Compact Silicon Photonic Mach-Zehnder Modulators for High-Energy Physics

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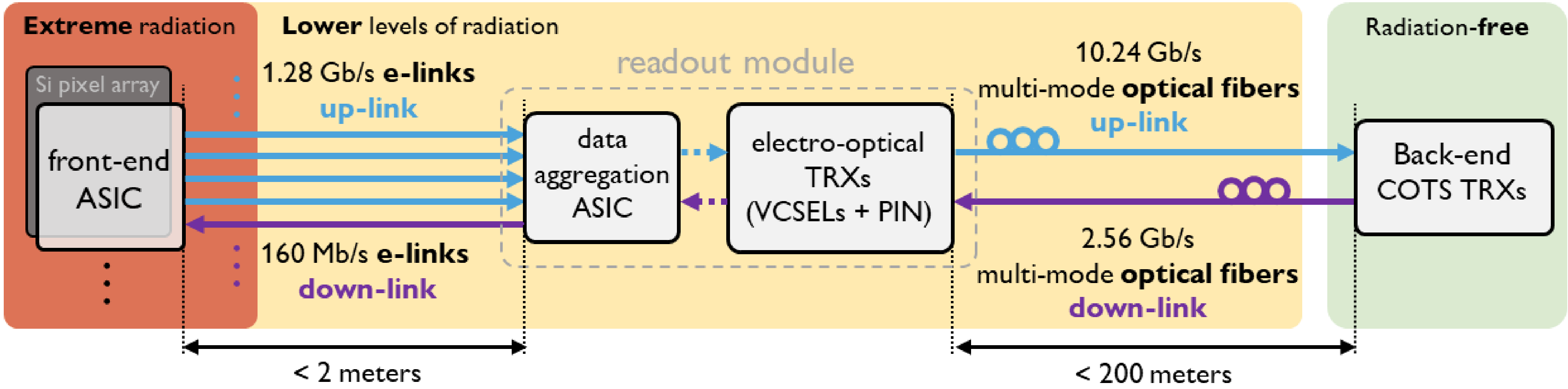
Outline

- Silicon photonic optical links in high-energy physics
- Silicon photonic modulators alternatives
- Folded Mach-Zehnder modulators design and characterization
  - Standard phase shifter
  - Rad-hard phase shifter
- Electro-optical bit-error-rate (BER) tests:
  - Standard vs. rad-hard comparison
  - CMOS-compatible driving
- Rad-hard FMZM ionizing irradiation results
- Conclusions

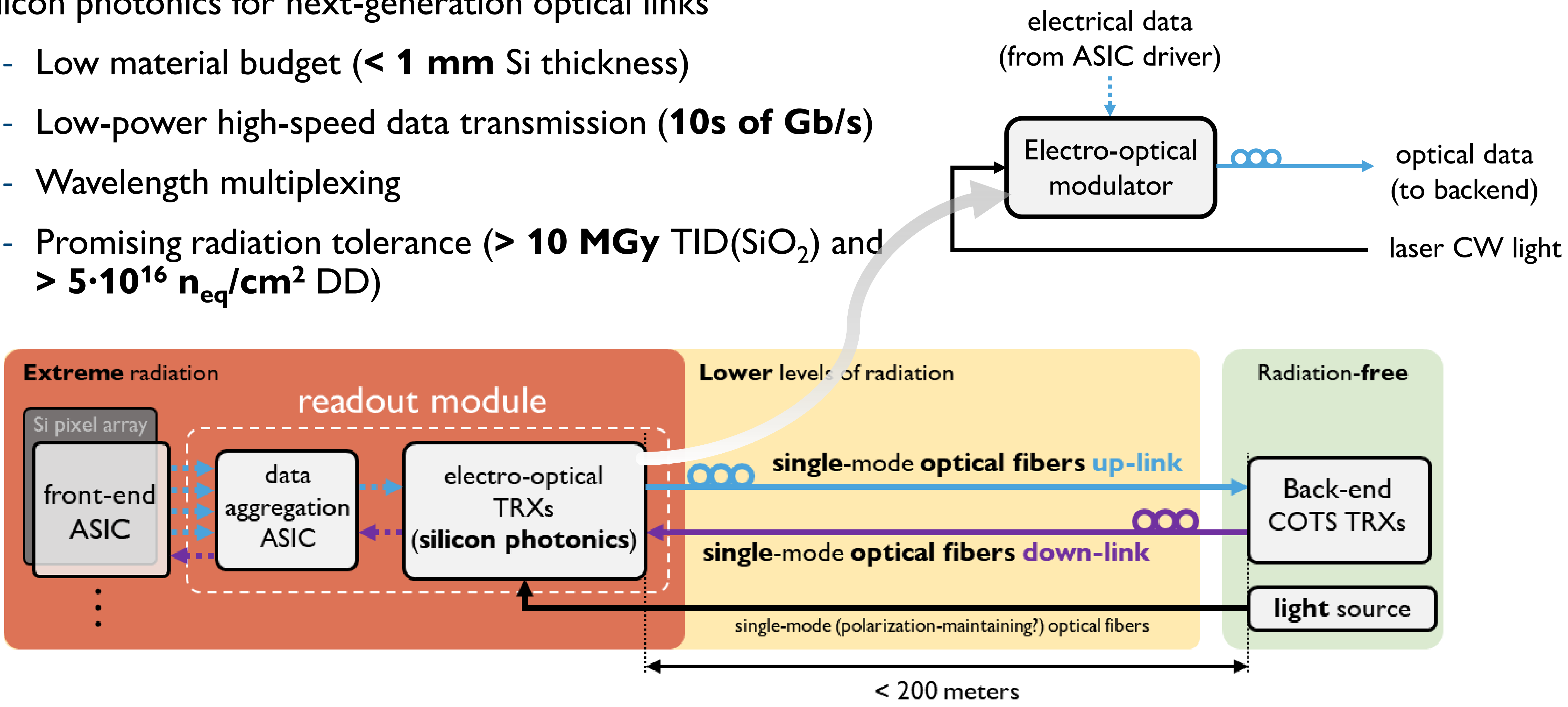
Introduction – Silicon Photonics for HEP (1/2)

