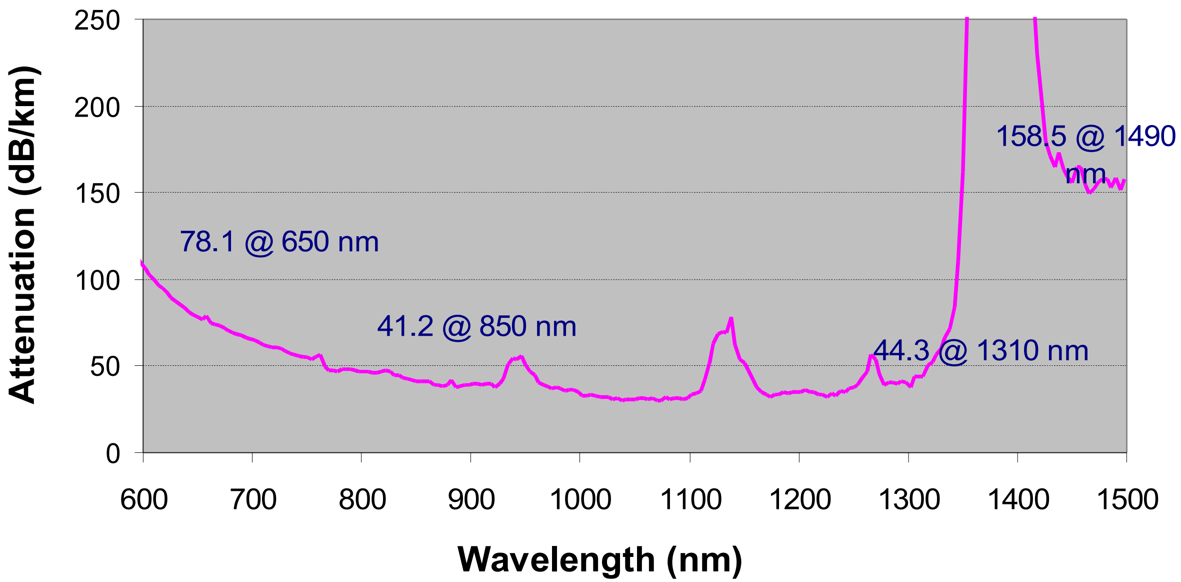
No.	<VT250>	<VT120>	<ID120>	<ID062>
Material	Partially Chlorinated (PCP)		Perfluorinated	
Cut surface				
Core diameter	250 μm	120 μm	120 μm	62.5 μm
Outer diameter	750 μm	490/750 μm	490/750 μm	490/750 μm
Light source	650 nm	770 nm	850 nm	850 nm
Bandwidth	2.5 GHz/ 50m	5 GHz/ 20m	3 GHz/ 100m	10 GHz/ 30m
Working temp.	85°C	100°C	70°C	70°C
N. A.	0.3	0.3	0.185	0.190
Features	Connector-less Eye Safety	High-thermal Easy connection	High Speed Easy connection	Super- High speed
Typical Application	IPTV System Residential	Inside TV OA / FA / Medical	Digital Signage	AV Link Datacenter

Perfluorinated, Graded-Index POF

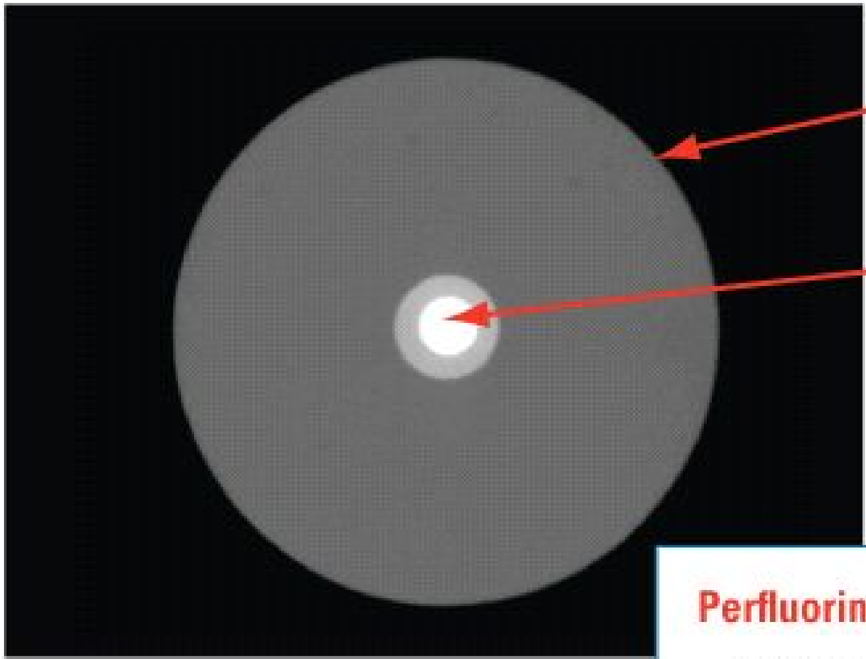
- Extruded perfluorinated polymers
- Very accurate geometries
- Wide useful spectral range
- High Bandwidth Graded Index
- Safe and easy to use



Amorphous fluoropolymers



New levels of geometric control



Over cladding:
250 to 1000 ± 3 µm

Graded index core:
50 ± 3 µm

Concentricity of Core/Over clad:
< 3.5 µm

Perfluorinated Plastic Fiber Features

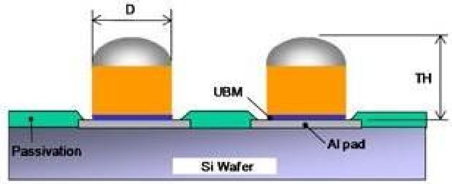
1) Simple end face preparation
2) Over cladding provides strength and the alignment feature

Off-Chip Detectors and Lasers

- For lower-performance applications, detectors can be on-chip
- For best performance, off-chip PIN detectors are required
- Laser transmitters (vertical-cavity surface-emitting lasers or VCSELs) are always off-chip as they require a non-silicon technology, such as GaAs
- For off-chip detectors and lasers connected using bond-wires, the speed is severely limited by the inductances of the bond-wires
- If the detectors and lasers are realized in a chip directly above a sub-micron CMOS chip and connected using flip-chip copper-pillar technology (available from Amkor), this limitation disappears.

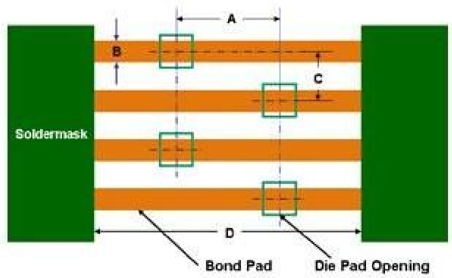
Amkor's Copper Pillar Flip-Chip Technology

Copper Pillar Bump Design Rules



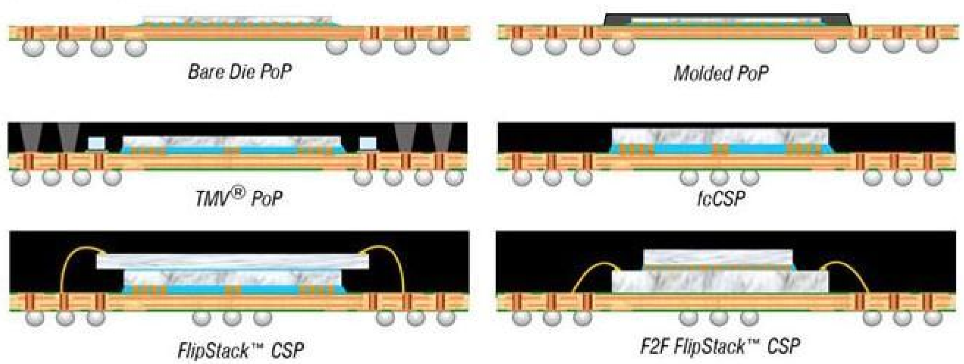
FEATURE	DIMENSION
Cu Pillar Diameter (D)	20 -50 µm
Total Height (TH)	30 - 45 µm

Pad Design Guidelines



General Design Rules	60 Pitch	50 Pitch	45 / 90 Pitch	40 / 80 Pitch	30 / 60 Pitch
(A) Row to Row Pitch	N/A	N/A	90	80	60
(B) Bond Pad Width	30	25	22	20	TBD
(C) Trace Pitch	60	50	45	40	30

Cross Sections



Inexpensive Optical Connectors

- An on-going area of development, but recent examples show this is certainly possible; for example Avago recently developed a 12-Channel PRIZM LT-Connector.
- Another example is a prototype of a plastic package that could be produced for less than $0.10 in volume: (Hak-Soon Lee, et. al., February 2011 / Vol. 19, No. 5/ Optics Express, pg 4301).
- New developments need ingenuity, but not new technology.

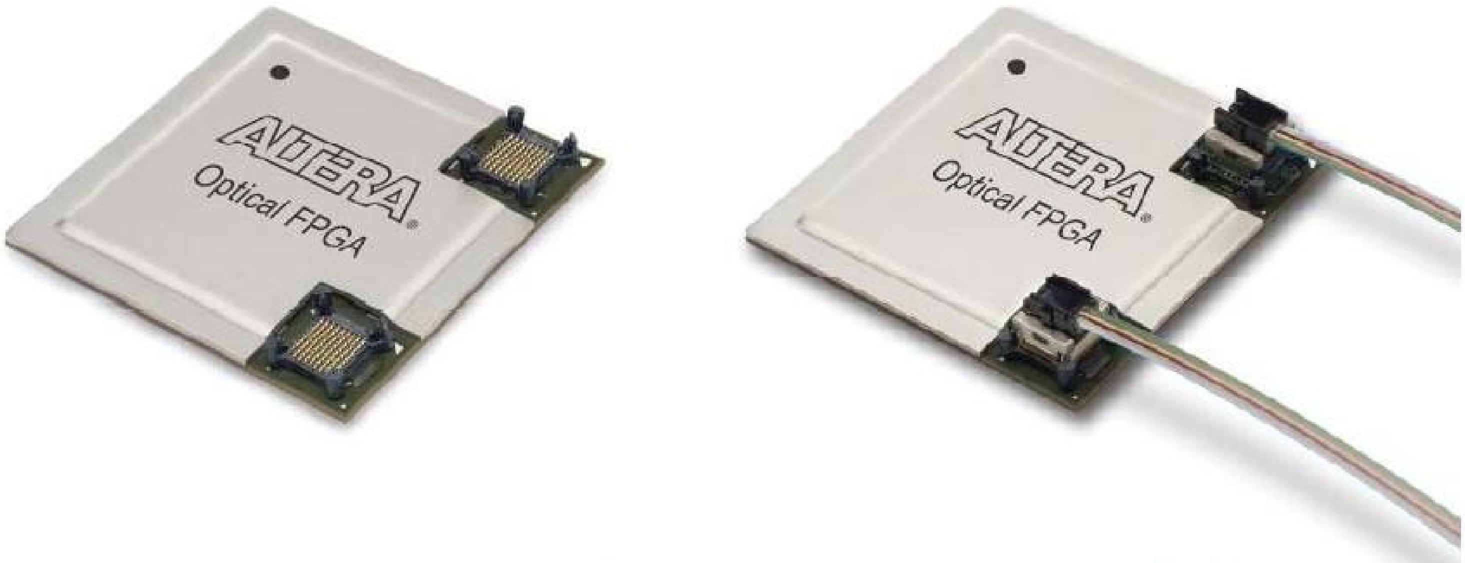


Figure 4. The Altera FPGA package hosts the optical transmitter and receiver sockets, one on each of two corners (left). The 12-channel optical transmitter and receiver modules from Avago plug into each of the sockets, and the PRIZM® LightTurn® cable assemblies plug onto these modules (right).

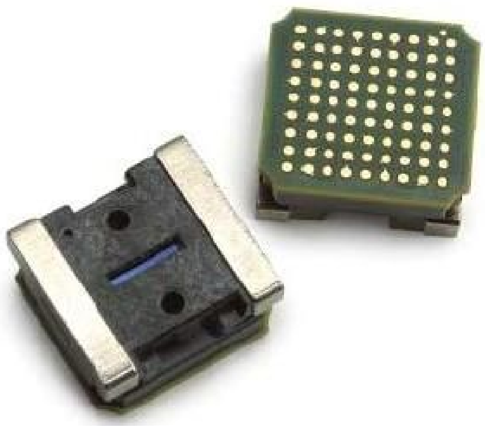


Figure 5. The MicroPOD optical modules mount on the FPGA package using an LGA and require a footprint of just 8.2 mm by 7.8 mm.

Figure 6. The 12-channel optical cable and the PRIZM® LT connector mount directly on the top of the optical modules. The combination forms a very compact high-speed interface capable of handling 120 Gbps.

