Electronics-Friendly
Si Micro-Ring Modulator Models

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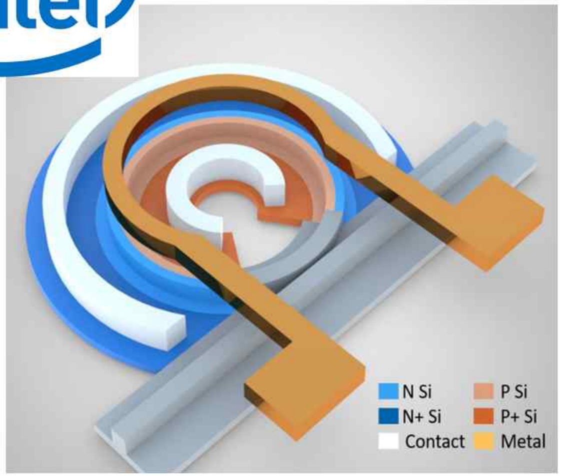
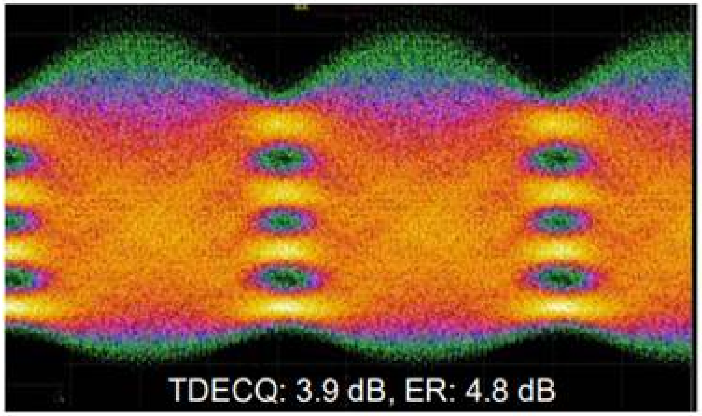
Si-MRM: State of the Art

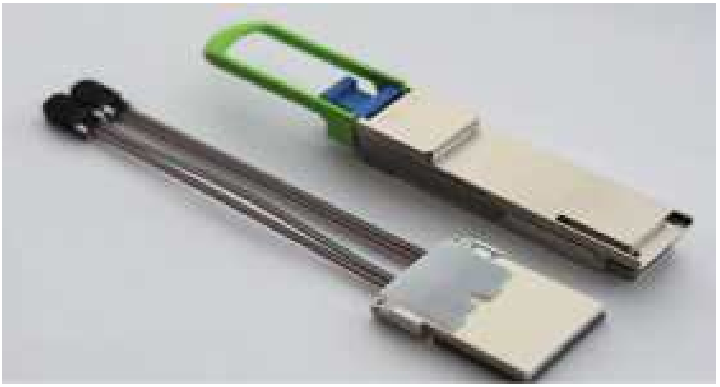


PAM4 240Gbps



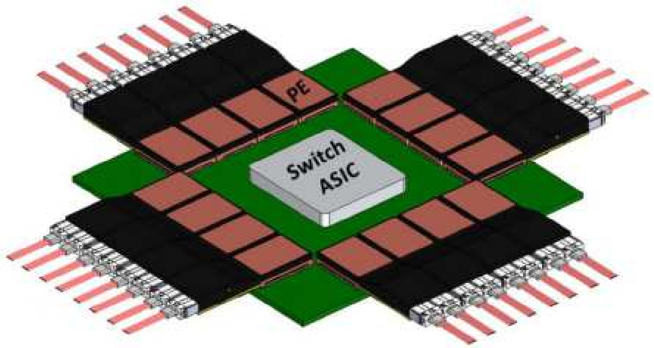
(CLEO 2022)

1.6Tbps Photonic Engine



16 x 100 Gbps =1.6 Tbps

Co-Packaged Optics



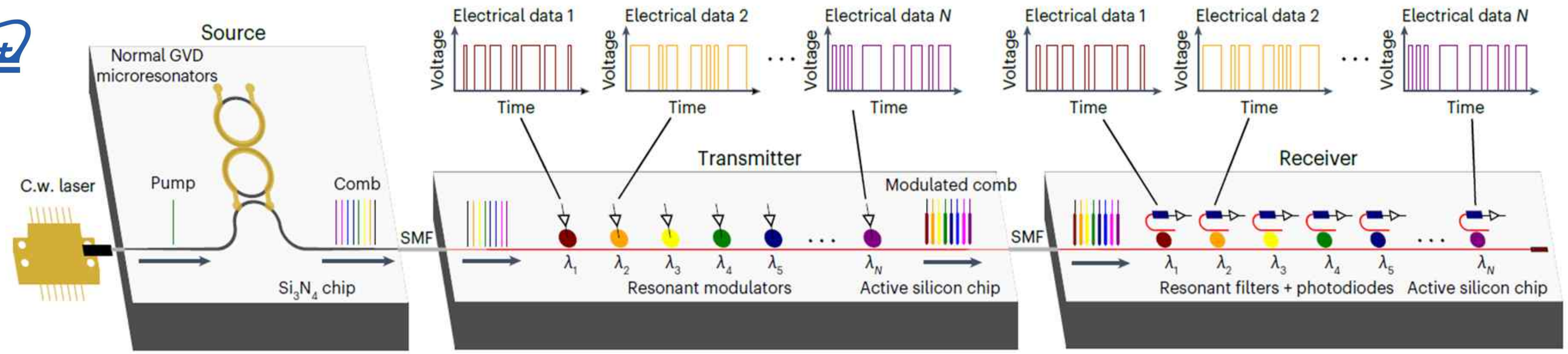
16 x 0.8 Tbps Photonic Engine
➔ 12.8 Tbps Ethernet Switch

