Single-Event Transient Tolerant Optical Receiver Using Triple Modular Redundancy

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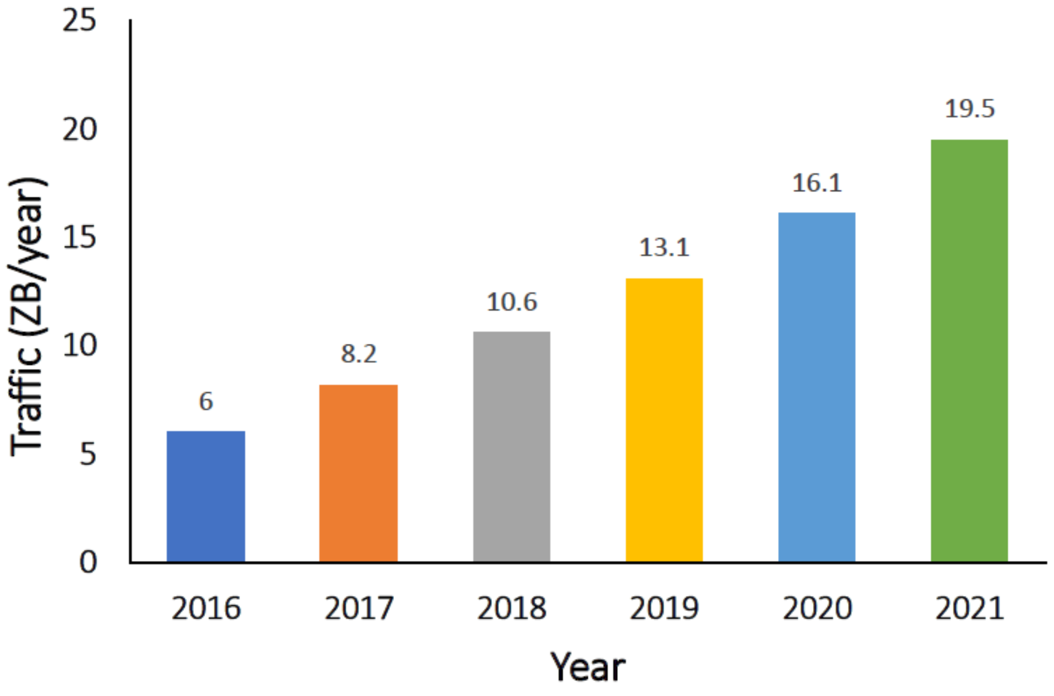
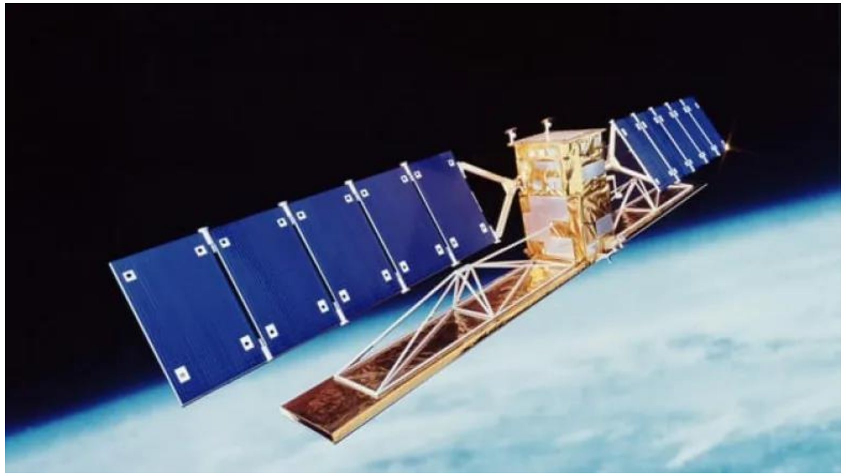
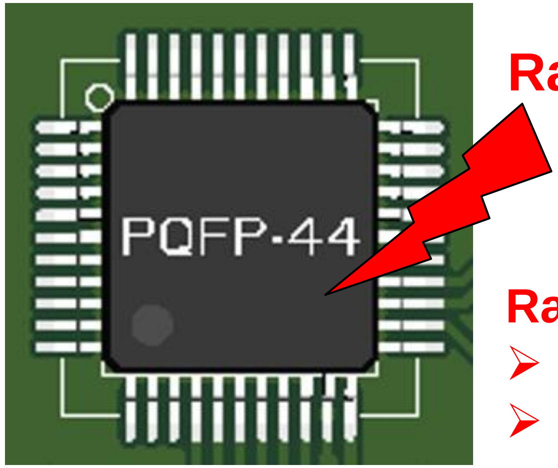
Motivation



Global Cloud Traffic Growth (Cisco)