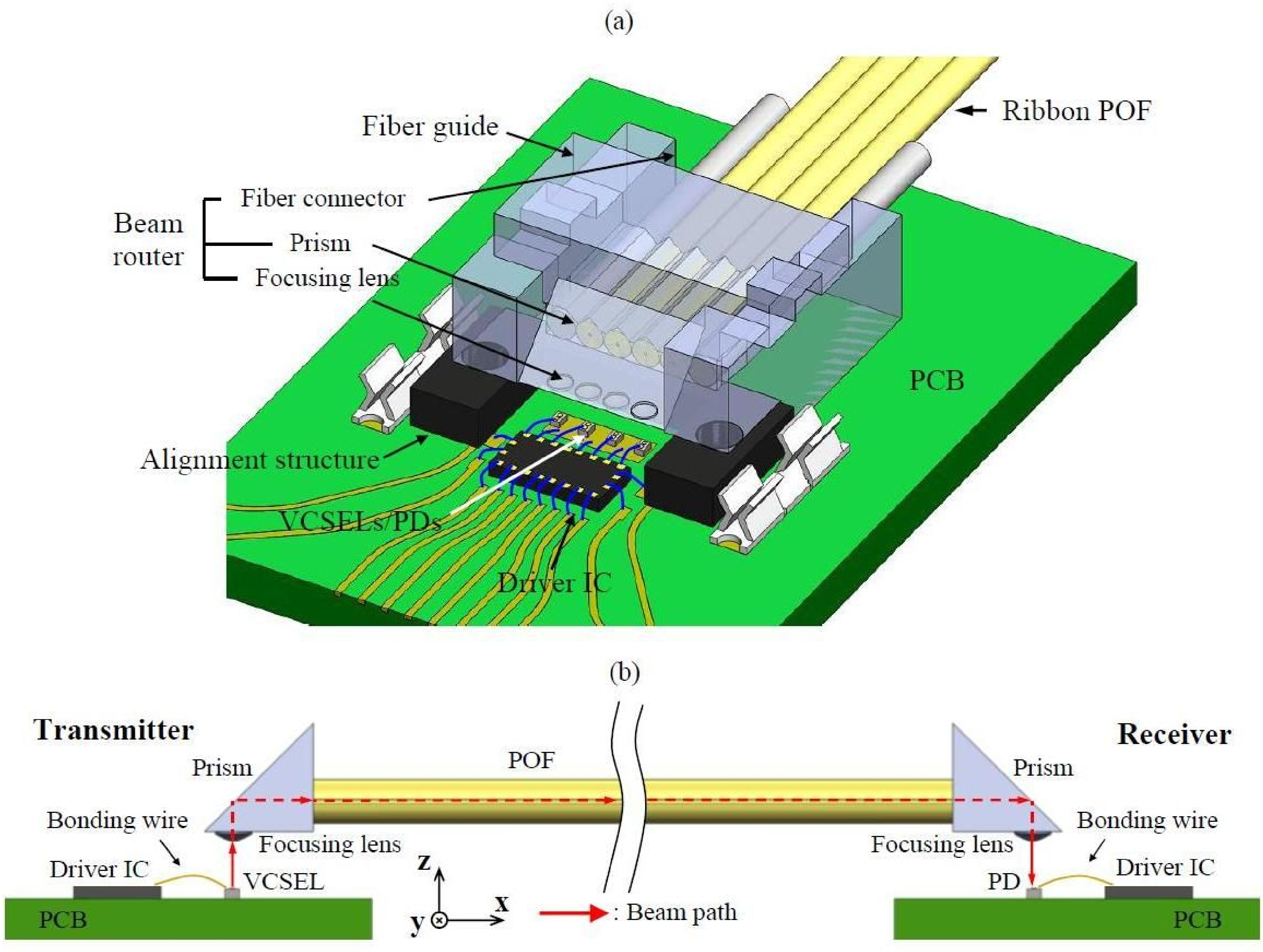


Fig. 1. Proposed Tx/Rx module. (a) Configuration. (b) Optical beam path.

POF Detectors

- Historically, POF communication systems had bandwidths severely limited by the large parasitic capacitances due to very large optical detectors
- In addition, integrated POF detectors exhibit very limited bandwidths, especially at 850nm wavelengths
- Addressing these issues was the research topic of Yunzhi Dong, my recent Ph.D. student, and is also the focus of this presentation

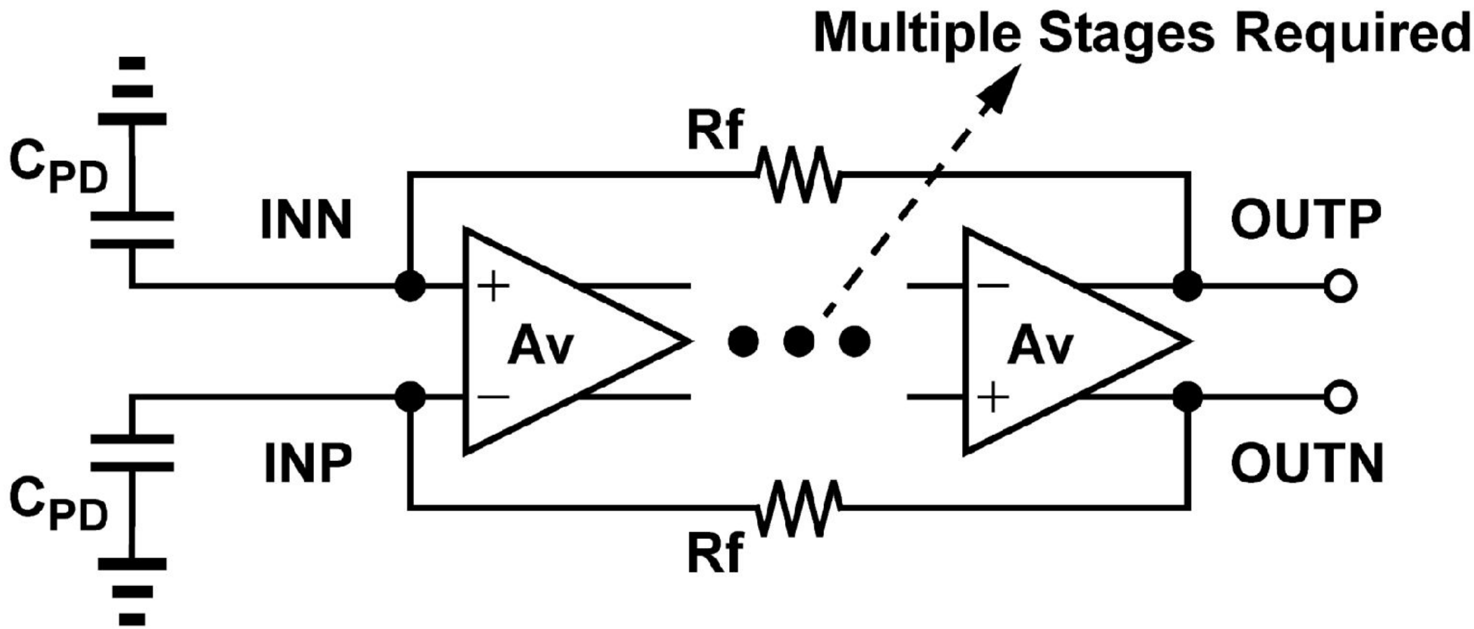
POF Detector Capacitances

- **Historically, 1mm POF with a matching width detector had parasitic capacitances of 15-30 pF. This was a major limitation on the speed.**
- **Newer graded-index POF can have an effective core diameter as small as 50um,which allows for much smaller detectors.**

In addition, sub-micron CMOS and *clever* circuit design techniques allows optical amplifiers to be designed which have very small input impedances, on the order of 2-3 ohms

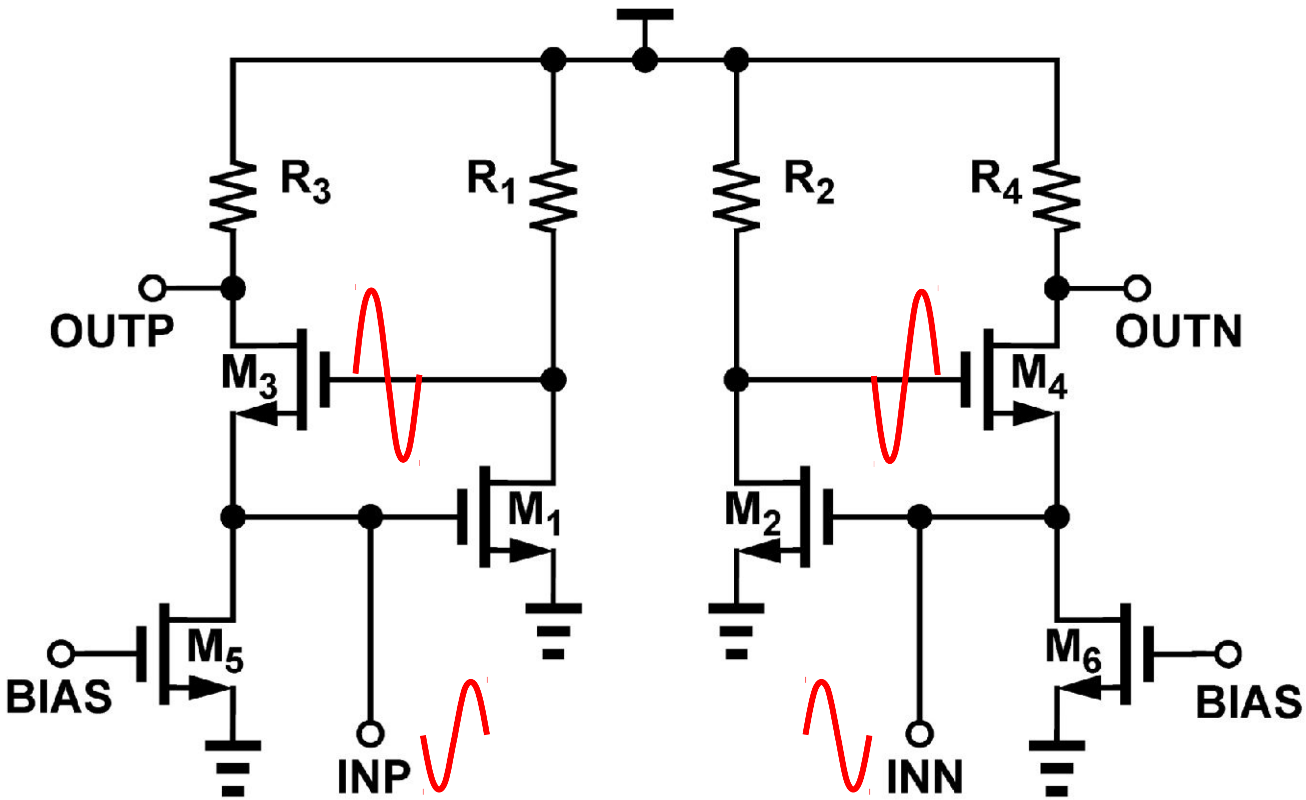
https://dl.dropbox.com/u/33848896/Theses/High_Speed_POF_Receiver_Yunzhi_Dong_RV1_Compressed.pdf

Classic Shunt-Shunt Feedback TIA



- C_{PD} = 14 pF, BW = 3 GHz, Rf = 150 Ω, PM = 50°
  - Z_{IN} < 3.7 Ω, requires 4 stages in 65 nm CMOS
  - To achieve the PM, need f_{-3dB} > 17 GHz/stage!
  - For input-referred I_N(rms) = 8.2 µA, I_{DC} > 125 mA!