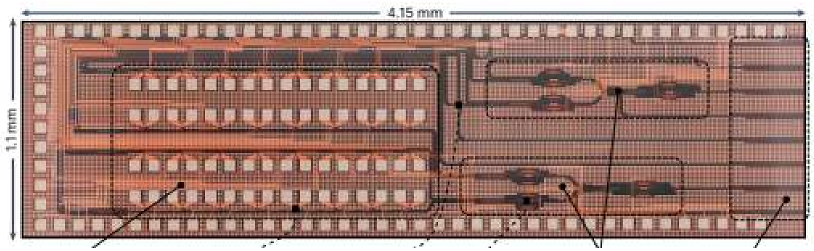
(JLT 2021)

Si-MRM: State of the Art

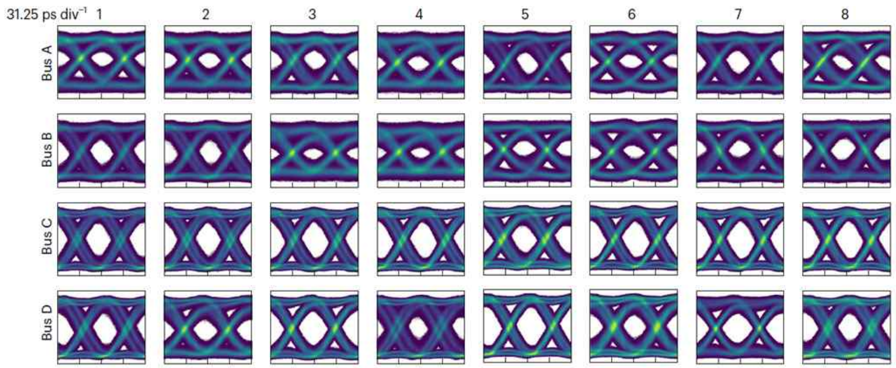
COLUMBIA UNIVERSITY

(Nature Photonics, 2023)





32 x 16Gbps



Applications:

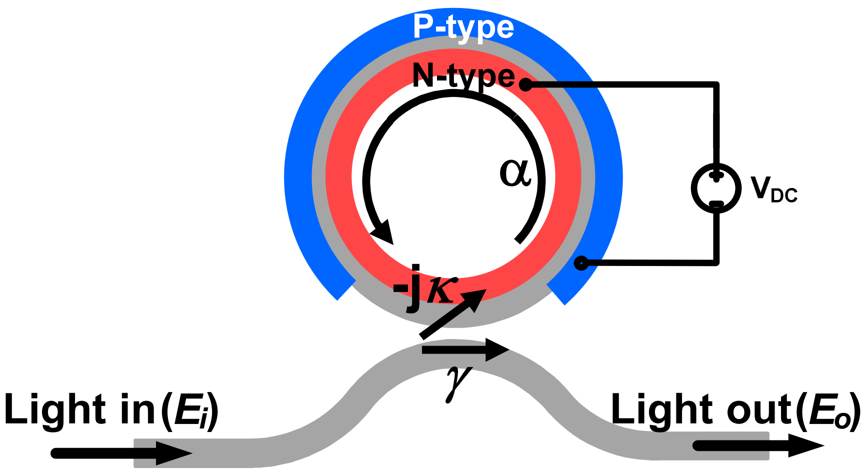
Optical I/O for ICs

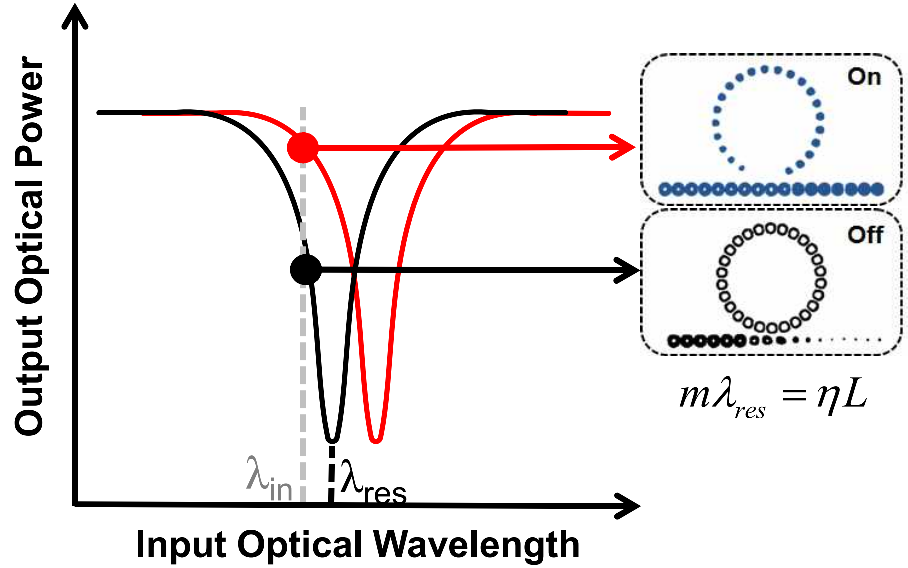
Energy efficiency
Bandwidth density

Co-design of electronics and photonics essential

➔ Electronics-friendly model for Si MRM

Si Micro-Ring Modulator

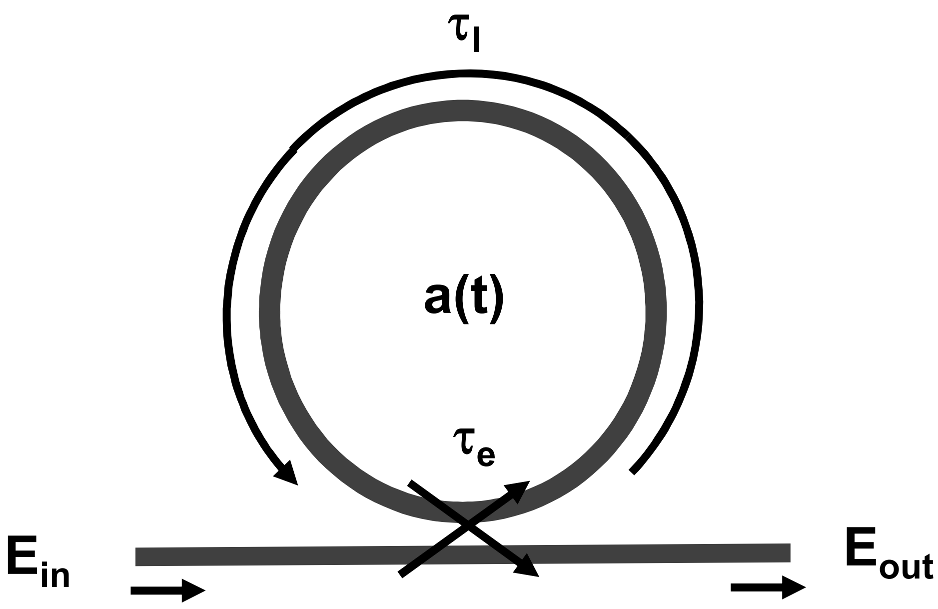




$$\frac{E_{out}}{E_{in}} = \gamma - \kappa^2 \sum_{n=1}^{\infty} \alpha^n \gamma^{n-1} \exp(-jn\theta) = \frac{\gamma - \alpha \exp(-j\theta)}{1 - \alpha\gamma \exp(-j\theta)} \quad \left(\theta = \frac{2\pi\eta L}{\lambda} \right)$$

Not convenient for *transient* simulation!

MRM CMT Model



$$\frac{d}{dt}a(t) = \left(j\omega_0 - \frac{1}{\tau_l} - \frac{1}{\tau_e}\right)a(t) - j\sqrt{\frac{2}{\tau_e}}E_{in}(t)$$

$$E_{out}(t) = E_{in}(t) - j\sqrt{\frac{2}{\tau_e}}a(t)$$

a(t) : optical amplitude inside the ring

τ_l : time constant for propagation loss $\quad Q_{unloaded} = \dfrac{\omega_0 \tau_l}{2}$

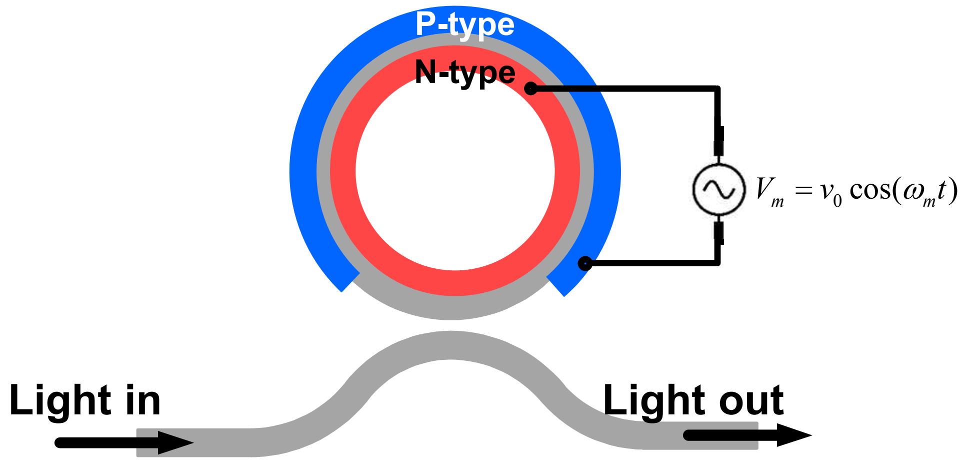
τ_e : time constant for coupling loss

$\left(\dfrac{1}{\tau} = \dfrac{1}{\tau_e} + \dfrac{1}{\tau_l} \right) \quad Q_{loaded} = \dfrac{\omega_0 \tau}{2}$