Space Satellite



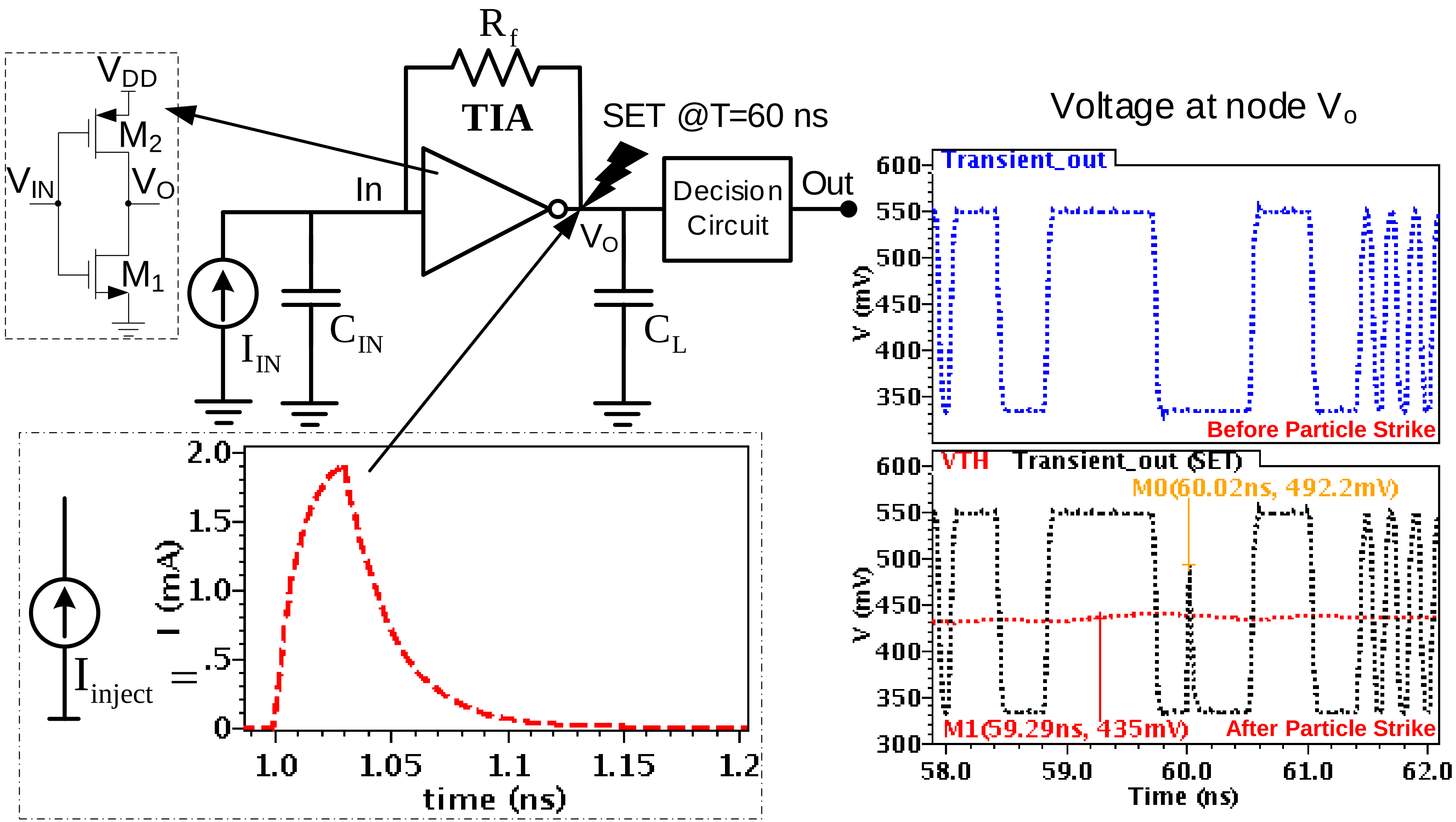
Chip Package

Radiation Particle Strike

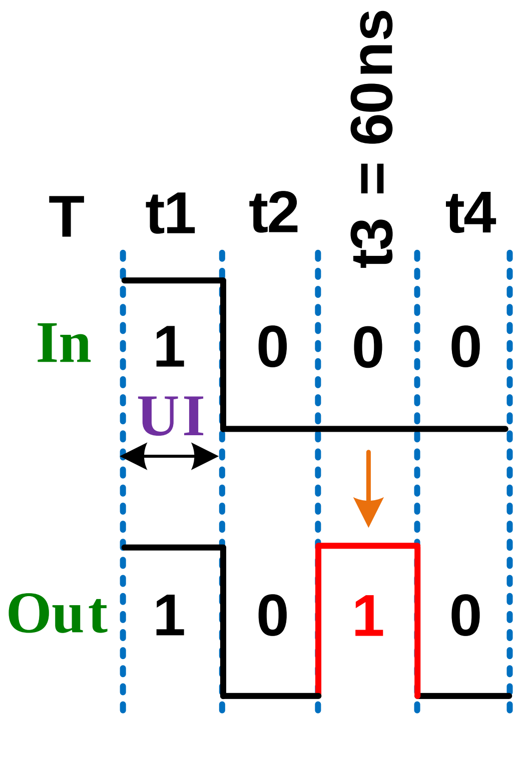
Radiation errors: e.g.

- **Single-event transients**
- **Total ionizing dose effects**

Problem with conventional Optical Receiver



Simplified Schematic of Conventional Optical Receiver and SET



Digital Output

Objectives

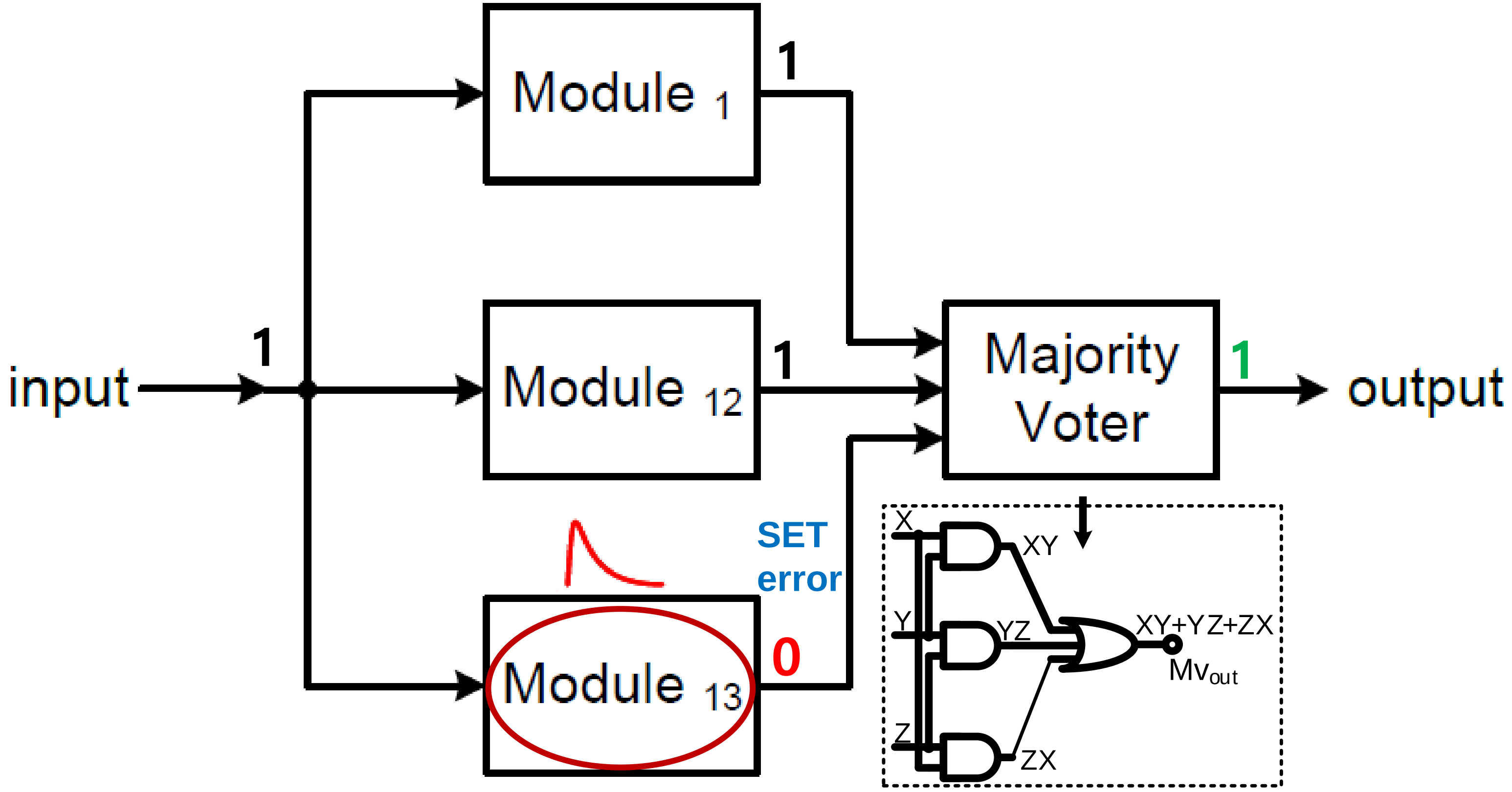
1. **To design an optical receiver which tolerates radiation induced single -event transient errors.**