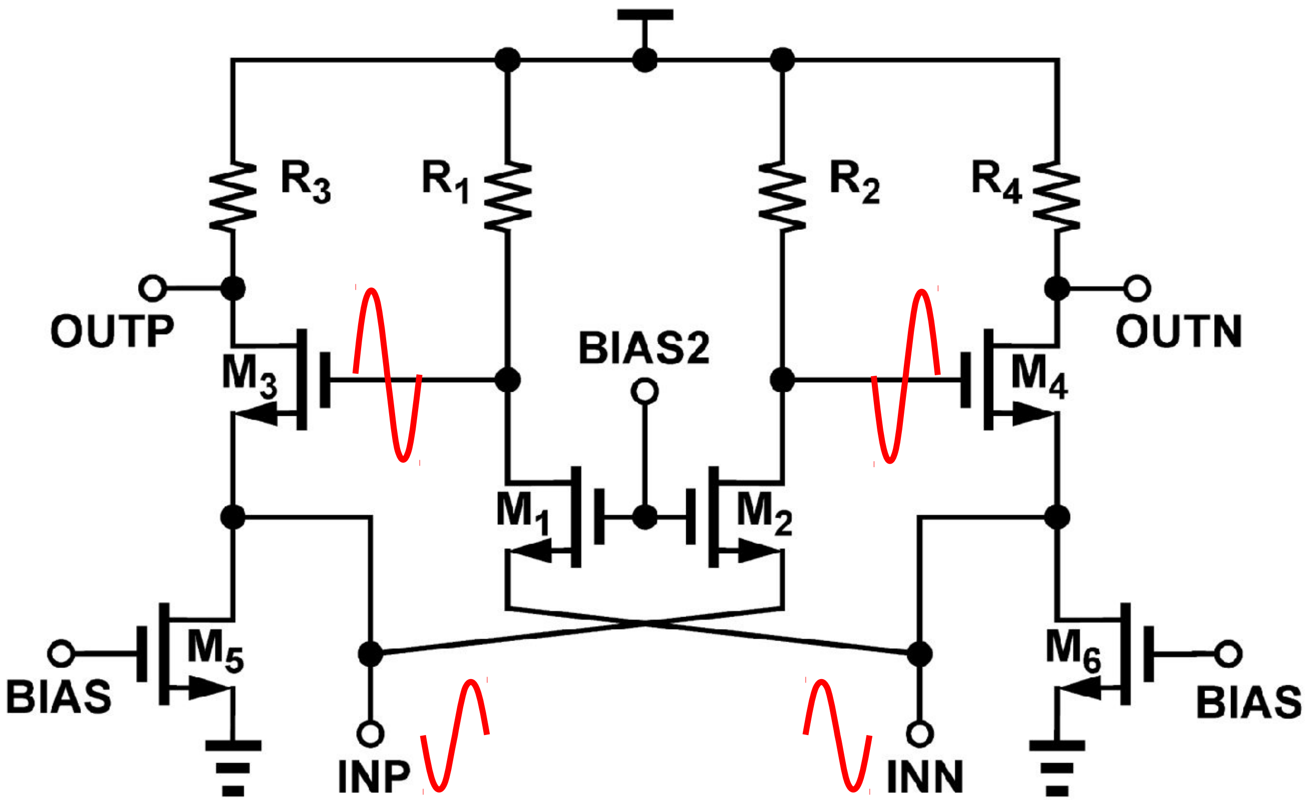
Regulated Cascode (RGC) Buffer



Local Feedback Enhances Gm of $M_{3,4}$

$$Z_{IN} = \frac{1}{Gm_3(1 + Gm_1 R_1)}$$

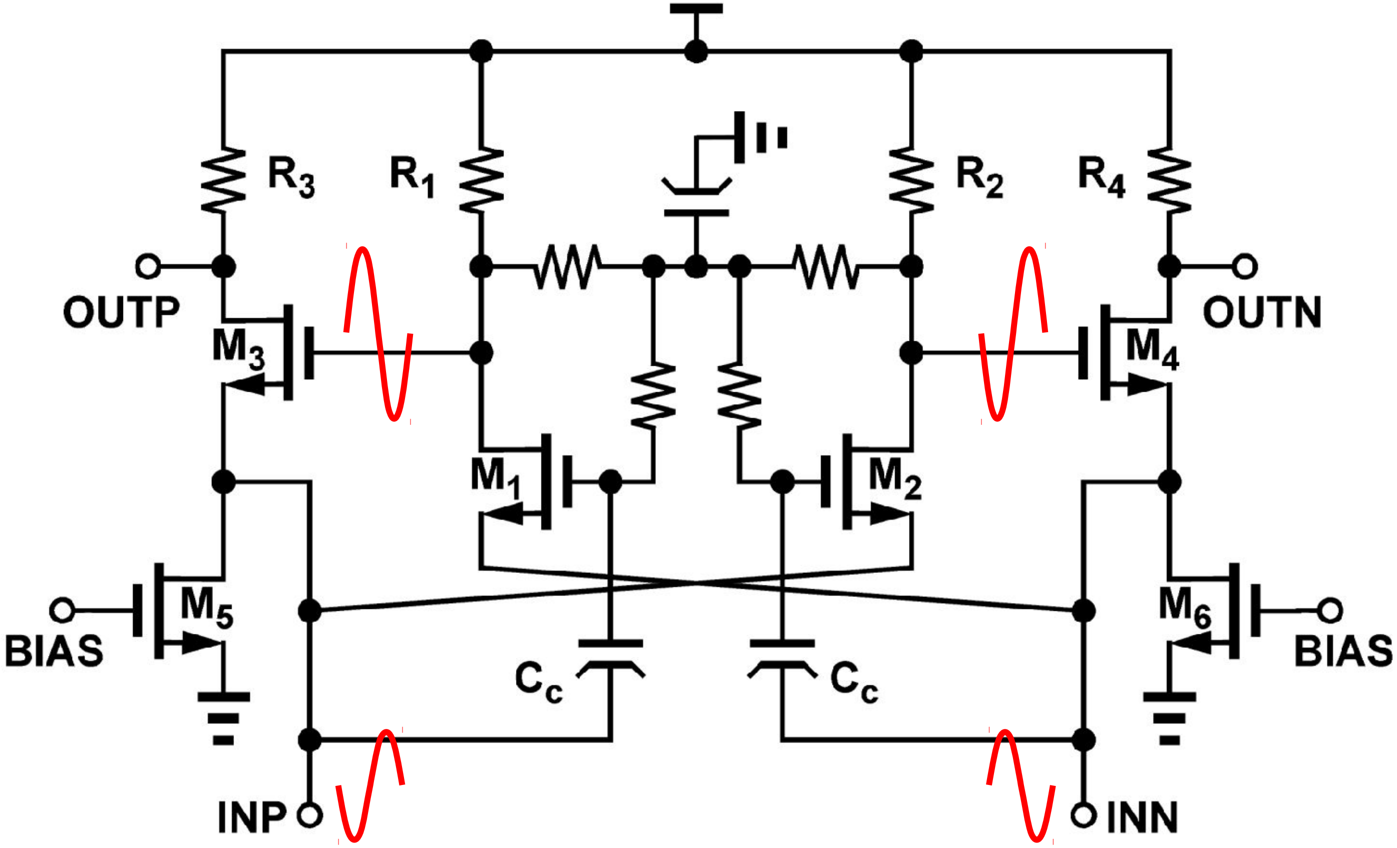
Cross-Coupled RGC (CC-RGC)



Cross-Coupling Improves Voltage Headroom

$$Z_{IN} \cong \frac{1}{Gm_3(1 + Gm_1 R_1)}$$

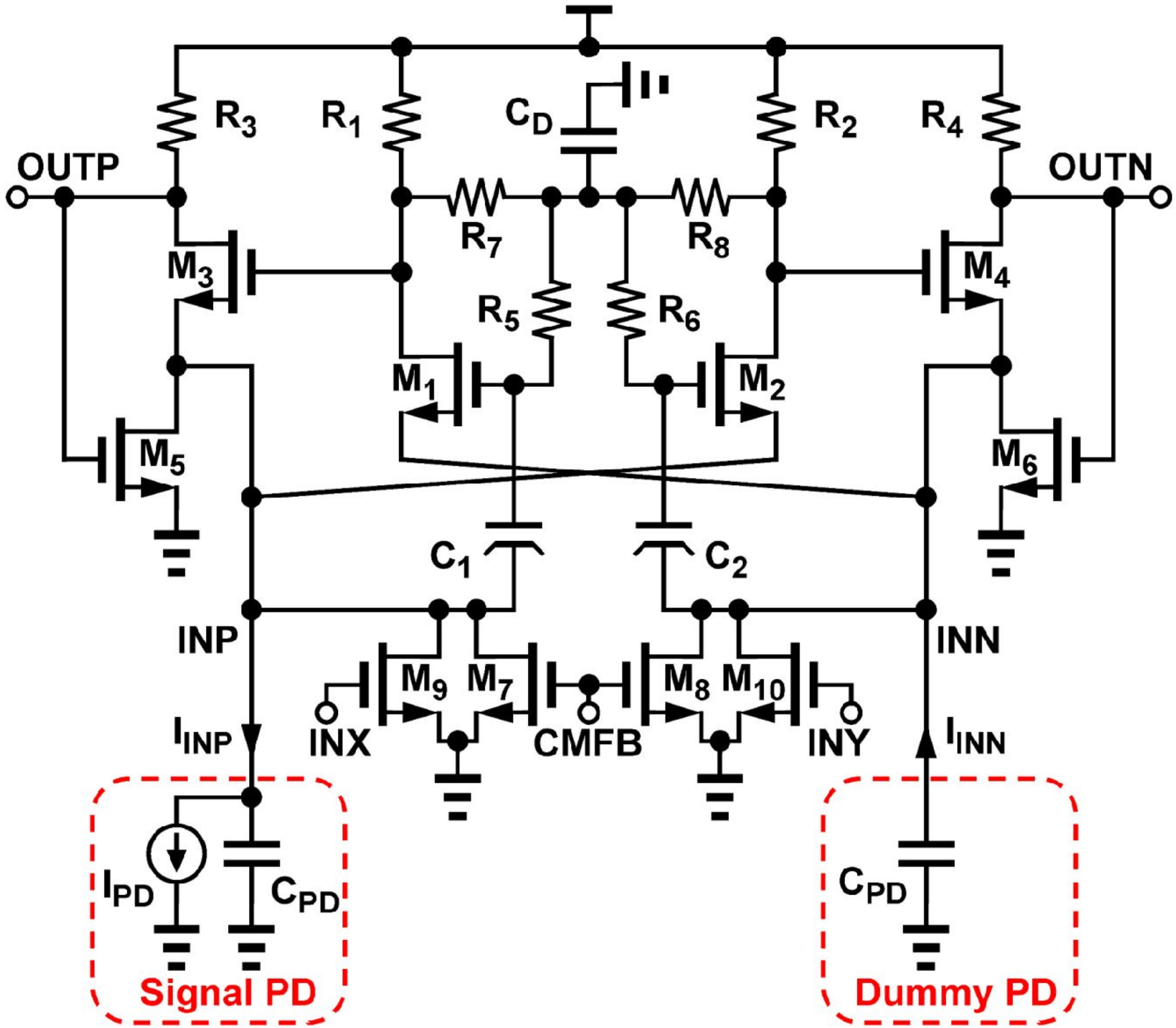
CC-RGC w. Passive Coupling



Passive Coupling Enhances Gm of $M_{1,2}$

$$Z_{IN} \cong \frac{1}{2Gm_3(1 + Gm_1 R_1)}$$

Complete Proposed Super-Gm TIA



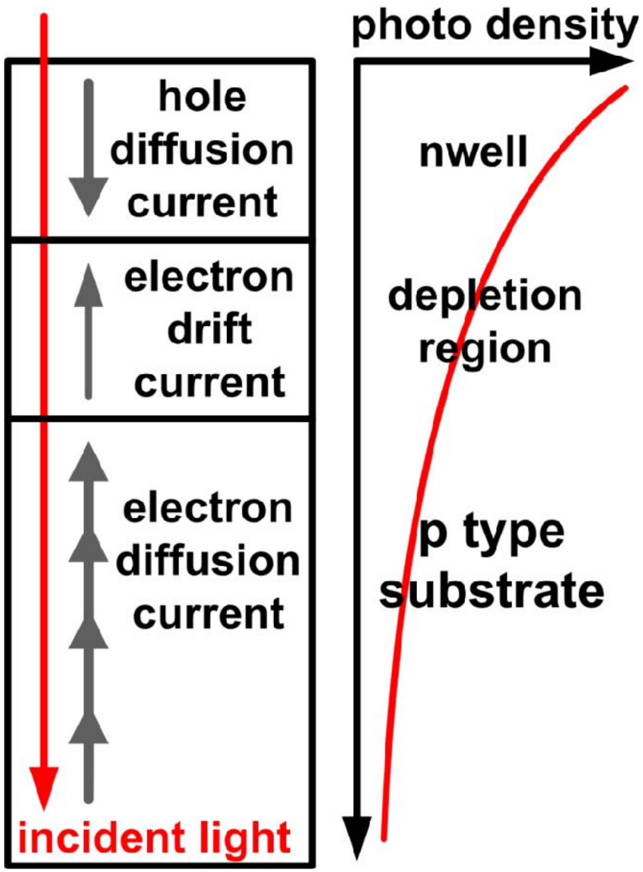
Design Considerations

- The cross-coupled auxiliary amplifier enhances the *differential bandwidth* by a factor of 3-4 so that in TSMC 65nm GP, bandwidths of over 5GHz are achievable. In 40G, bandwidths on the order of 10GHz are probably achievable (the necessary bandwidth is approx. 0.7 times the bit rate).
- With the low input impedance, and extended bandwidth, then the main consideration is a design trade-off of cheaper connectors having relaxed alignment requirements versus higher speed smaller detectors but with more expensive alignment requirements.
- There is also a trade-off between on-chip detectors (causing lower input sensitivities) versus off-chip detectors where either copper-pillar flip-chip technology is required or bond-wires can limit speeds.

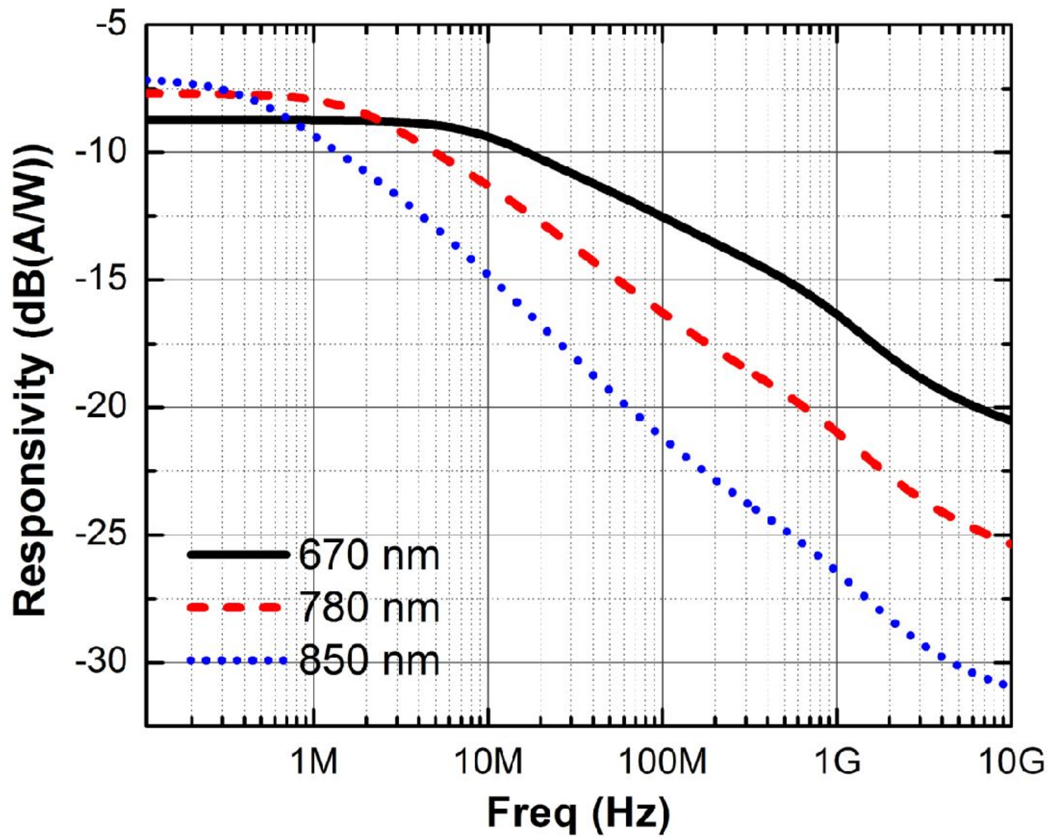
Detectors

- **Off-chip detectors are normally PIN (p-insulator-n) detectors designed to have deep depletion regions on the order of 20um which is closer to the absorption lengths on near infrared light: 4 μm @ 670nm, 12 μm @ 780 nm, 18.7 μm @ 850 nm**
- **On-chip CMOS detectors typically have much smaller depletion regions (this is not as limiting in a BiCMOS process) which implies many of the optically generated carriers are in the substrate and take much longer to travel to the receiver which limits the speed.**
- **On-chip detectors require high-frequency boost equalization**
- **On-chip detectors work better at 670nm wave-lengths, but current VCSELs at 670nm have difficulties at temperatures above 70C – this is getting better**