Numerical solution possible

But not very efficient

Small-Signal Linear Model

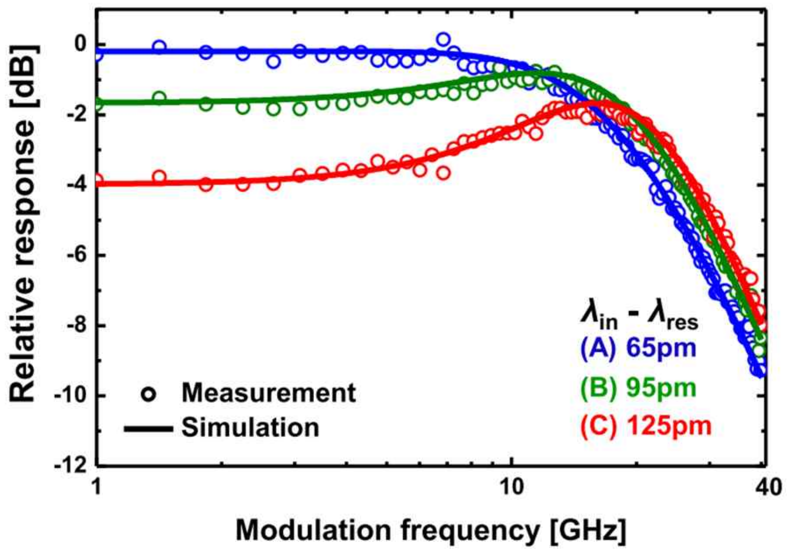


$$\frac{d}{dt}a(t) = \left(j\omega_0 - \frac{1}{\tau_l} - \frac{1}{\tau_e} \right) a(t) - j\sqrt{\frac{2}{\tau_e}} E_{in}(t)$$

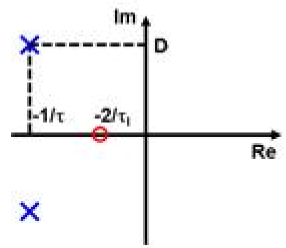
$$E_{out}(t) = E_{in}(t) - j\sqrt{\frac{2}{\tau_e}} a(t)$$

$$(D = \omega_{in} - \omega_0)$$

$$\frac{\Delta P_{out}}{\Delta V_m}(s) \sim \frac{2/\tau_e}{\eta_0} \cdot \frac{\partial \eta}{\partial V_m} \cdot \frac{2\omega_0 D}{D^2 + 1/\tau^2} \cdot \frac{s + 2/\tau_l}{(s + 1/\tau + jD)(s + 1/\tau - jD)}$$



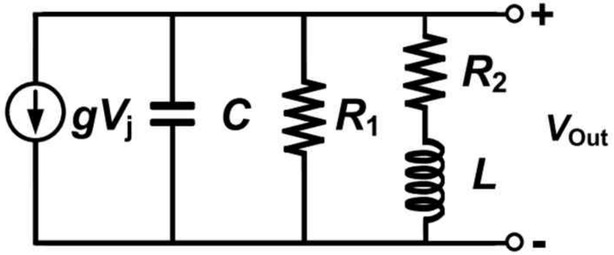
Shin et al., TED, 2017



(Ban, MS Thesis, 2015)

Equivalent Circuit

$$\frac{\Delta P_{out}}{\Delta V_m}(s) \sim \frac{2/\tau_e}{\eta_0} \cdot \frac{\partial \eta}{\partial V_m} \cdot \frac{2\omega_0 D}{D^2 + 1/\tau^2} \cdot \frac{s + 2/\tau_l}{s^2 + \frac{2}{\tau}s + \left(\frac{1}{\tau^2} - D^2\right)}$$



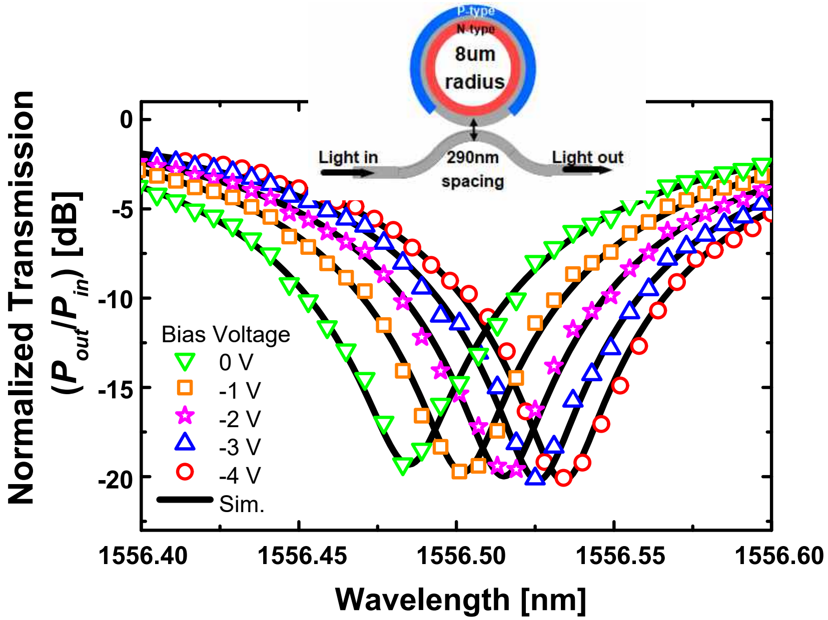
$$\frac{g}{C} \frac{s + \frac{R_2}{L}}{s^2 + \left(\frac{1}{CR_1} + \frac{R_2}{L}\right)s + \frac{1}{LC}\left(\frac{R_2}{R_1} + 1\right)}$$