2. **Minimal performance degradation in gain, bandwidth, sensitivity and an overall power dissipation.**

DESIGN SPECIFICATIONS OF THE PROPOSED RECEIVER

Transimpedance Gain	$\geq 75\ \mathrm{dB\Omega}$
Data Rate	$10\ \mathrm{Gbit\,s^{-1}}$
-3 dB Bandwidth	≈ 5 - $7\ \mathrm{GHz}$
Power Dissipation	$\leq 30\ \mathrm{mW}$
Single-Event Transient Tolerant	Yes

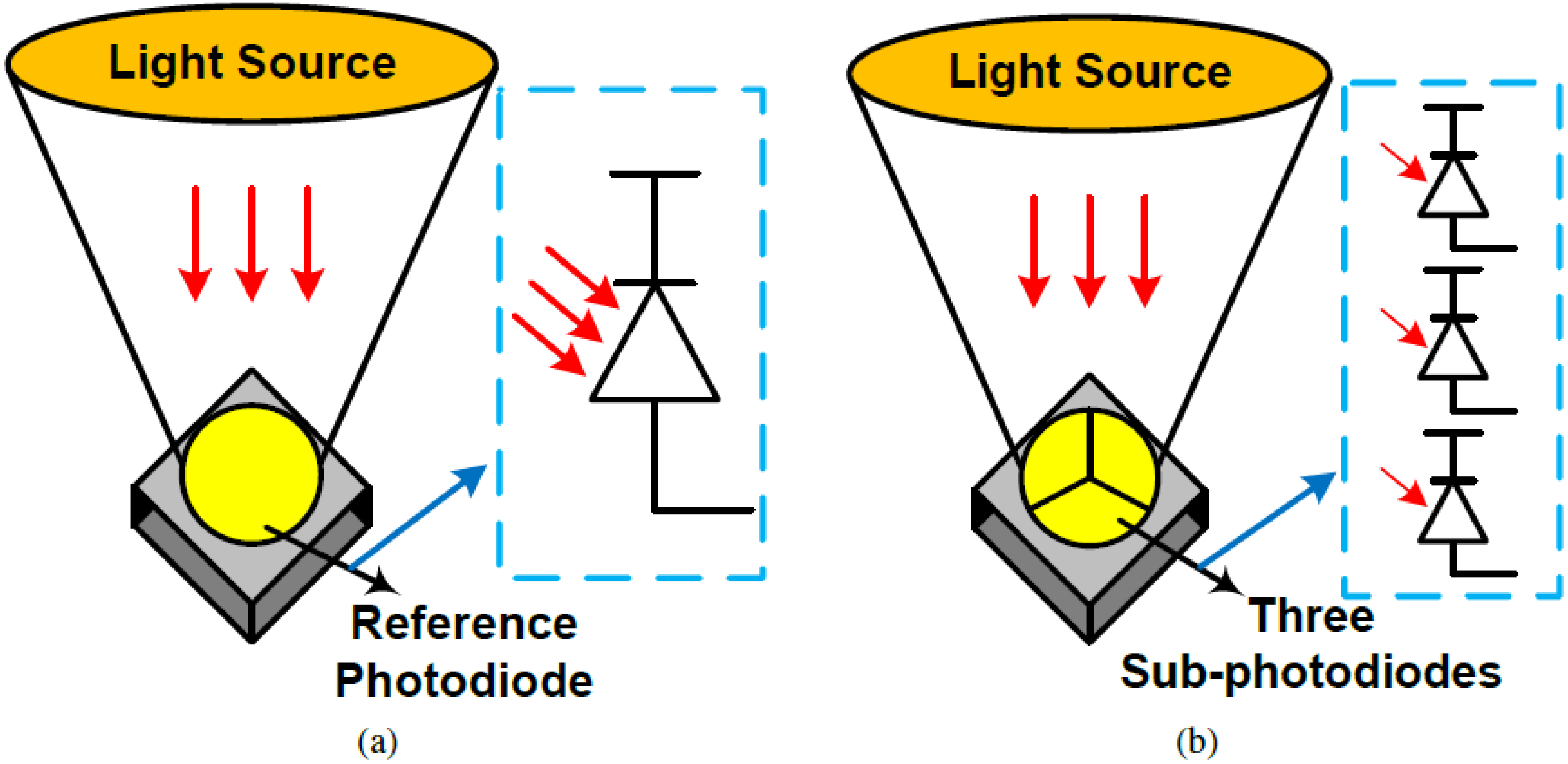
Fault Tolerance Using Triple Modular Redundancy



Triple Modular Redundancy (TMR) Technique

- <u>Drawback</u>: Consumes 3 times larger area and power

Proposed Hypothesis



(a) Reference Photodiode, (b) Three sub-photodiodes

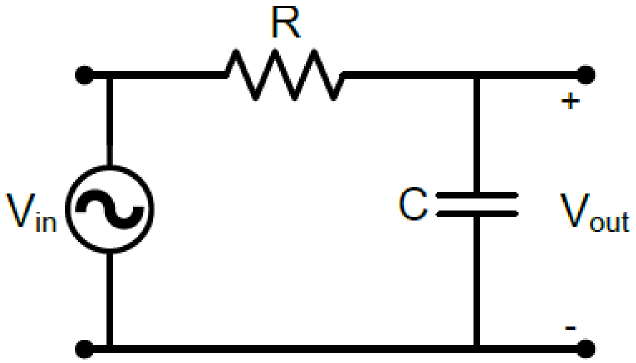
Impedance Scaling Technique[1]