NW/P-sub PD at 670 nm in CMOS



smaller wavelengths = larger bandwidths



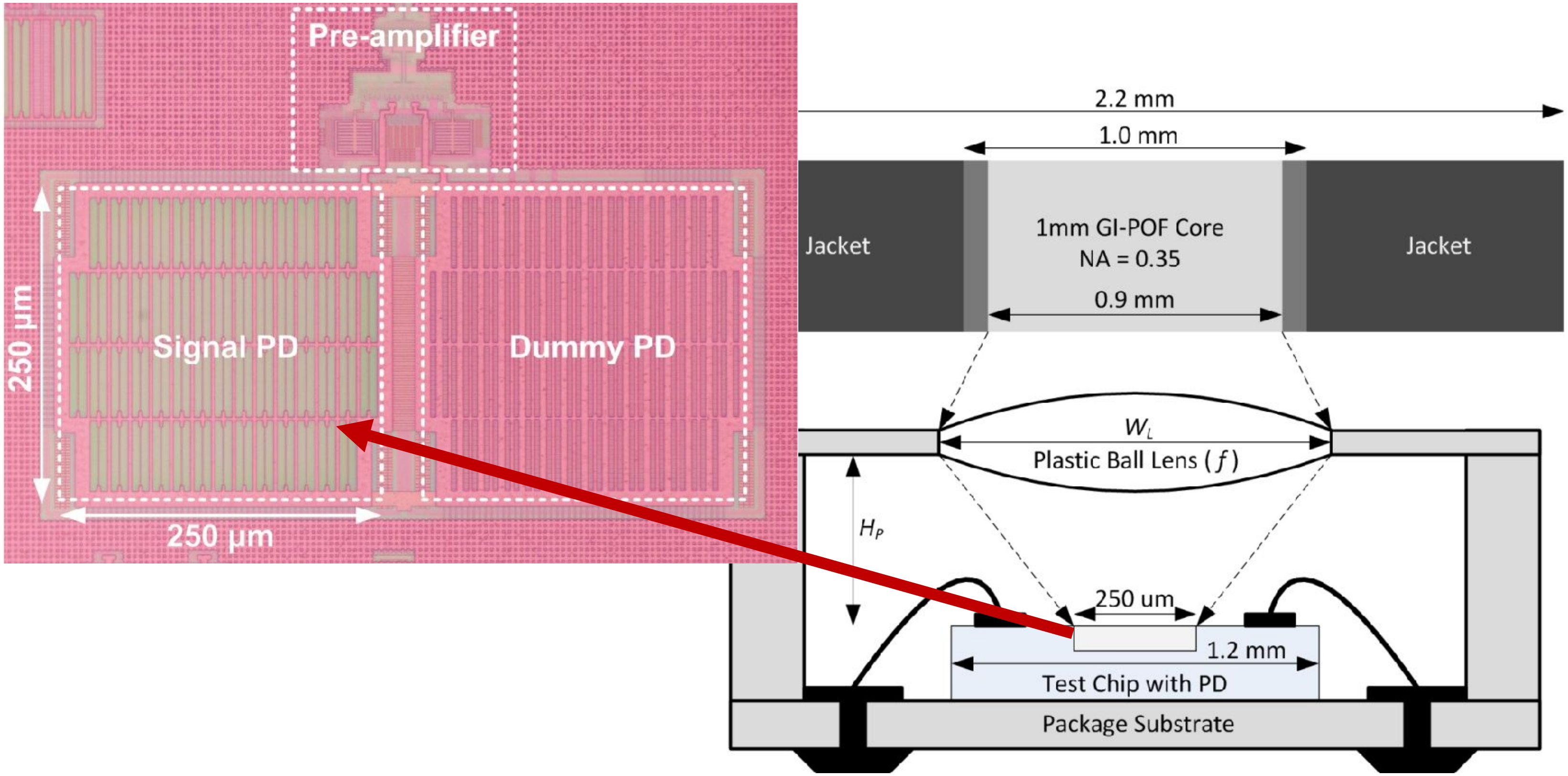
Absorption length in silicon

4 µm @ 670nm, 12 µm @ 780 nm, 18.7 µm @ 850 nm

TestChips

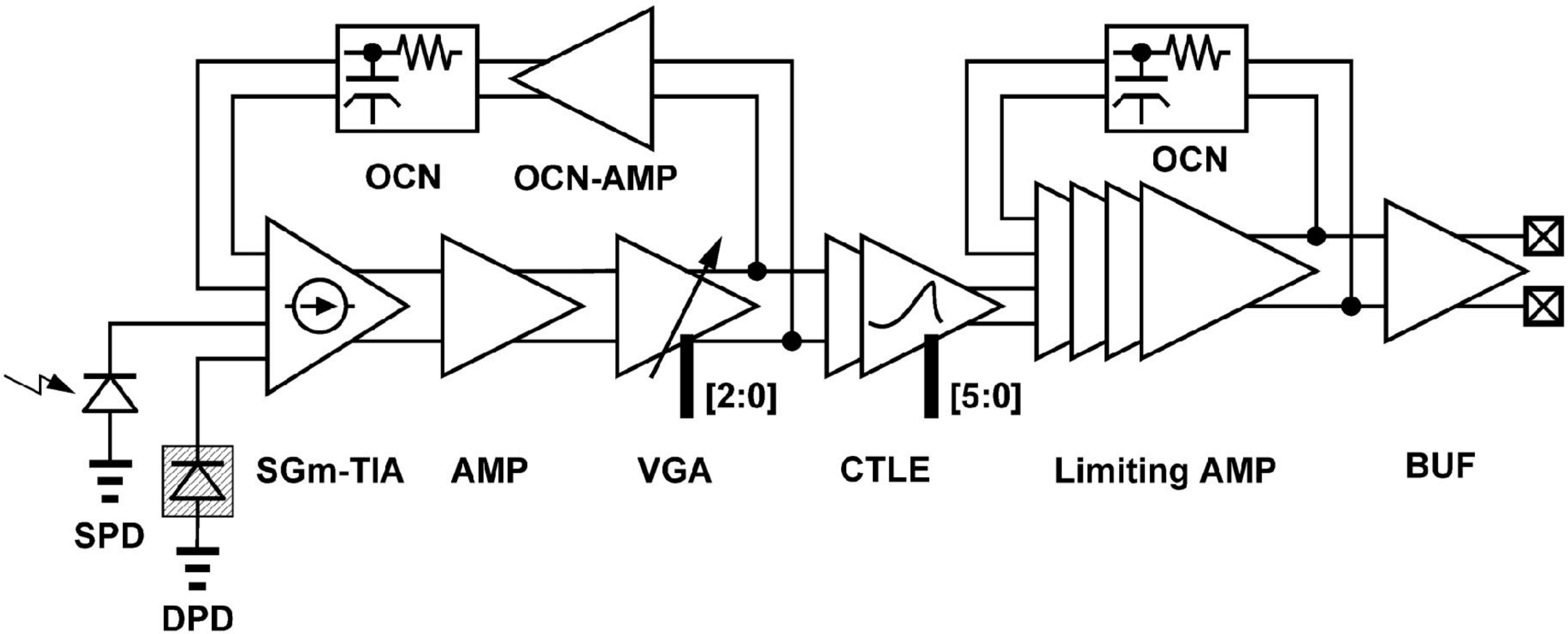
- Two test chips were processed: the first one was in TSMC’s 65 LP (low-power) process, the second was in TSMC’s 65 GP process (a faster process).
- The first test chip had a “classical” equalizer structure; the second one had a new architecture which is good for applications where it is known that equalization is always required
- Unfortunately, the first test chip had 55% of the the photo-detector windows covered by salicide; the second chip corrected this.
- In addition, both chips had receivers that could be tested electrically (i.e. no on-chip photo-detectors included)

NW/P-sub PD at 670 nm in CMOS



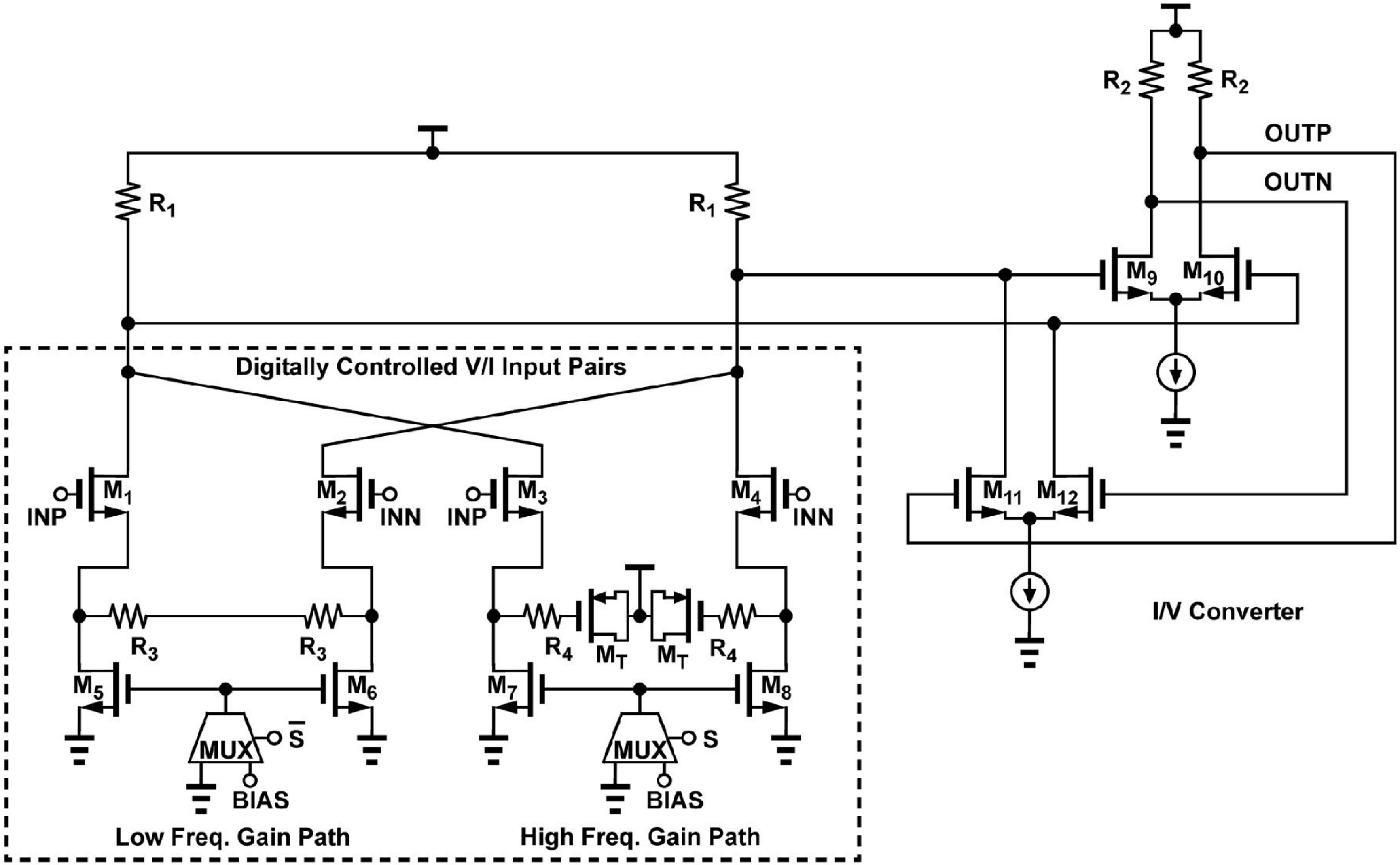
- A pseudo-diff PD w. a signal PD and a dummy PD
- PDs are 250 µm by 250 µm w. 60 µm by 15 µm strips
- Each PD exhibits a post-simulated C_{PD} of 14 pF