$$R_1 C = \frac{\tau_e}{2}$$

$$\frac{L}{R_2} = \frac{\tau_l}{2}$$

$$\frac{R_1}{R_2} = [(1/\tau^2 + D^2)\tau_e \tau_l / 4 - 1]$$

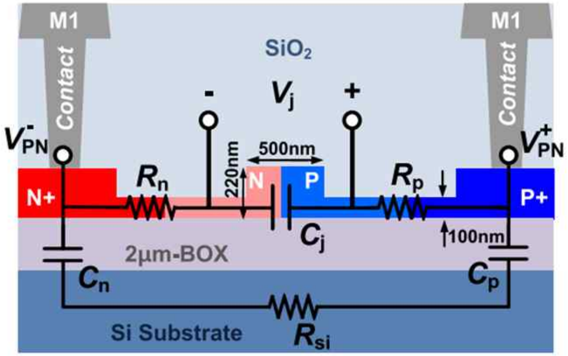
$$g = \frac{2}{\eta_0} \cdot \frac{\delta\eta}{\delta} \cdot \frac{\omega_r D}{D^2 + 1/\tau^2} \frac{1}{R_1}$$



V_{Bias} (V)	R_1 (kΩ)	C (fF)	R_2 (kΩ)	L (nH)
0	2.07	7.14	10.00	114.41
-1	3.15	4.70	9.96	
-2	5.15	2.87	9.71	
-3	7.19	2.06	9.71	
-4	8.99	1.65	9.71	

(Shin et al., TED 2017)

Equivalent Circuit



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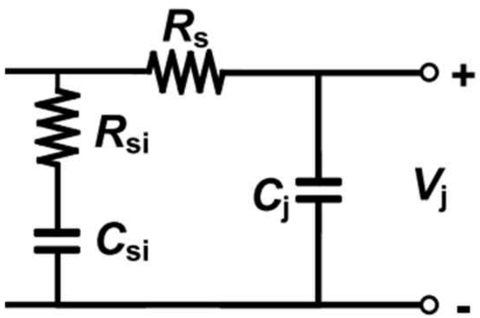
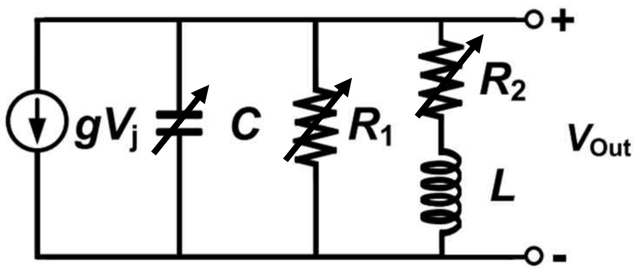
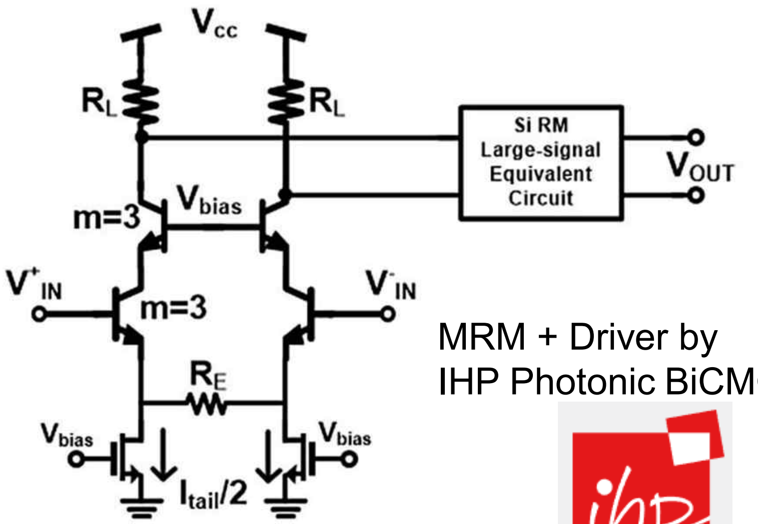