- **Scale Impedances**
- **Scaling Factor**
- **VTF remains unchanged**
- **Frequency response remains unchanged**

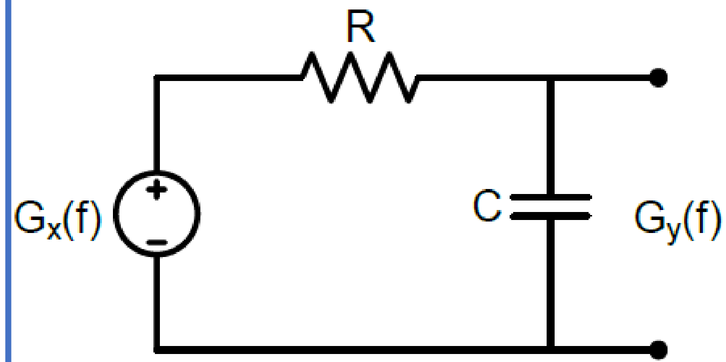
Circuit Elements	Assumptions
Capacitance	÷ by M
Resistance	× by M
Inductance	× by M

(M=Scaling Factor)

Example



RC Low Pass Filter



Noise Equivalent Model of RC Filter

Circuit Elements and Performance Summary

Before Impedance Scaling

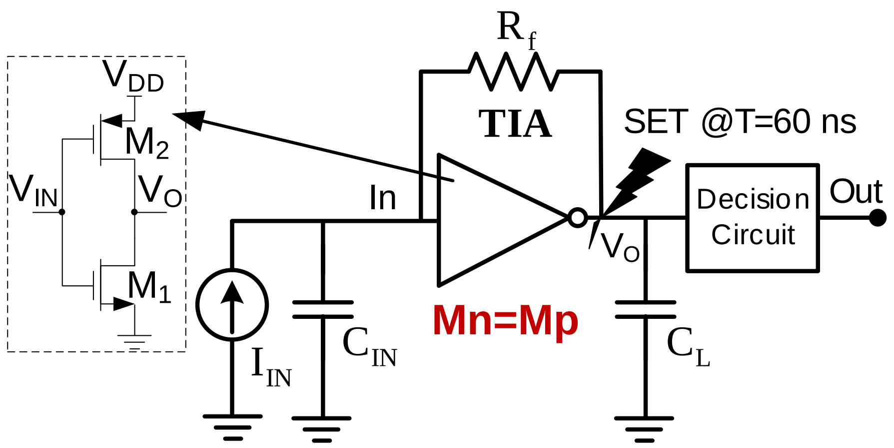
- $R = 3.2\ k\Omega$, $C = 10\ nF$
- $f_{-3dB} = 5\ kHz$
- MS output noise = $26.39\ aV^2/Hz$
- RMS output noise = 610.8 nV

After Impedance Scaling (M = 3)

- $R = 9.6\ k\Omega$, $C = 3.34\ nF$
- $f_{-3dB} = 5\ kHz$
- MS output noise = $79.17\ aV^2/Hz$
- RMS output noise = $1.058\ \mu V$

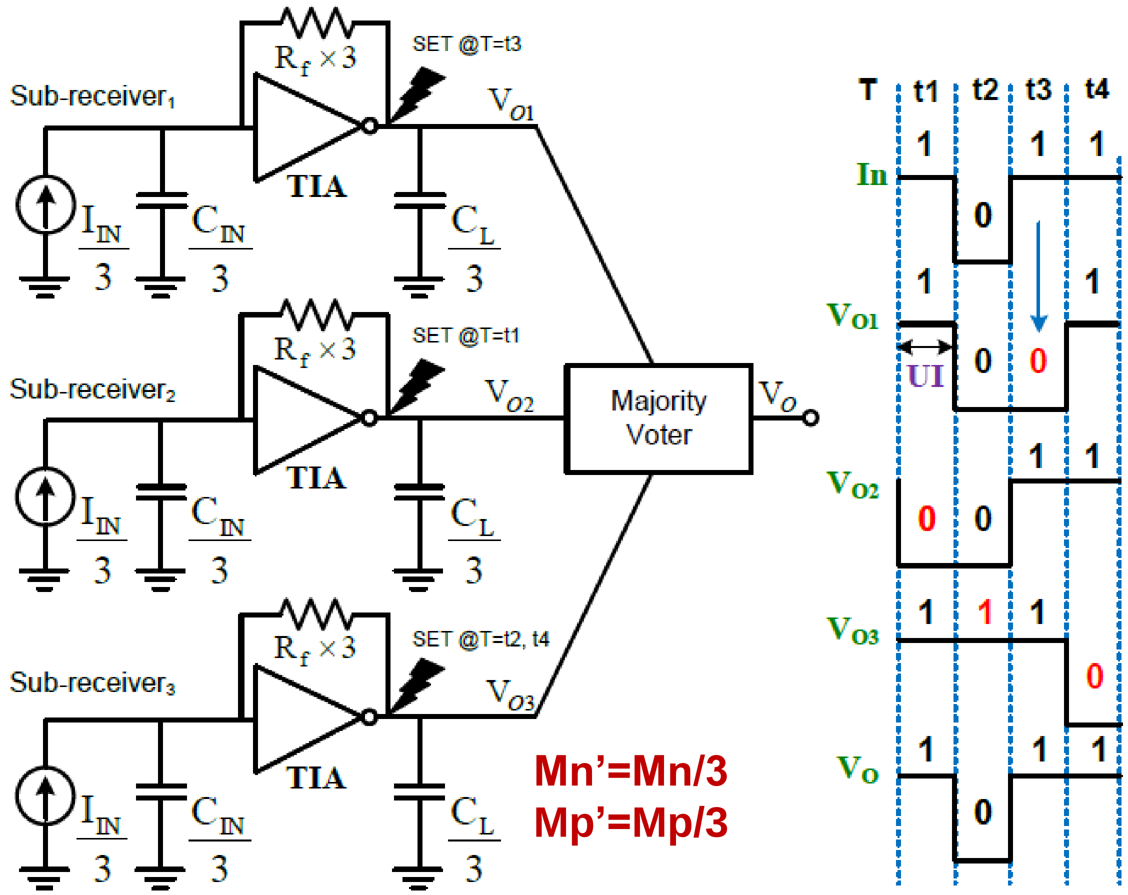
[1]- R. Raut and M. N. S. Swamy, "Modern Analog Filter Analysis and Design: A Practical Approach," Germany, Wiley, 2011.