- Optical links in HEP currently not routed down to innermost detector layers (bulky e-links)
- State-of-the-art readout modules (LpGBT, VTRX+) limited in radiation-hardness:
  - **< 1 MGy** TID(SiO_2)
  - **< $1 \cdot 10^{15}$ n_{eq}/cm^2** fluence (1-MeV neutron equivalent DD)



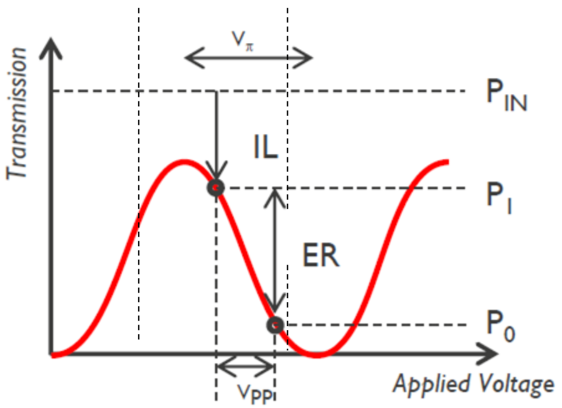
Introduction – Silicon Photonics for HEP (2/2)

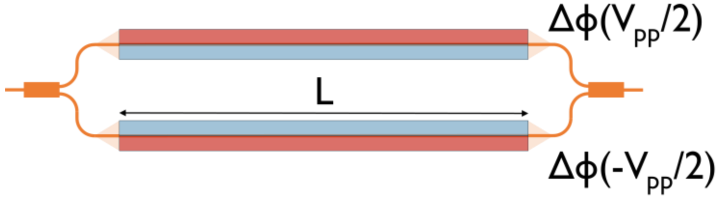
- Silicon photonics for next-generation optical links
  - Low material budget (**< 1 mm** Si thickness)
  - Low-power high-speed data transmission (**10s of Gb/s**)
  - Wavelength multiplexing
  - Promising radiation tolerance (**> 10 MGy** TID(SiO_2) and **> 5·10^{16} n$_{eq}$/cm^2** DD)



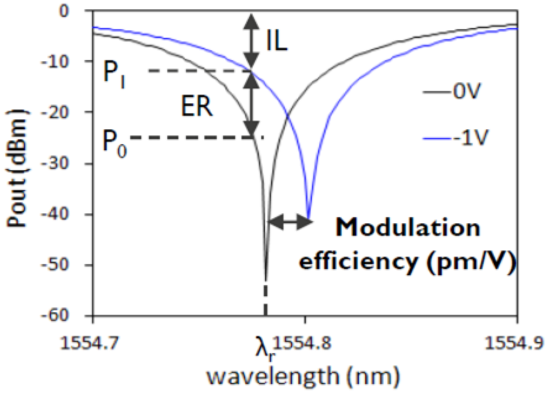
Introduction – All-Silicon EO Modulator Alternatives