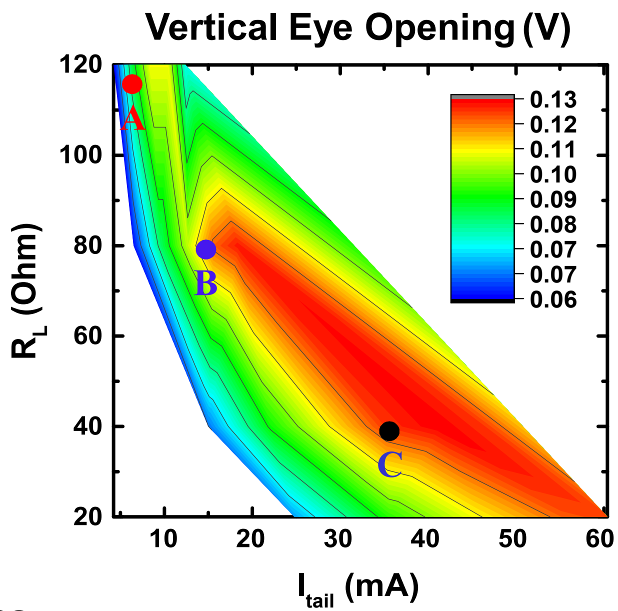


Very efficient piece-wise linear simulation in SPICE

Optical Transmitter Design Optimization

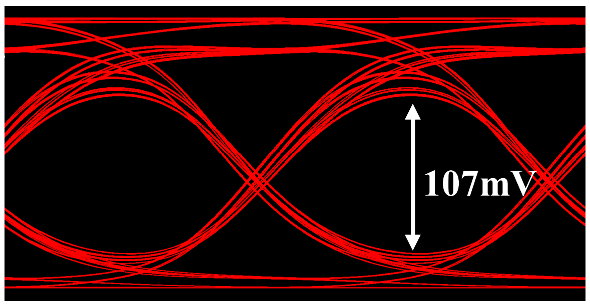


MRM + Driver by
IHP Photonic BiCMOS Tech.



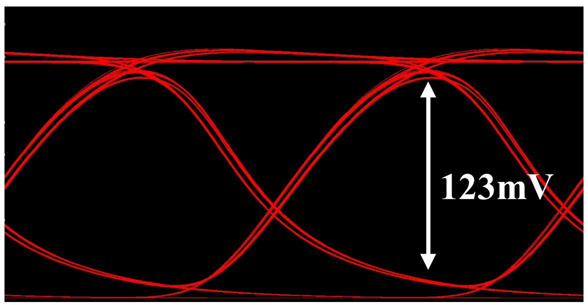
4V_{pp}, PRBS31, 25-Gbps

A (I_{tail} = 10.4mA)



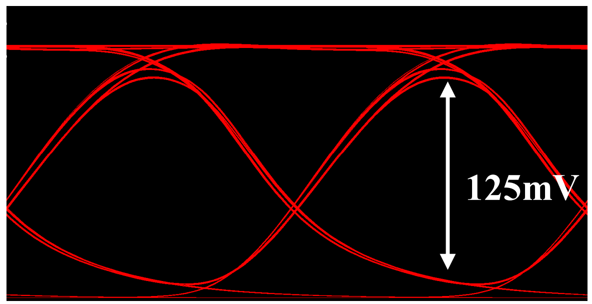
Large RC time constant

B (I_{tail} = 18.4mA)



(Optimum design)

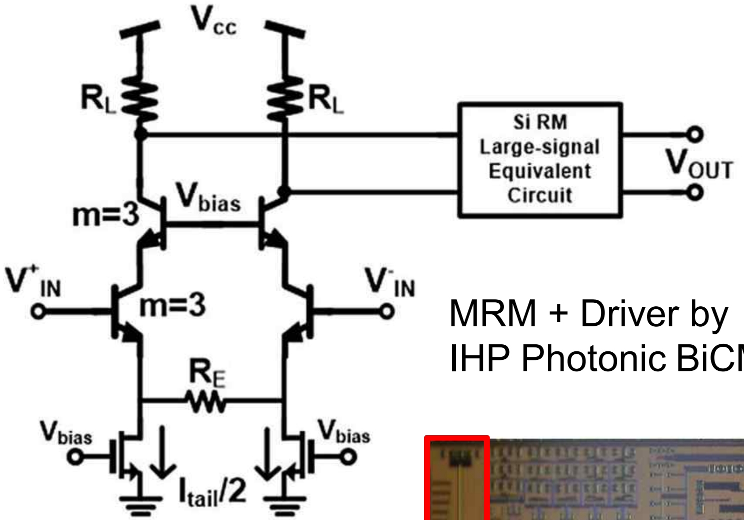
C (I_{tail} = 41.3mA)