Proposed Hypothesis Cont'd



Simplified Schematic of Conventional Receiver

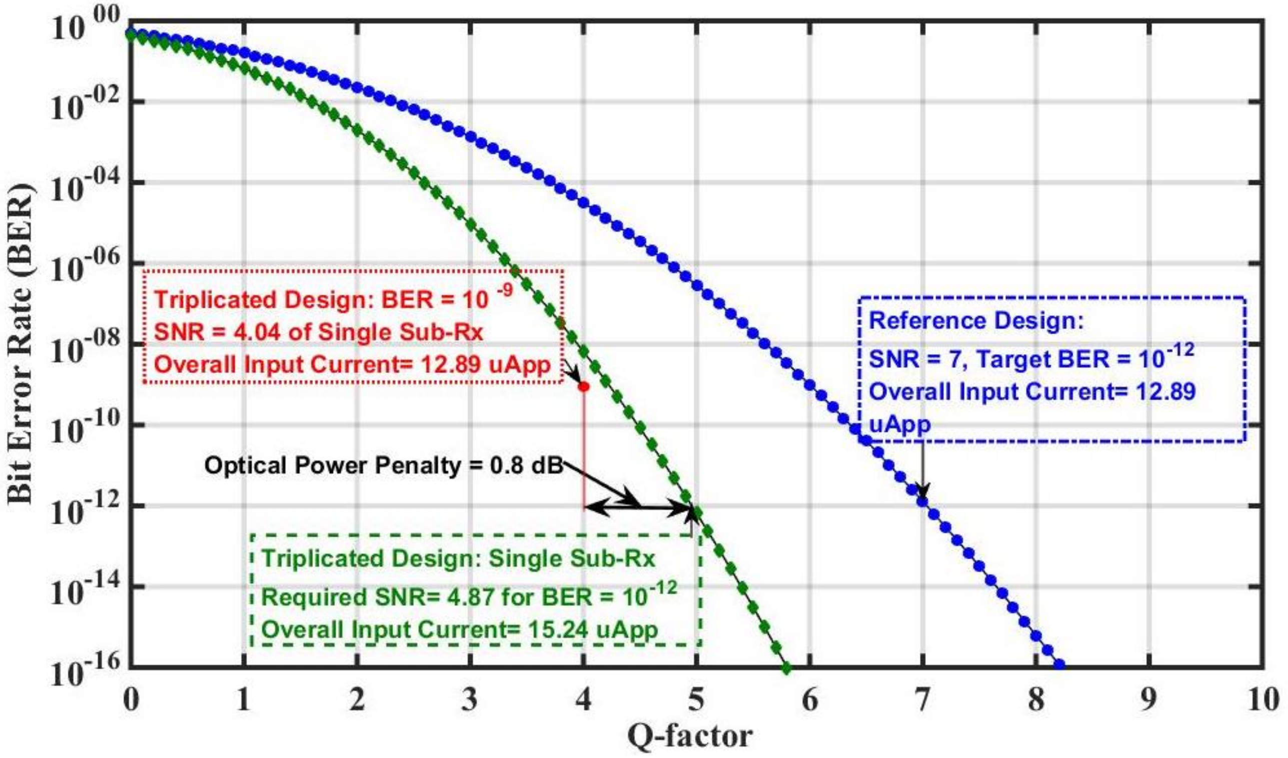
Triplicated Receiver Design



Simplified Schematic of Triplicated Receiver

- Three identical impedance scaled sub-receivers in parallel
- Similar Area, Power Dissipation as the conventional design
- TMR removes errors due to SETs
- TMR can improve BER of sub-receivers

Triplicated Receiver Bit-Error Rate (BER)



Sensitivity of Conventional and Triplicated Design

Consideration: Required BER of 10^{-12}

BER of a conventional receiver = z

Where $z(x) = \frac{1}{x\sqrt{2\pi}} e^{\frac{-x^2}{2}}$ [2], $x = SNR(Q\ factor)$

And $z(7) \approx 10^{-12}$

BER of a triplicated receiver $\approx 3z^2$

$\approx 3(\text{BER}_{\text{sub-receiver}})^2$

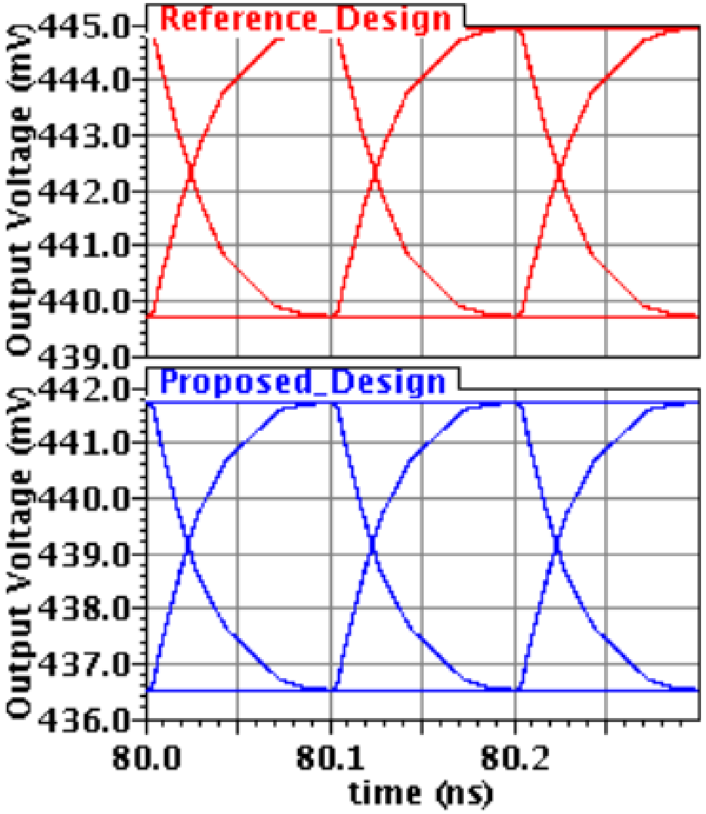
$\text{BER}_{\text{sub-receiver}} \approx 5.773 \times 10^{-7}$