Complete POF Receiver Front-end



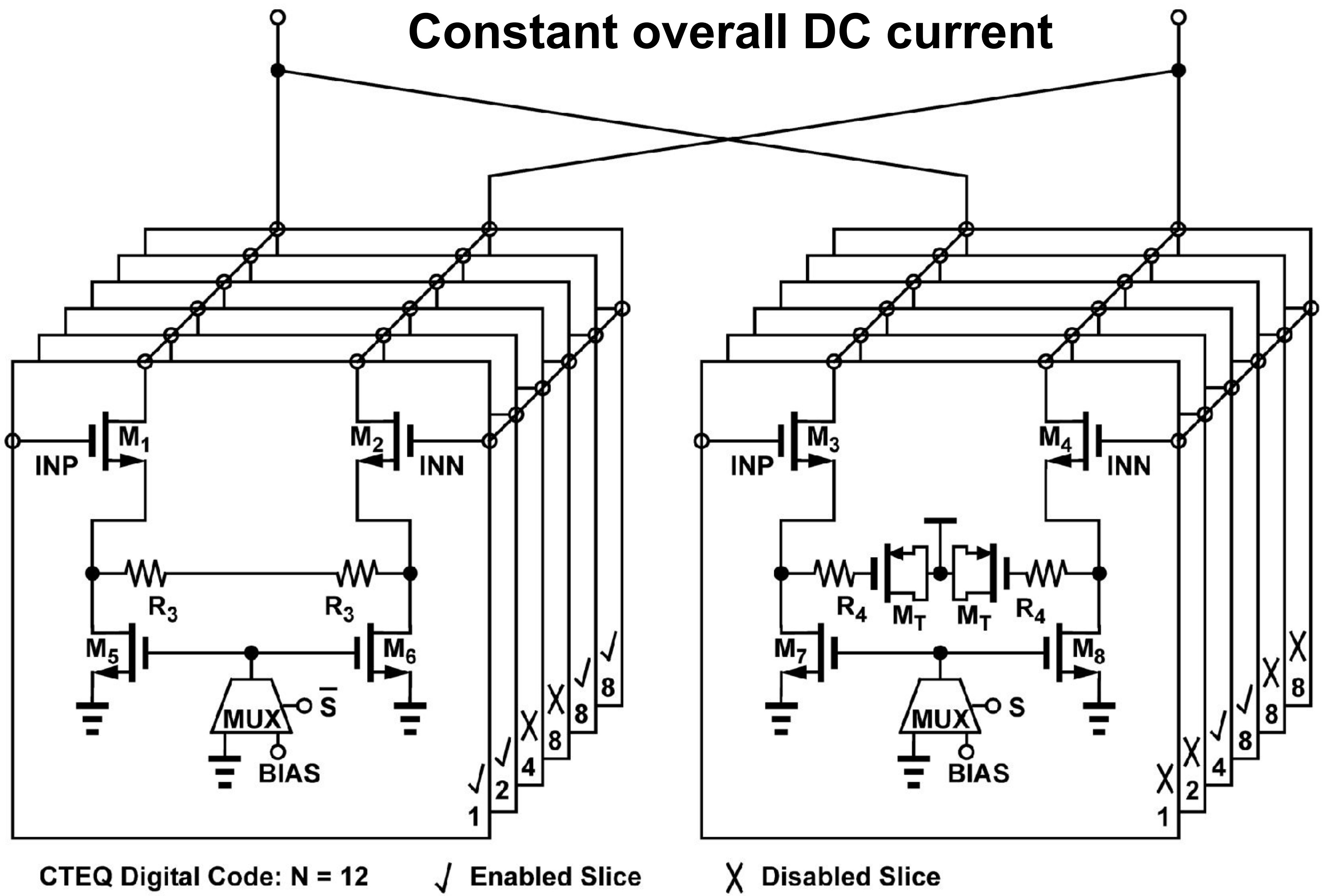
- ❑ 250 um NW/P-sub PD exhibits a 14 pF C_{PD}
- ❑ SGM-TIA drives C_{PD} up to 4.5 GHz (Post TT 50^{o}C)
- ❑ Integrated dual offset-cancellation networks (OCN)
- ❑ Also includes a VGA, a four-stage LA, and a buffer