Large power consumption

Kim et al., OFC 2018

Optical Transmitter Design Optimization



MRM + Driver by
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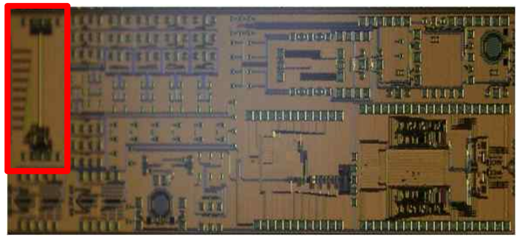
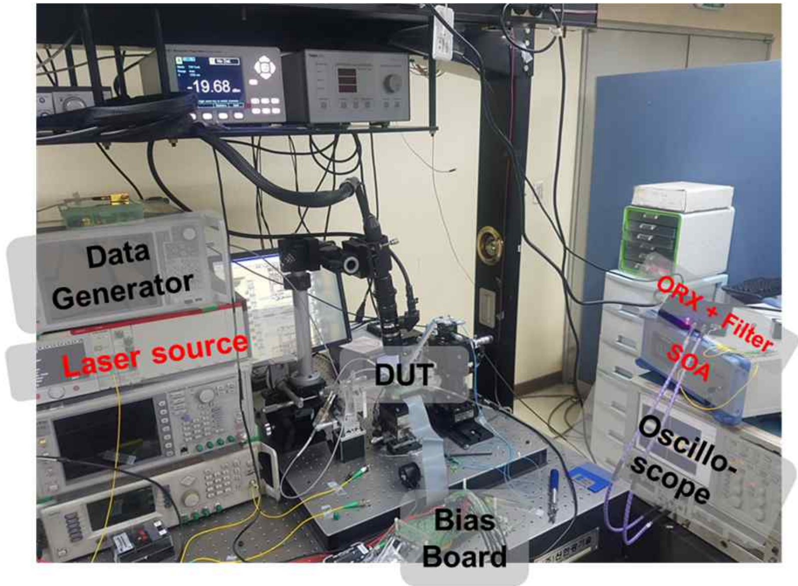
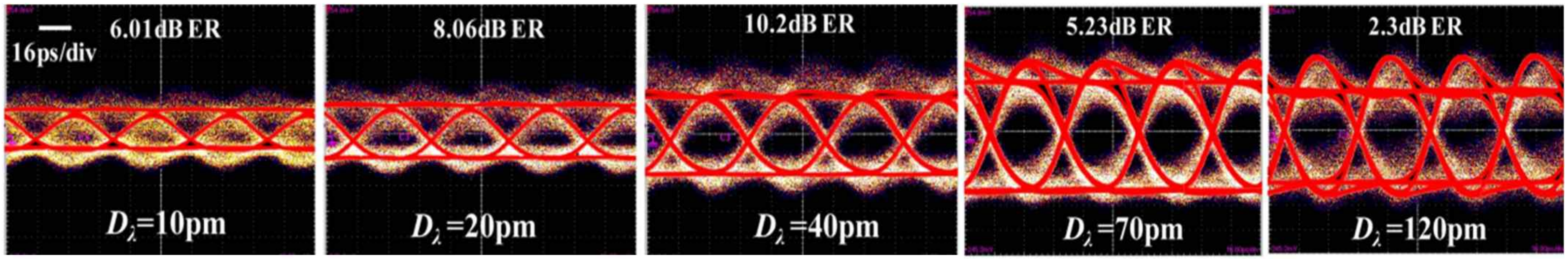