Required SNR/sub-receiver $= 4.87$

$\text{SNR}_{\text{sub-receiver}} = 4.04$

Optical power penalty $= 10 \log \frac{4.87}{4.04}\ \text{dB} = 0.8\ \text{dB}$

Comparison of Conventional and Triplicated Design



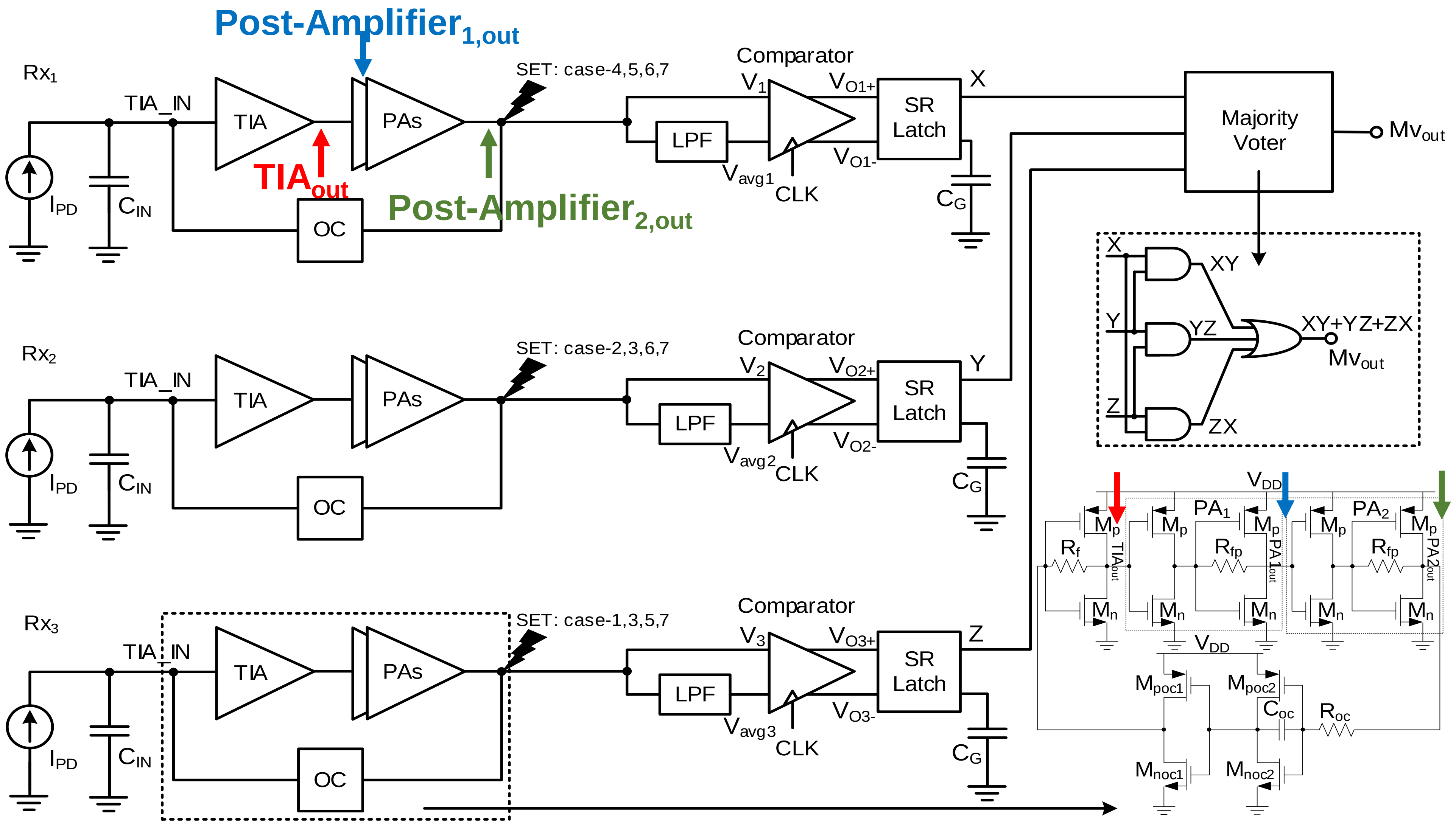
Transient Response of Convent -ional and Triplicated Design

RESULTS SUMMARY OF CONVENTIONAL AND TRIPLICATED DESIGN

Parameters	Reference Design	Proposed Hypothesis	Triplicated Design[b]
Data Rate [Gbps]	10	10	10
Z_{TIA} [Ω]	400	$Z_{\mathrm{TIA,ref}}$	400
BW [GHz]	7.31	$\mathrm{BW_{ref}}$	7.25
Pdc [mW]	2.20	$\mathrm{Pdc_{ref}}/3 = 0.734$	0.73 **(×3 = 2.19)**
$v_{n,rms}$ [μV]	372.8	$\sqrt{3} \times v_{n,ref} = 645.7$	631.1
Iin_{pp} [μA]	12.89	$\mathrm{Iin_{ref}}/3 = 4.296$	4.29
VEO_{pp} [mV]	5.216	$\mathrm{VEO_{ref}}$	5.19
SNR	7.0	4.04	4.1
SNR[a]	7.0	4.87	4.87
Power penalty [dB]	-	0.8	0.8

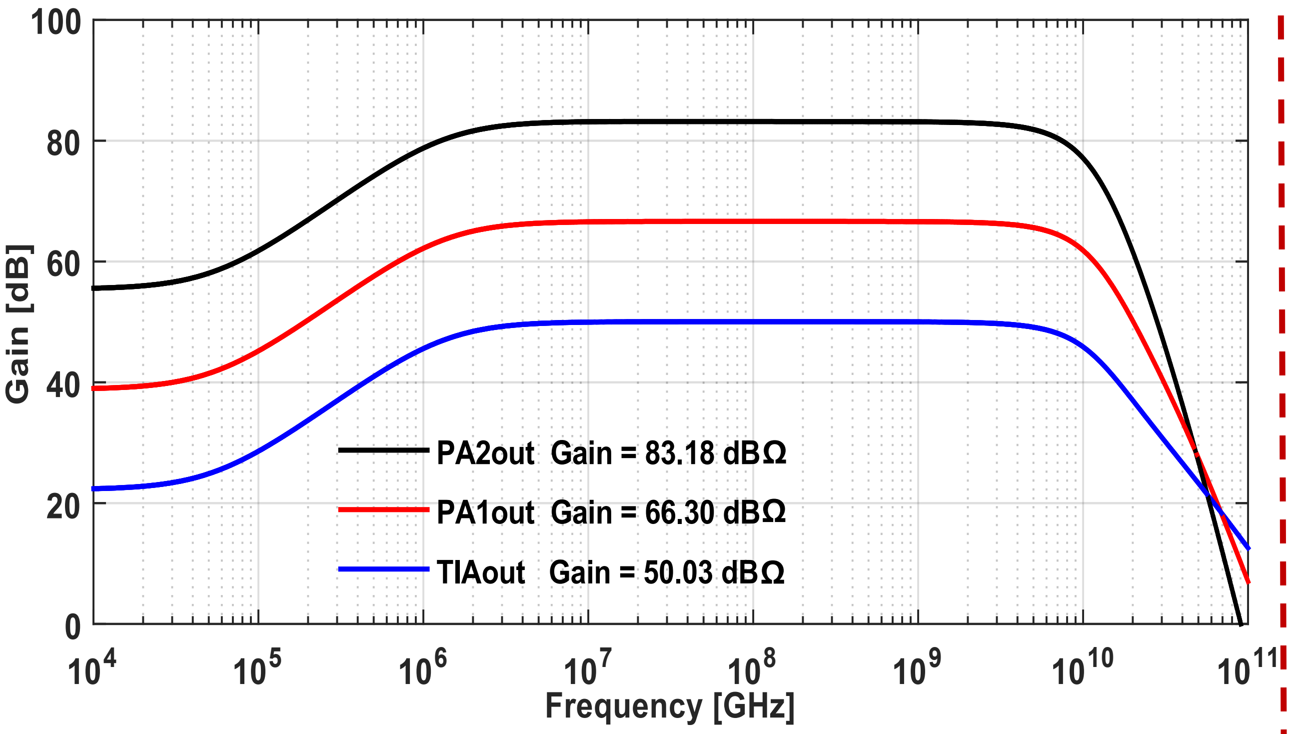
[a]SNR required to achieve the BER of 10^{-12}, [b]Values of a single sub-receiver