Source-Degenerated CTLE #2

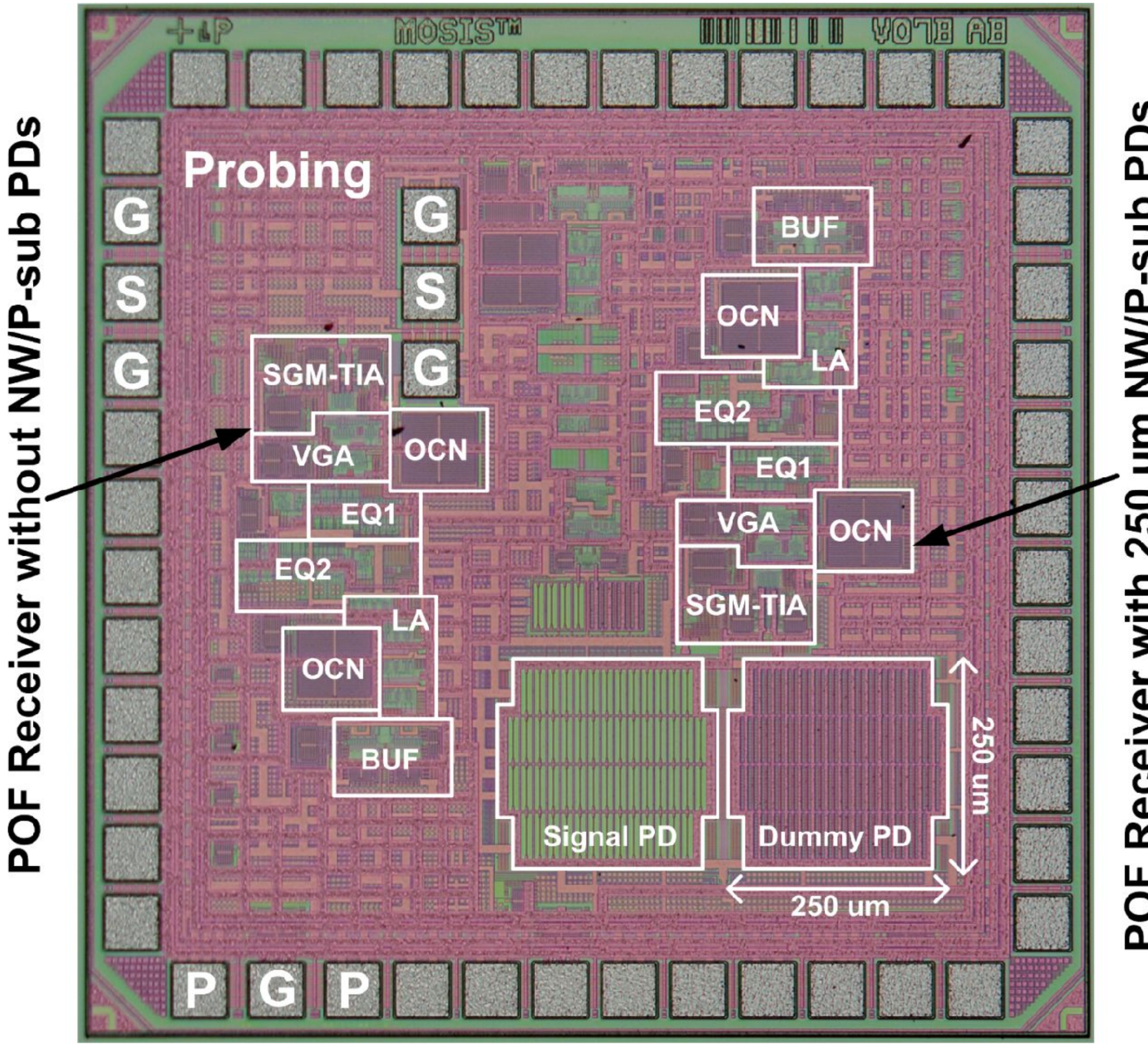


Low Freq. Gain High Freq. Gain I/V Converter

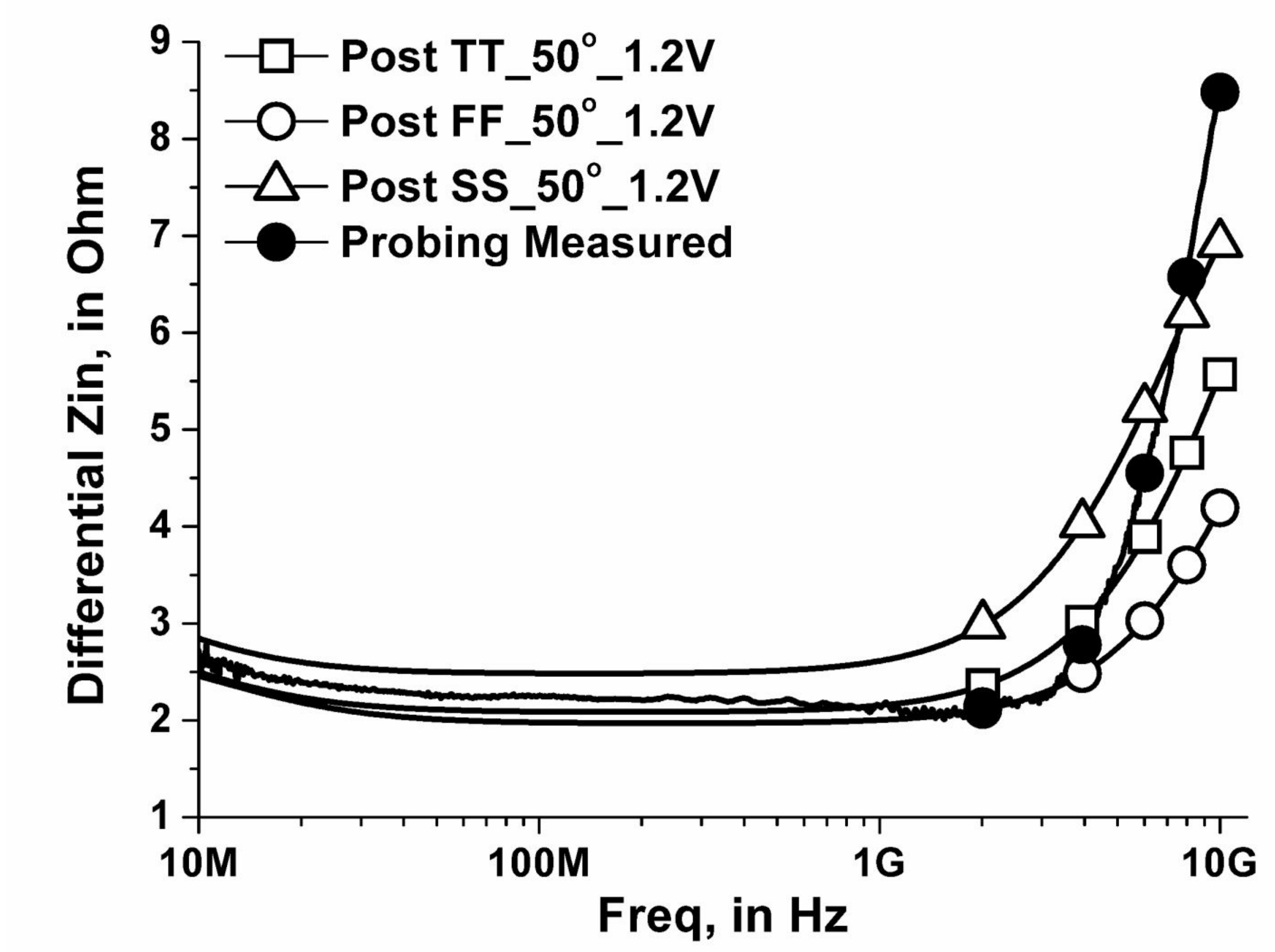
CTEQ Digital Tuning Scheme



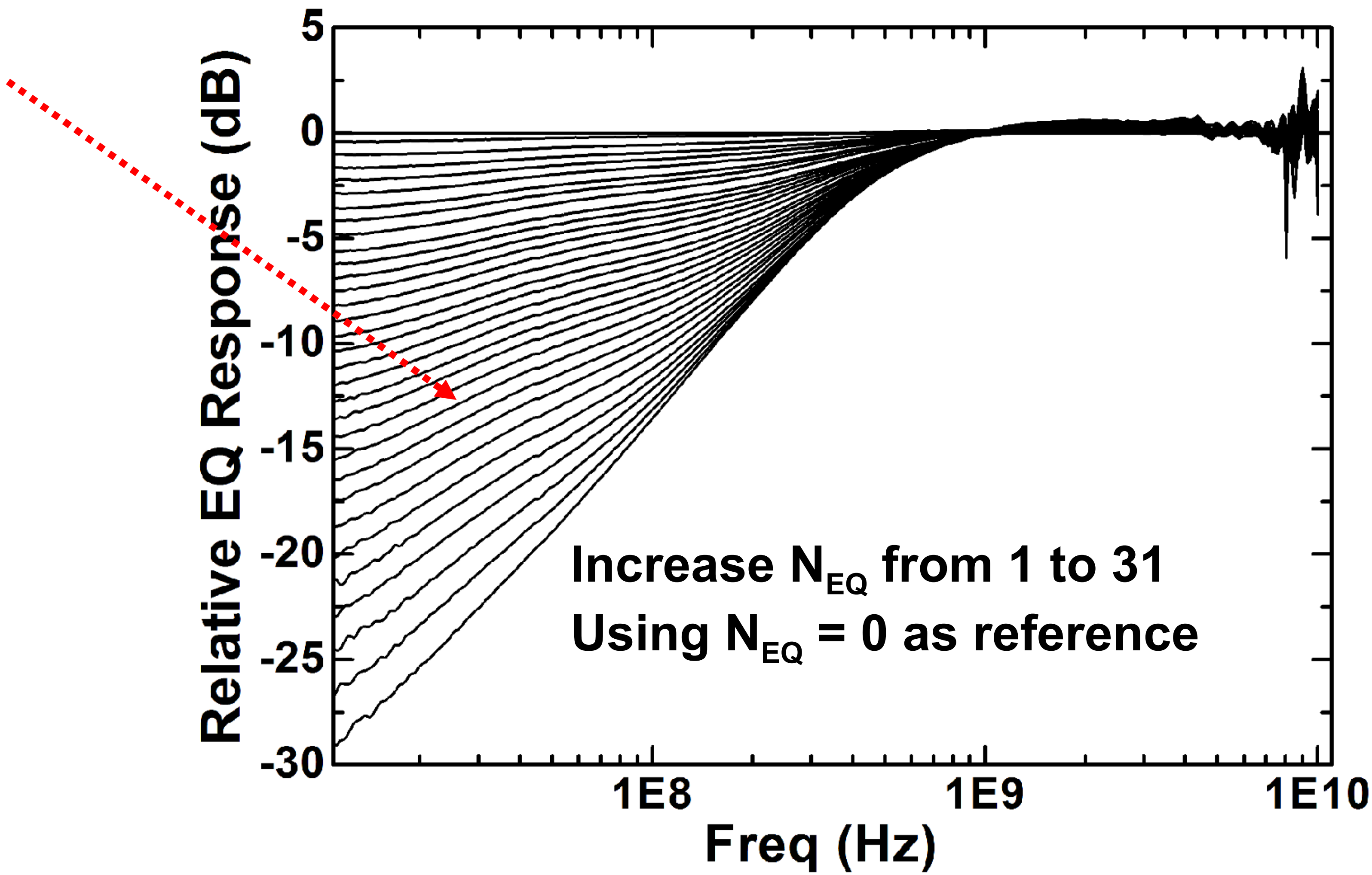
Test Chip 1 in TSMC 65 nm LP CMOS



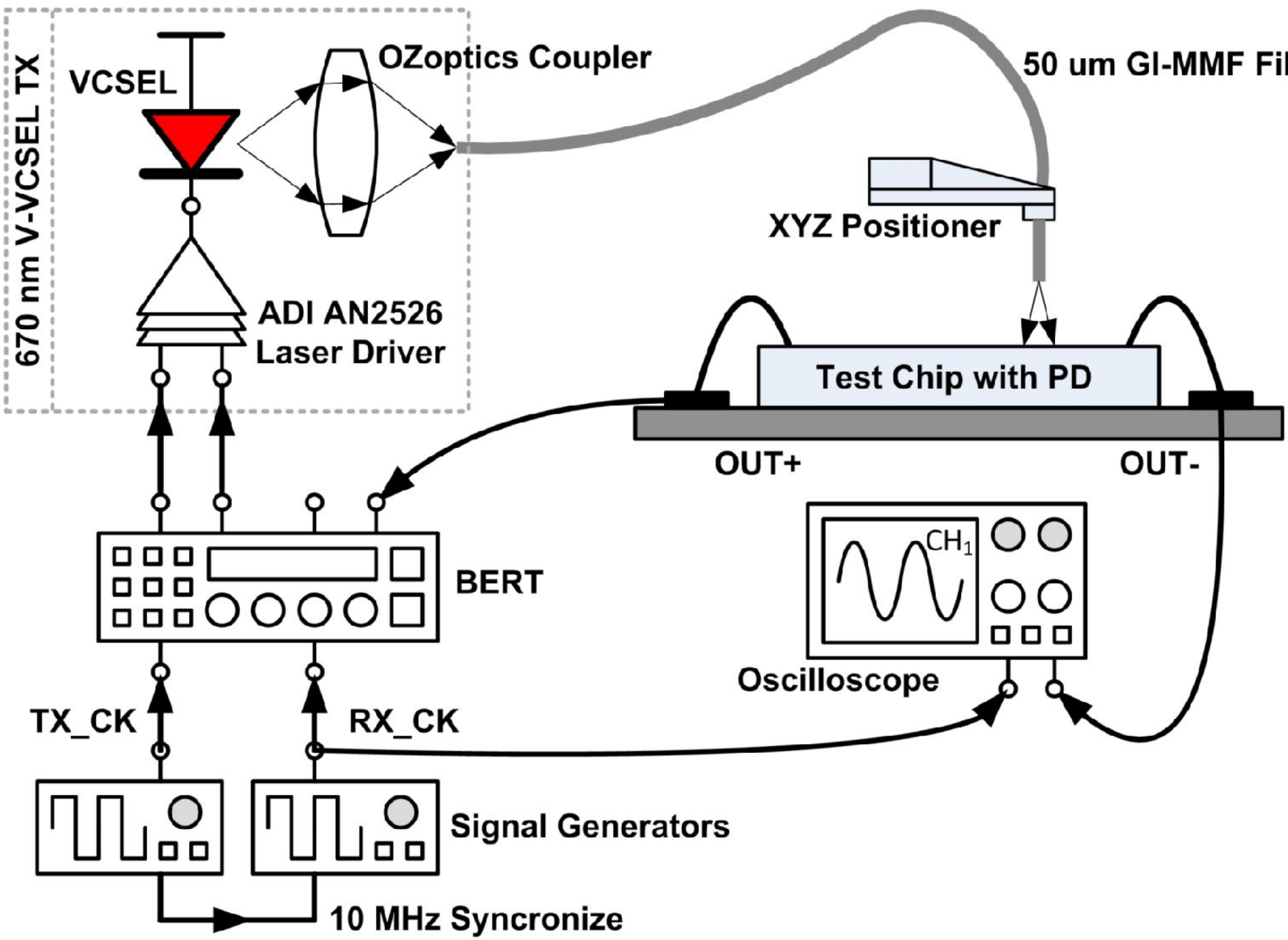
Differential Z_{IN} via on-wafer Probing



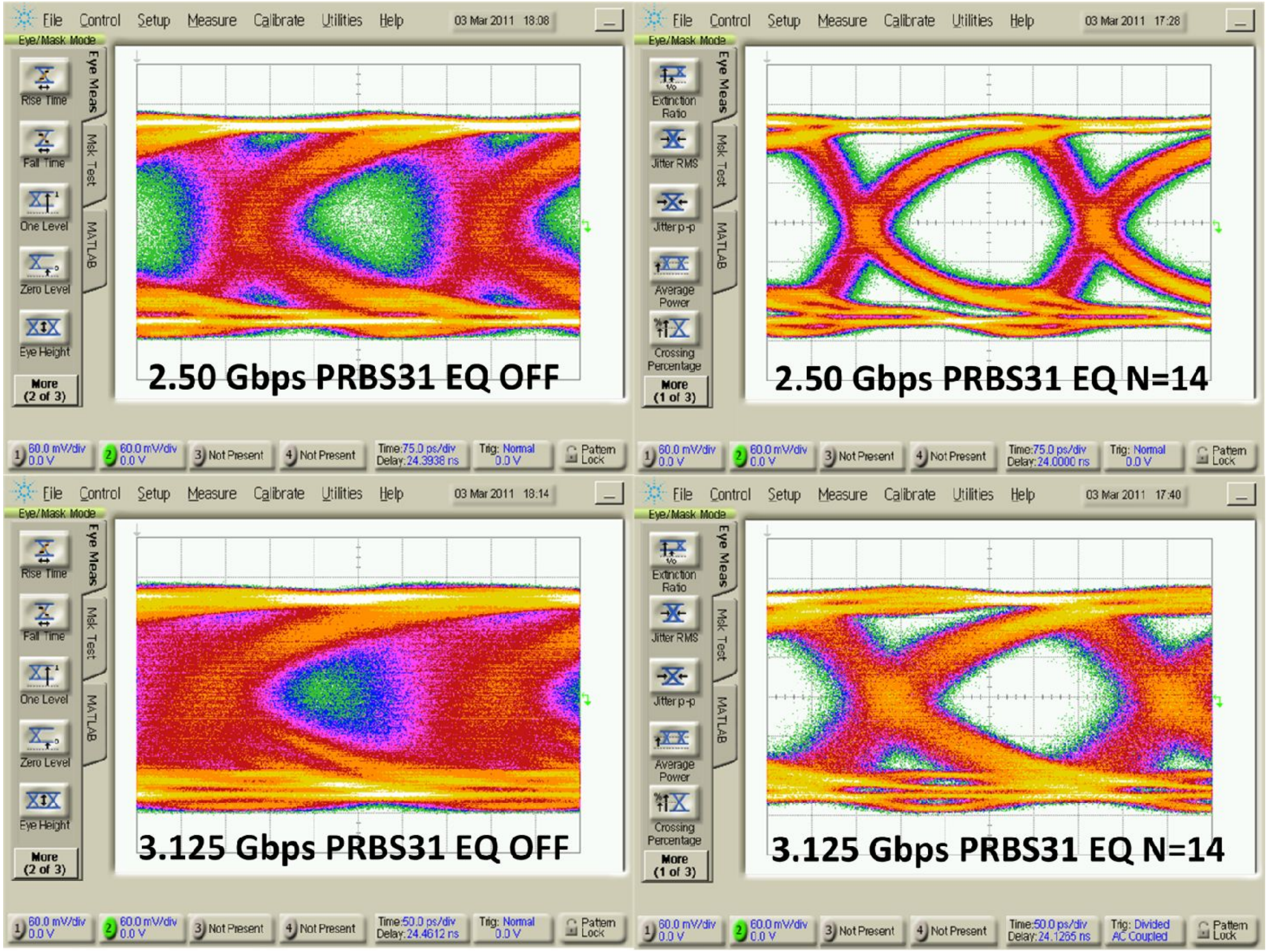
Measured CTLE Boosts (1^{st} & 2^{nd} zeros)