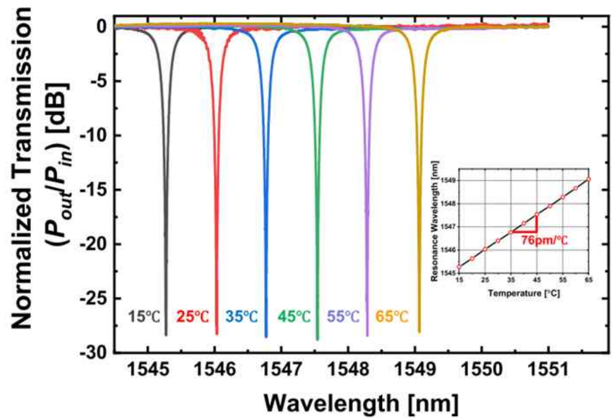


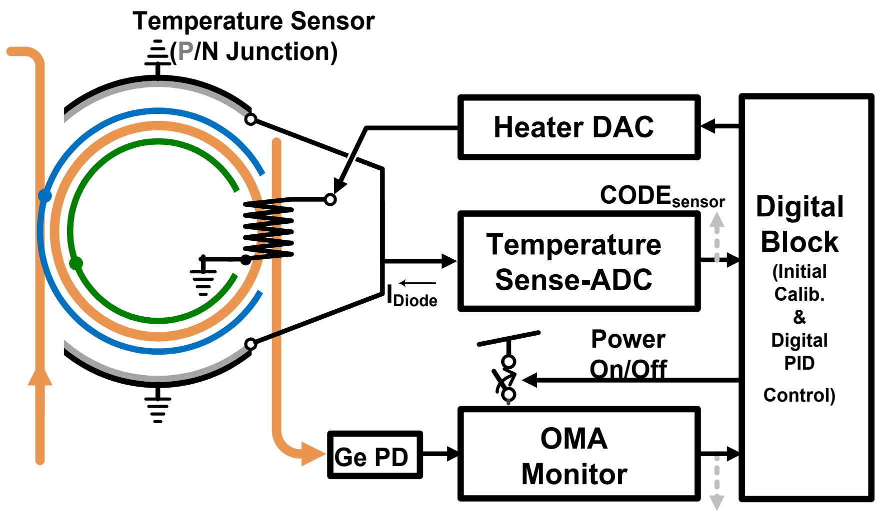
4V_{pp}, PRBS31, 25-Gbps

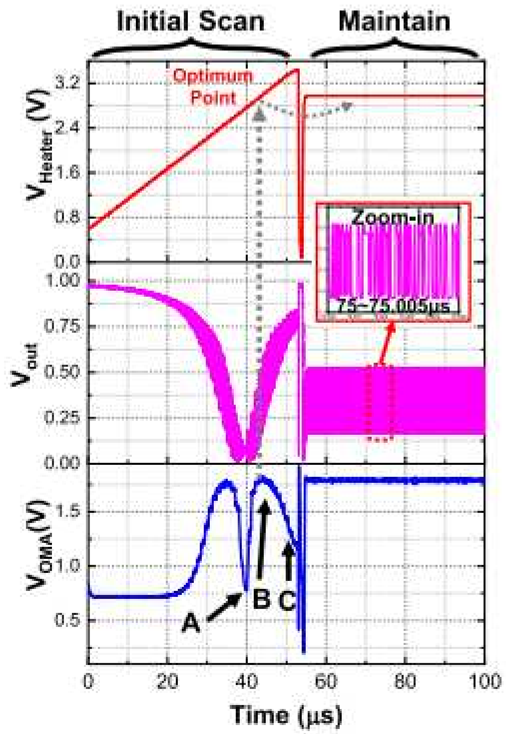


Kim et al., PR 2019

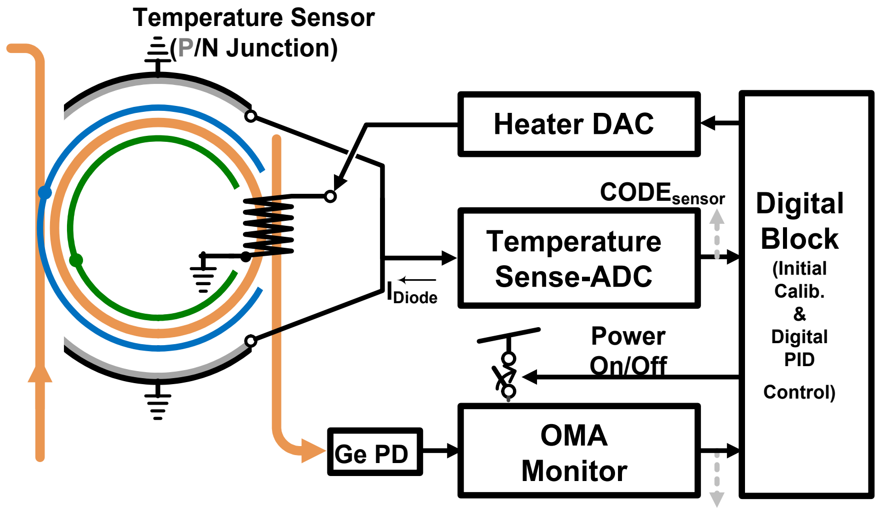
Integrated Temperature Controller

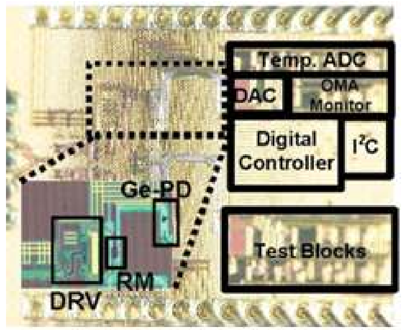


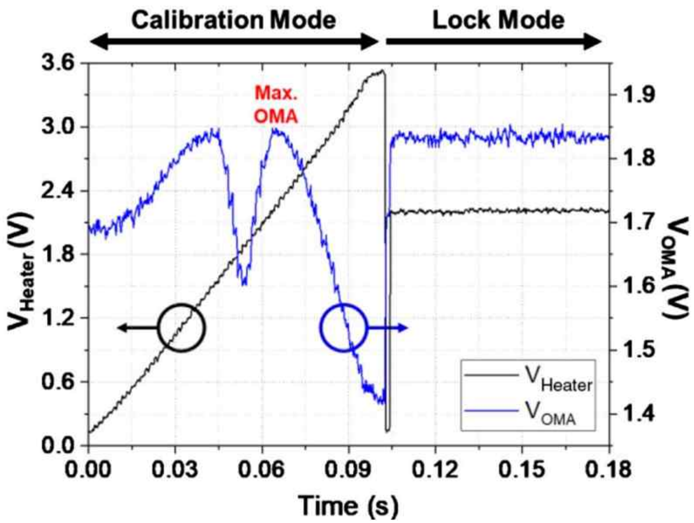


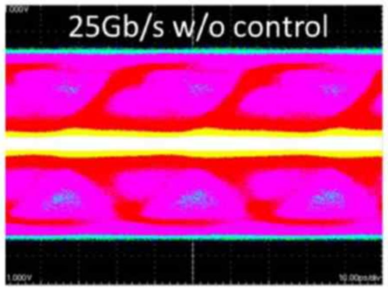


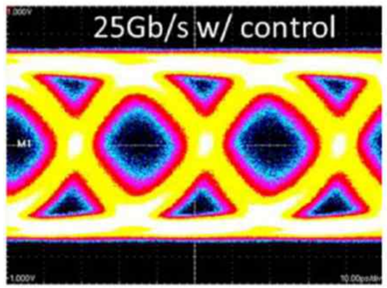
Integrated Temperature Controller











Kim et al., PR 2021

Summary

- **Si MRM essential for photonic I/O applications**
- **Simple and computationally efficiency SPICE model for Si MRM established**
- **Optimal design for Si photonic transmitter containing Si MRM, driver, temperature controller demonstrated**

Acknowledgements

ihp

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SAMSUNG ELECTRONICS