Complete Design of a Proposed Receiver

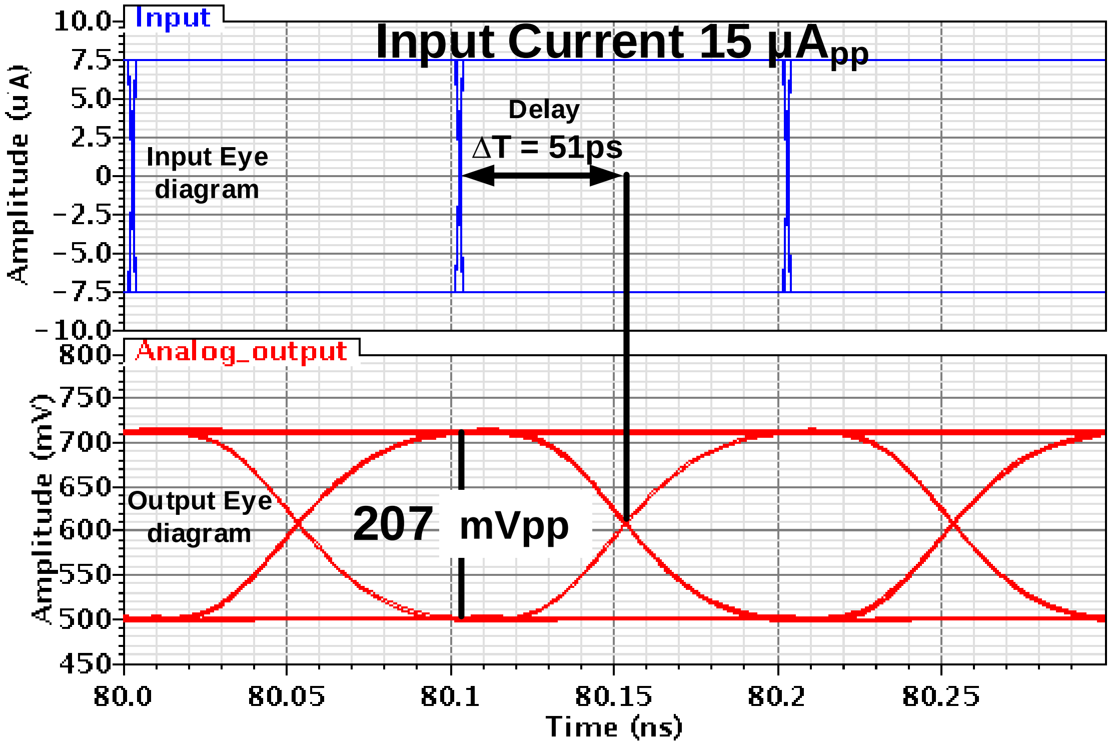


$W_n = W_p = 23$ µm, $W_{noc1} = W_{poc1} = 200$ nm, $W_{noc2} = W_{poc2} = 2.5$ µm, $R_f = R_{fp} = 400$ Ω, $R_{oc} = 440$ kΩ, $C_{IN} = 200$ fF, $C_{oc} = 1$ pF, $C_G = 10$ fF