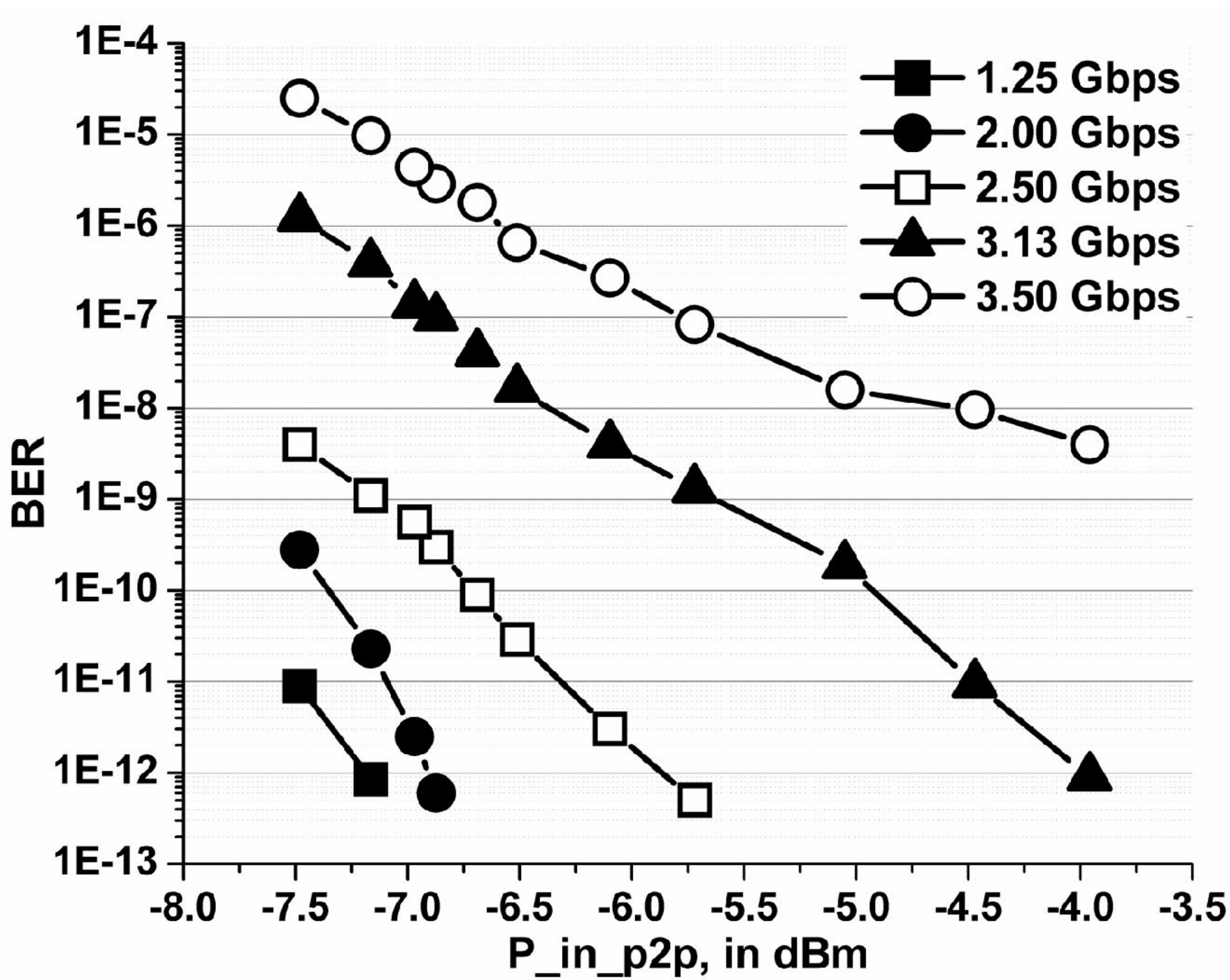
Opto-Electro BER Experiment Setup



Eye Diagrams w.o./w. CTEQ

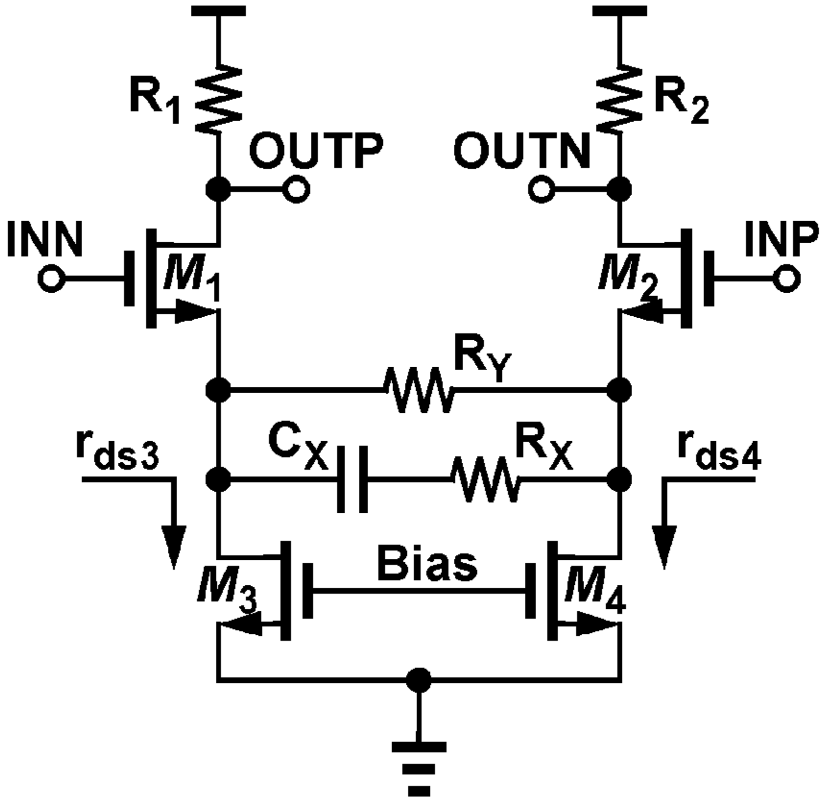


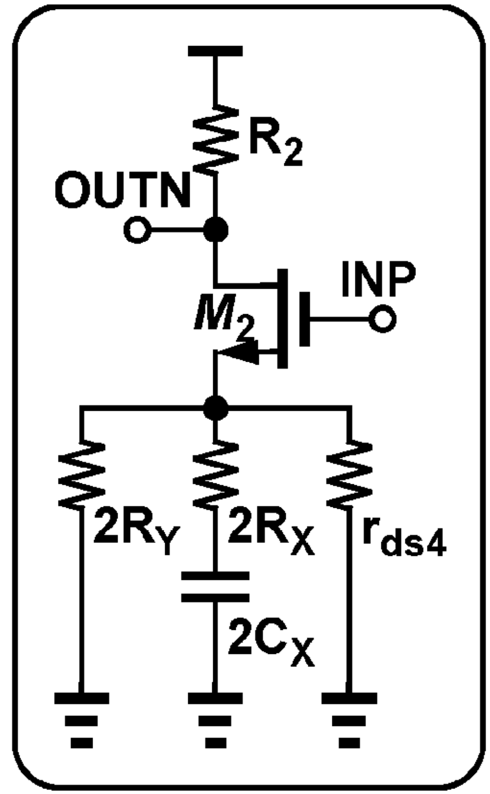
Bit Error Rate (BER) Test Chip 1



* P_in_p2p are extrapolated from measured values to those expected when salicide doesn't cover the 55% of PD windows

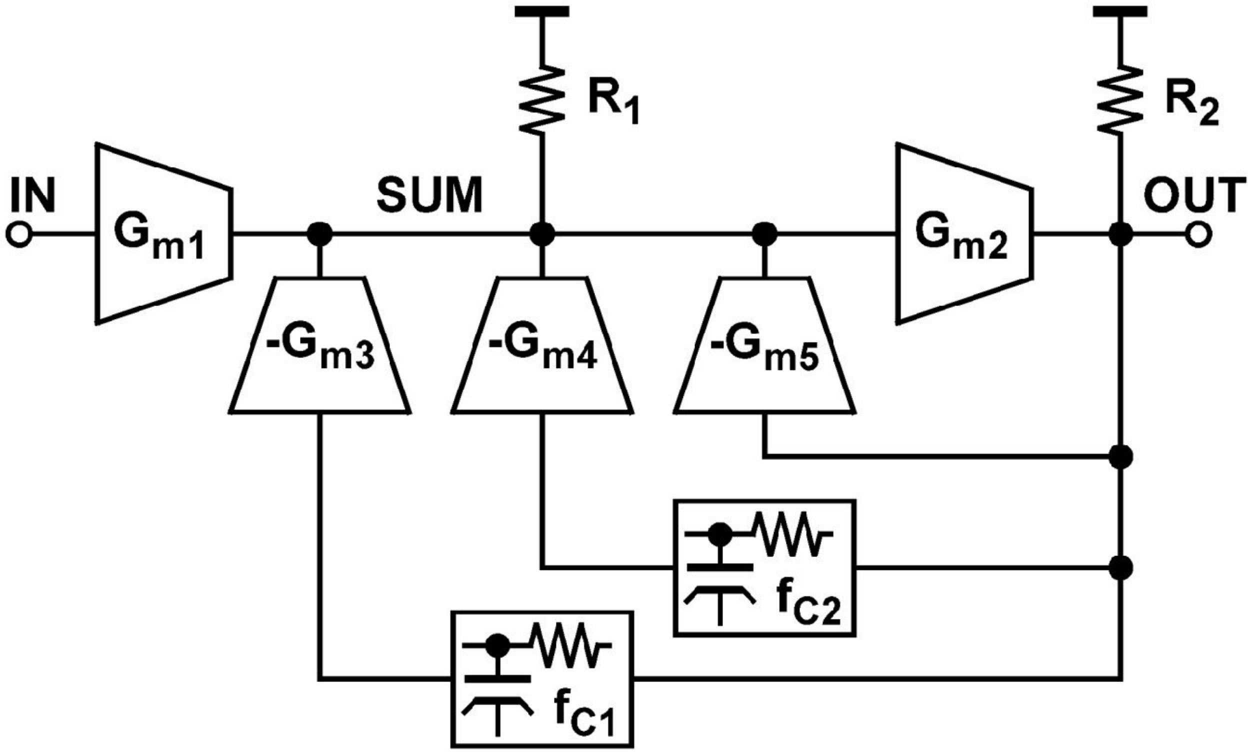
Traditional CTLE Circuits





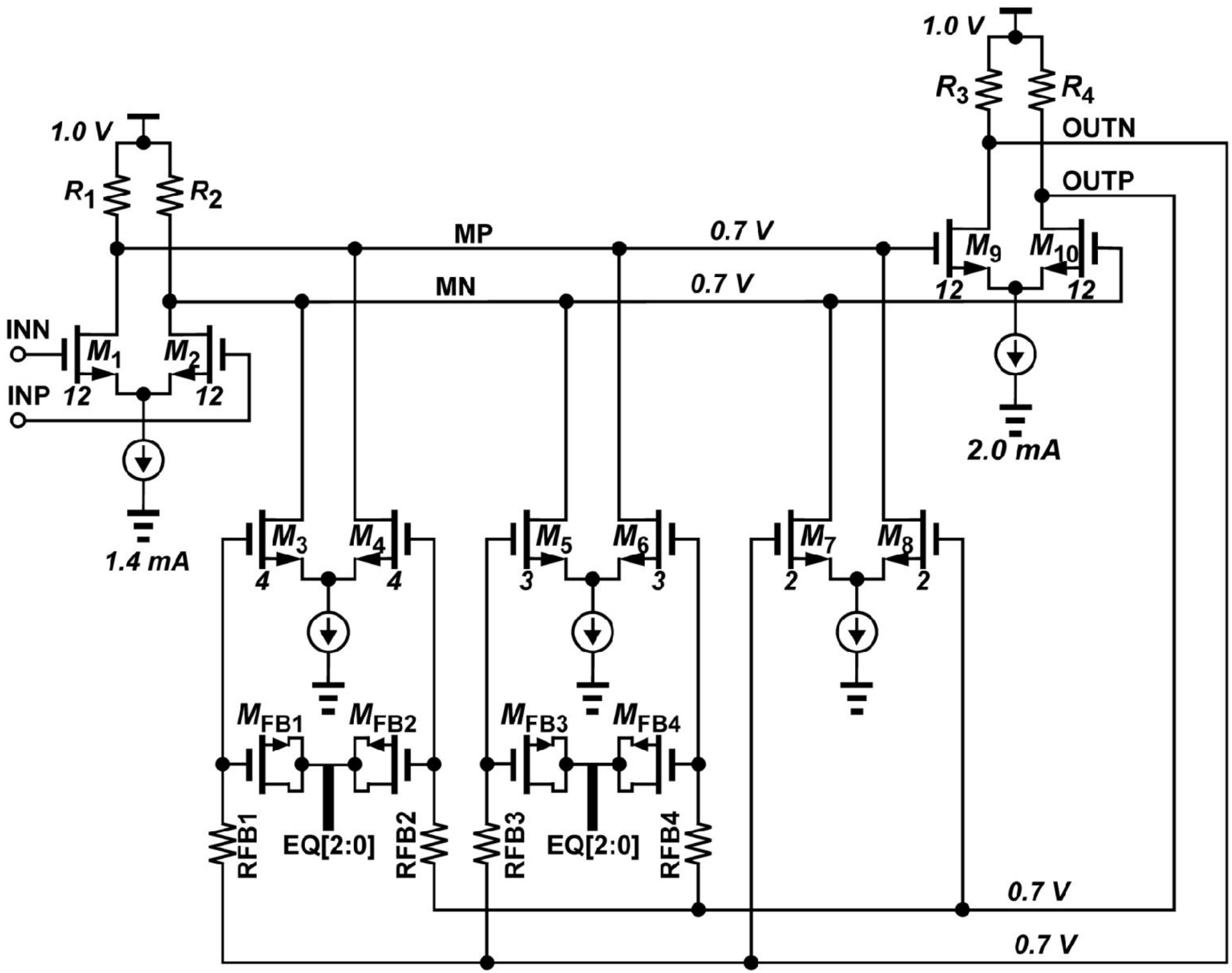
- For a given zero/pole pair, min. C_X is set by max. r_{ds4}
- r_{ds4} is reduced for smaller gate lengths
- Reduce I_{DC} helps, but offsets, noise, robustness
- Large C_X: difficulty in layout, degrades speed

CTLE w. Multi-Shunt-Shunt FB

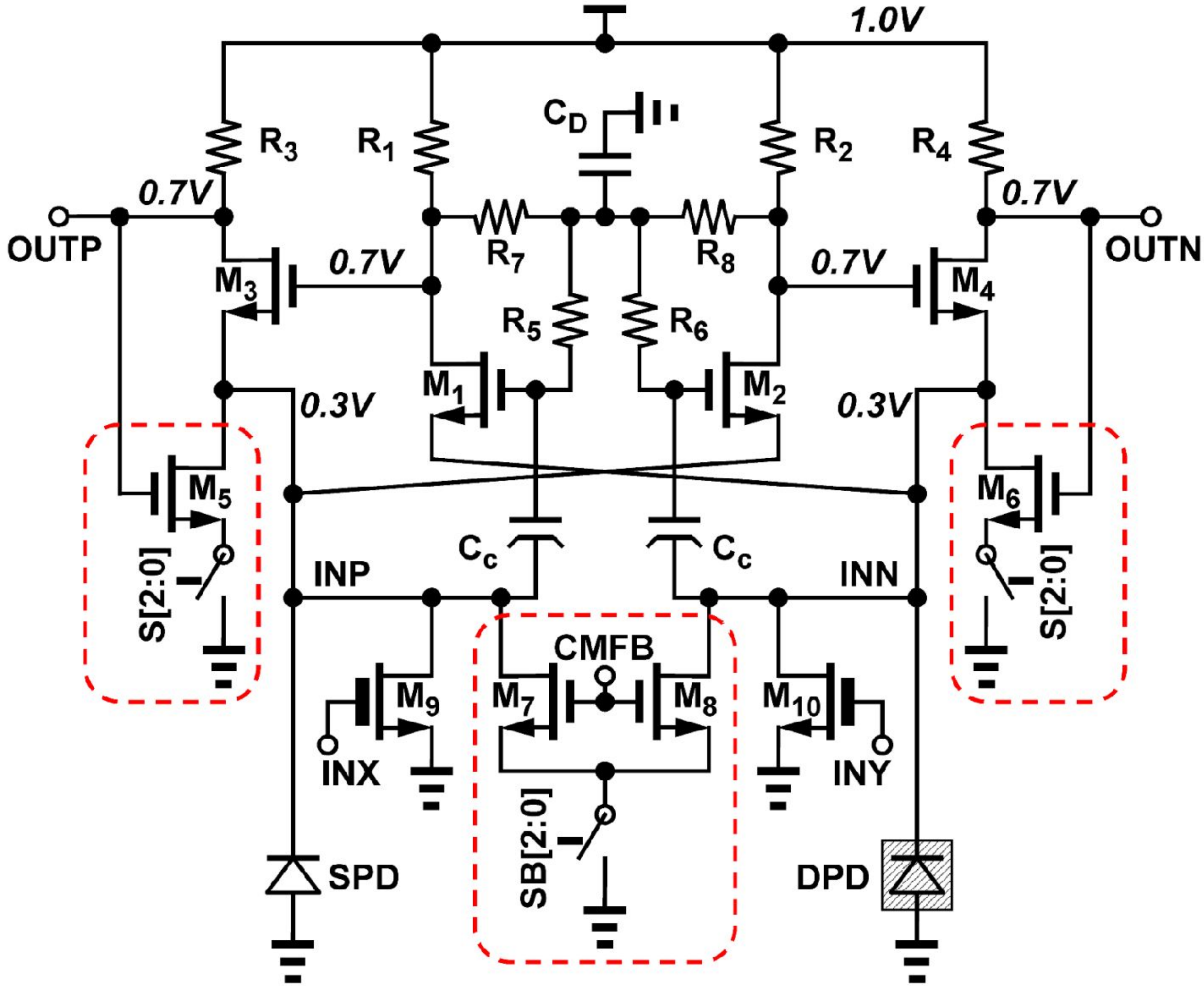


- At $f < f_{C1}$, $(G_{m3}+G_{m4}+G_{m5})$ Feedback
- At $f_{C1} < f < f_{C2}$, $(G_{m4}+G_{m5})$ Feedback
- At $f > f_{C2}$, (G_{m5}) Feedback

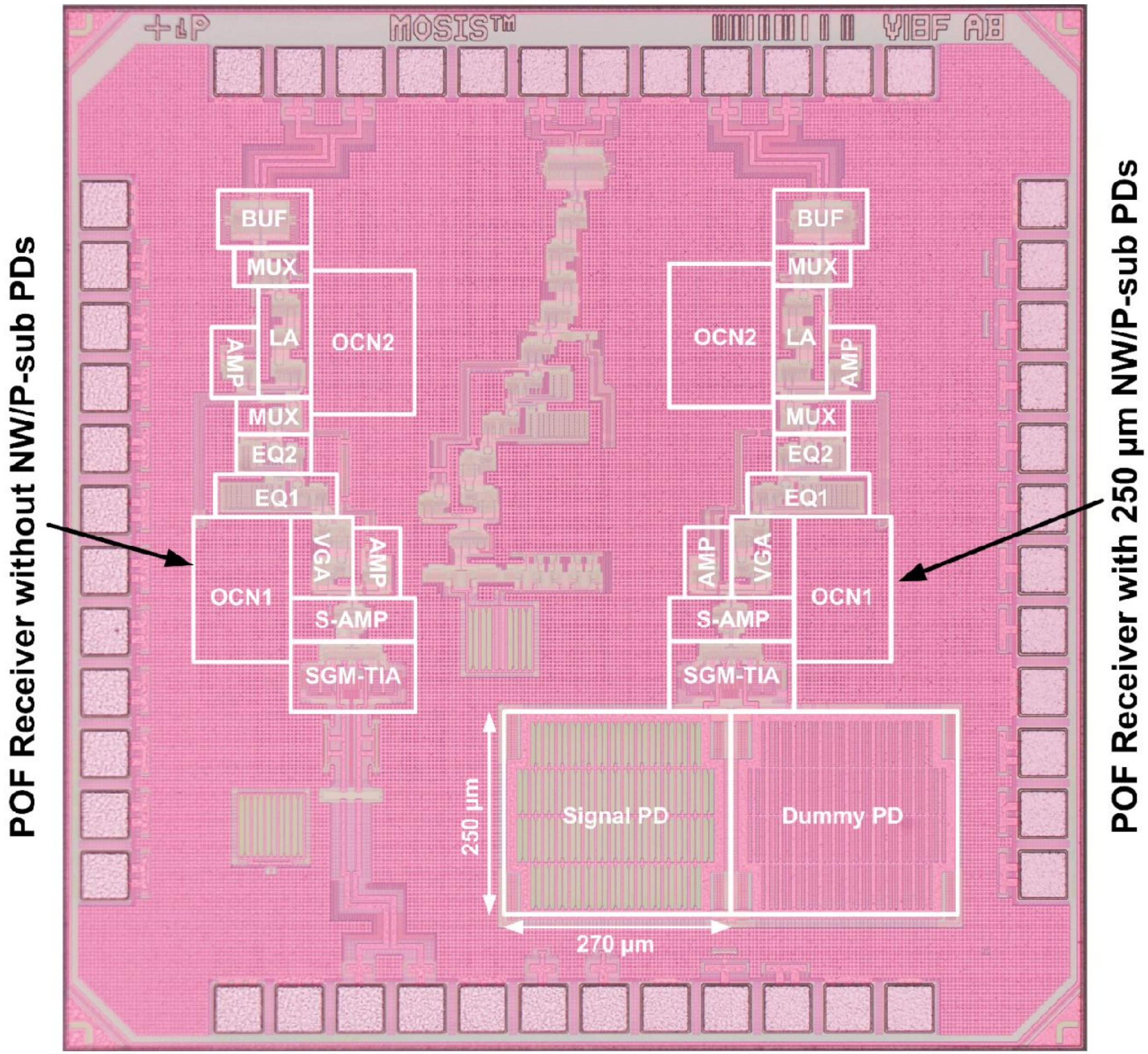
CTLE w. Multi-Shunt-Shunt FB



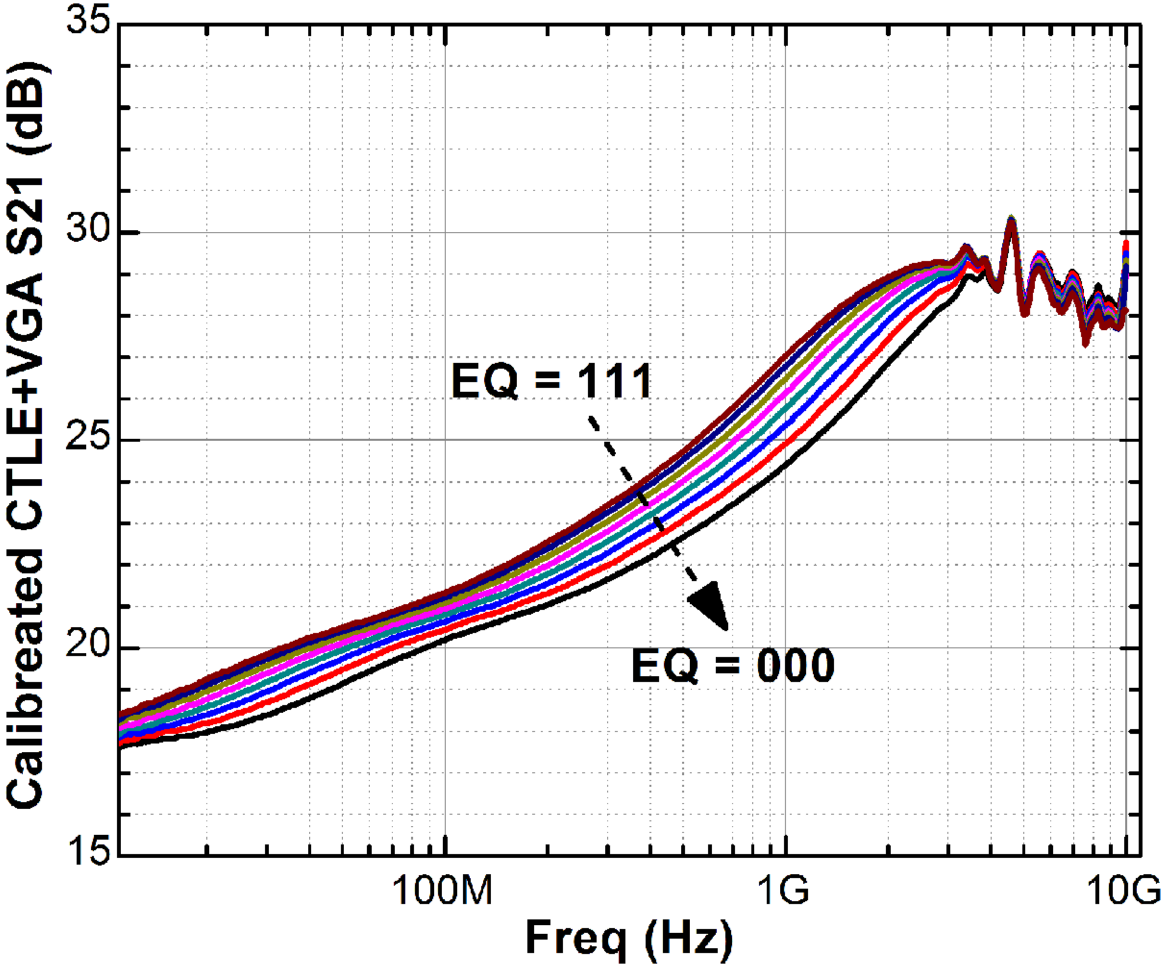
SGM-TIA w. Adjustable BW & Noise



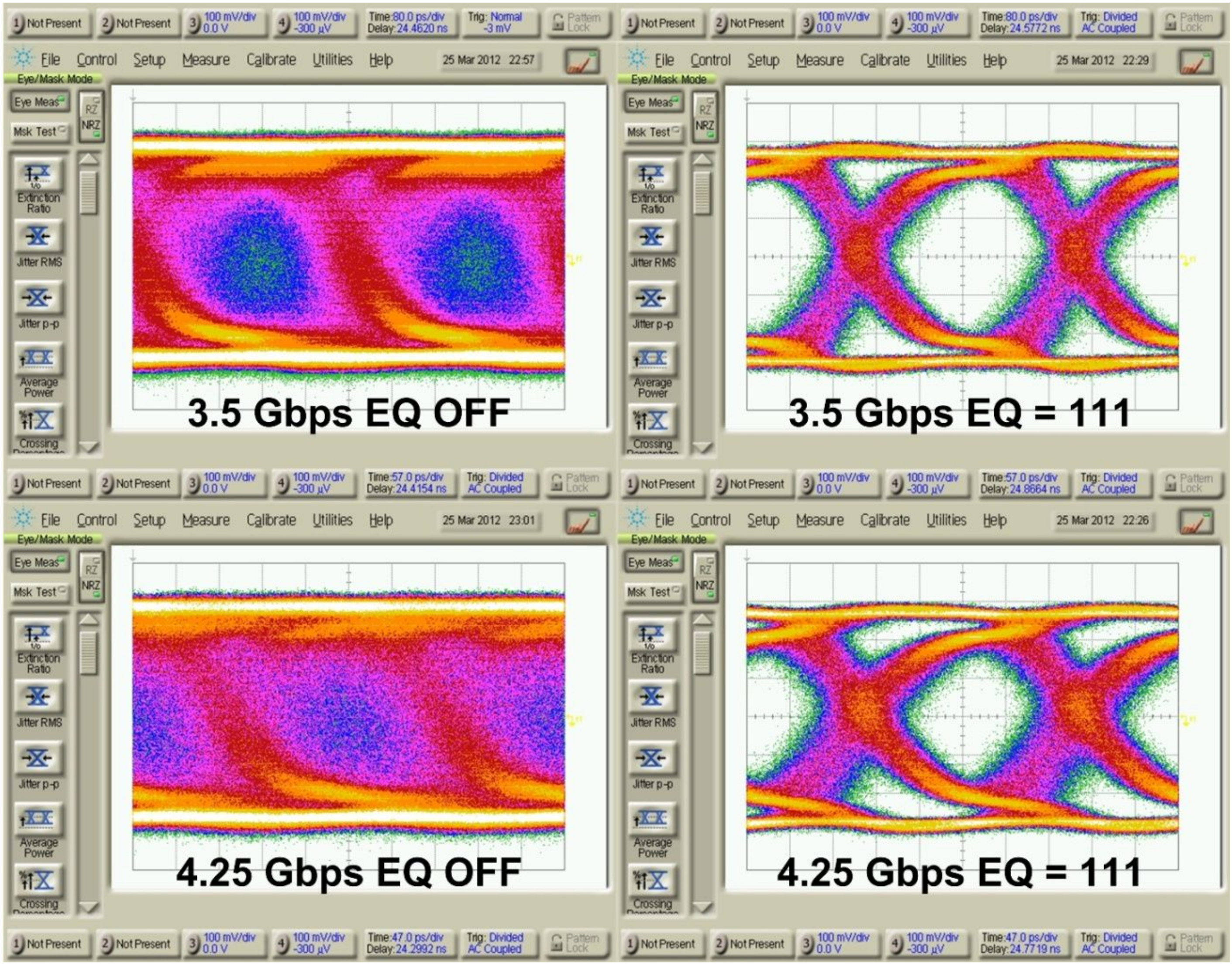
Test Chip 2 in TSMC 65 nm GP CMOS



Measured CTEQ w. MASSFB Boosts



Eye Diagrams w.o./w. CTEQ



Summary of Two Test Chips

	1st Implementation	2nd Implementation
Operating Wavelength λ	670 nm ± 10 nm	670 nm ± 10 nm
Technology	65 nm LP CMOS	65 nm GP CMOS
PD Structure	non-SML NW/P-Sub	non-SML NW/P-Sub
PD Diameter Φ	250 µm	250 µm
Photo Capacitance C_{PD}	14 pF	14 pF
BER	< 1e-12	NA
PRBS Sequence	2^{31}-1	2^{31}-1
Max Data Rate	3.125 Gb/s	4.25 Gbps*
Power Consumption	42 mA	46 mA
Supply Voltage	1.2 V	1.0 V
Total Active Chip Area	0.27 mm^2	0.24 mm^2
Sensitivity @ Max Data Rate	-3.8 dBm p-p*	-3.3 dBm p-p**

* This sensitivity value is extrapolated to the expected power levels had 55% of the photo detector not been inadvertently covered by the salicide layer

** Not verified with a BERT, based on output eye diagrams

Discussions

- Integrated PDs are good for applications were POF lengths are less than 30m; but, off-chip VCSELs are still needed
- Off-chip PDs allow for operation at 850nm which has cheaper more available detectors, VCSELs, better POF etc.
- Off-chip arrays of detectors and VCSELs in a GaAs chip connected to a TSMC40G chip (using copper pillars in a chip-on-chip) with arrays of receivers and SERDESs for data compression is compelling. I believe this is coming; it's just a matter of who will develop it and when.
- A sub-micron TSMC40G chip, under an optical chip, could contain many digital circuits in addition to receivers.
- Assuming the POF connector was cheap (it’s only plastic), the over-all cost is probably below $10 for a very fast channel.

Conclusions

- ❑ Sending hundreds of Gbs over POF is coming and it should be inexpensive; this could enable applications such as high-resolution video and optical back-planes in server farms.
- ❑ There are no significant bottle-necks that can't be solved; there is still much “engineering and development” and hard work needed, perhaps as much in “plastic packaging” as anything else.
- ❑ This could be a good area of research for a Mexican industrial/university collaboration with a number of different groups involved. The impact on the country compared to the necessary funding should be large.