Frequency and Transient Response



Frequency Response of the Proposed Receiver

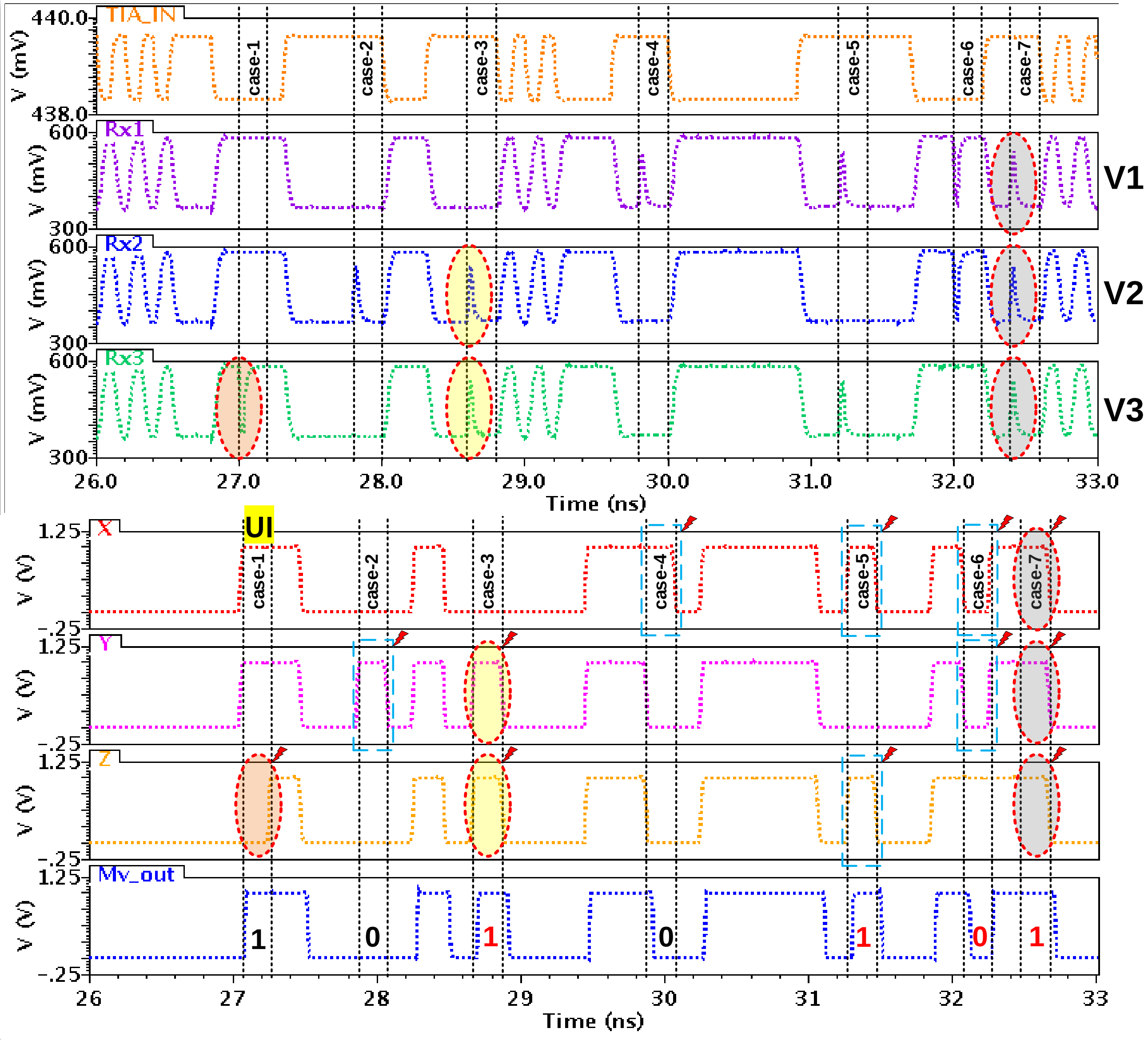


Eye-Diagram of the Proposed Receiver

Data Rate =10 Gbps
Gain = 83 dBΩ
Bandwidth = 7.2 GHz
Lower cut-off frequency = 31 MHz

VEO= 207 mVpp at Iin=15 µApp
ISI = 6 mVpp

SET Simulation Results



- Injected Current > 2 mA at node V1,V2,V3
- V1,V2,V3 output nodes of analog front-end

Example of SETs Occurrence

- Case-1/2/4: One Rx has SET event in 1 UI
- Case-3/5/6: Two Rxs have SET concurrently
- Case-7: All three Rxs have SET concurrently

SIMULATION AND MAJORITY VOTER RESULTS

Case	TIA_{input}	V1	V2	V3	Mv_{out}	Error	Comments
1	0	1	1	0	1	1	error removed
2	1	0	1	0	0	1	error removed
3	1	0	1	1	1	2	error propagated
4	1	1	0	0	0	1	error removed
5	1	1	0	1	1	2	error propagated
6	0	0	0	1	0	2	error propagated
7	1	1	1	1	1	3	error propagated

Inverted version of TIA_{input}

Summary of Results Comparison

RESULTS COMPARISON

References	This Work	[4]*-2019	[5]*-2013	[6]*-2019
Bit Rate [Gb/s]	10	2.56	5	10
Gain [dBΩ]	83.18	-	86	68.3
Bandwidth [GHz]	7.2	-	-	8.5
$I_{in,rms}$ [µA]	0.93	-	-	0.97
Power Dissipation [mW]	33	70	120	81
Supply Voltage [V]	1.0	2.5	2.5	1.8
Technology [nm]	65	65	130	180
Type of Tolerance	SET	TID	TID	None
*Measurement Results				

[4]-M. Menouni et al., “The lpGBTIA, a 2.5 Gbps Radiation-Tolerant Optical Receiver using InGaAs photodetector,” *Topical Workshop on Electronics for Particle Physics*, Sep 2019, Santiago de Compostela, Spain. pp.030, ⟨10.22323/1.370.0030⟩. ⟨hal-0257251)

[5]-M. Menouni, T. Xi, P. Gui, and P. Moreira, “A 5-Gb/s Radiation-Tolerant CMOS Optical Receiver,” *in IEEE Transactions on Nuclear Science*, vol. 60, no. 4, pp. 3104-3109, Aug. 2013, doi: 10.1109/TNS.2013.2264477

[6]-D. Li et al., “Low-Noise Broadband CMOS TIA Based on Multi-Stage Stagger-Tuned Amplifier for High-Speed High-Sensitivity Optical Communication,” *in IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 66, no. 10, pp. 3676-3689, Oct. 2019, doi: 10.1109/TCSI.2019.2916150

Conclusions

1. A new single event transient tolerant optical receiver is proposed and implemented in a 65 nm CMOS.

2. The proposed receiver use a TMR technique for radiation hardening.

3. An impedance scaling technique helps to maintain the gain, bandwidth, and an overall power dissipation similar to the reference design.

4. The proposed receiver removes the bit errors at the cost of 0.8 dB sensitivity degradation.

5. The proposed receiver removes the bit error if and only if single sub-receiver has SET in one UI.

References

[1]- R. Raut and M. N. S. Swamy, “Modern Analog Filter Analysis and Design: A Practical Approach,” Germany, Wiley, 2011.

[2]- B. Razavi, “Design of integrated circuits for optical communications,” John Wiley and Sons, 2012.

[3]- D. G. Toro, “Temporal Filtering with Soft Error Detection and Correction Technique for Radiation Hardening Based on a C-element and BICS,” *PhD Thesis, Universite de Bretagne ´* Occidentale, 2014.

[4]- M. Menouni et al., “The lpGBTIA, a 2.5 Gbps Radiation-Tolerant Optical Receiver using InGaAs photodetector,” *Topical Workshop on Electronics for Particle Physics*, Sep 2019, Santiago de Compostela, Spain. pp.030, ⟨10.22323/1.370.0030⟩. (hal-0257251)

[5]- M. Menouni, T. Xi, P. Gui, and P. Moreira, “A 5-Gb/s Radiation-Tolerant CMOS Optical Receiver,” *in IEEE Transactions on Nuclear Science*, vol. 60, no. 4, pp. 3104-3109, Aug. 2013, doi: 10.1109/TNS.2013.2264477

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THANK YOU!
Q & A