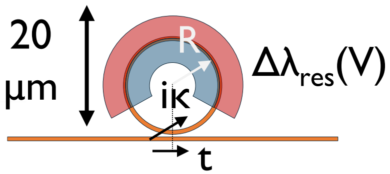
Mach-Zehnder modulator





Ring modulator



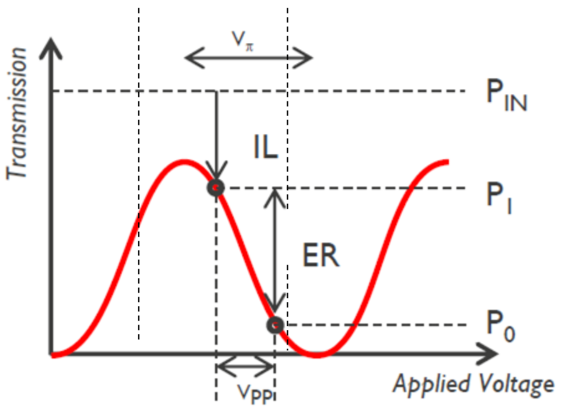


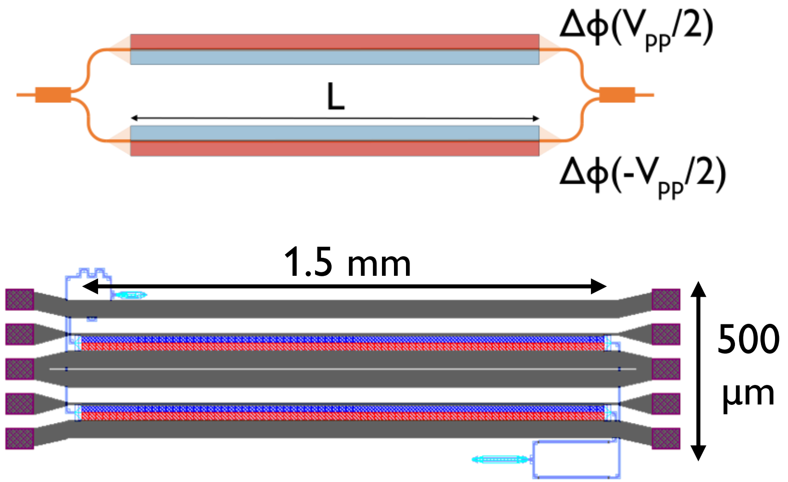
Metrics	Mach-Zehnder Modulator	Ring Modulator
Optical bandwidth	Broadband (if balanced)	Narrow-band (~ 1 nm)
Process/Temperature sensitivity	Robust	Active resonance control required

[2 images from Rakowski, "Silicon Photonics Platform for 50G Optical Interconnects", Cadence Photonics Summit and Workshop 2017]

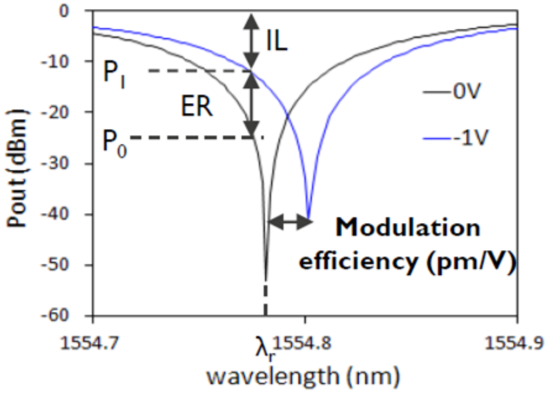
Introduction – All-Silicon EO Modulator Alternatives

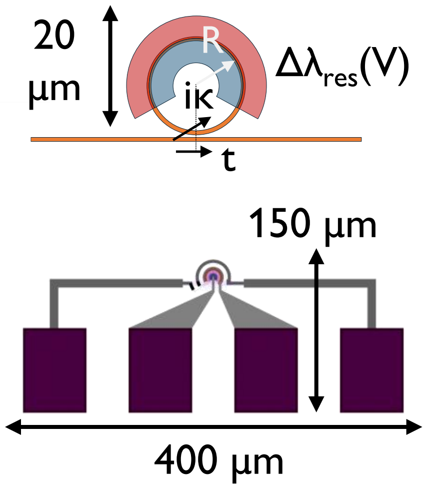
Mach-Zehnder modulator





Ring modulator





Metrics	Mach-Zehnder Modulator	Ring Modulator
Optical bandwidth	Broadband (if balanced)	Narrow-band (~ 1 nm)
Process/Temperature sensitivity	Robust	Active resonance control required
Footprint	Large (**mm**-scale)	Small (**10 µm**-scale, **w/o pads!**)
Power consumption	Large (DC + RF: **10 pJ/bit**-scale)	Small (RF: **10 fJ/bit**-scale)
Common driving condition	Traveling-wave (RF terminated)	Lumped-element

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Introduction – All-Silicon EO Modulator Alternatives

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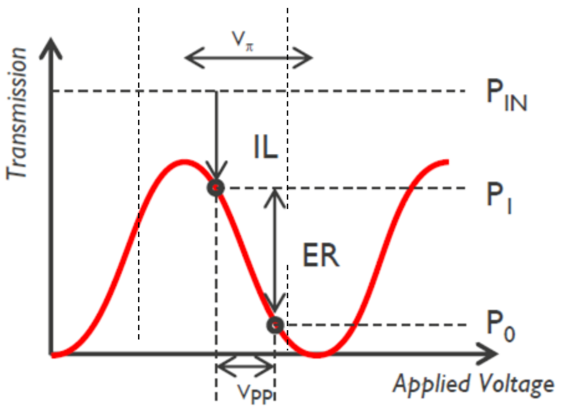

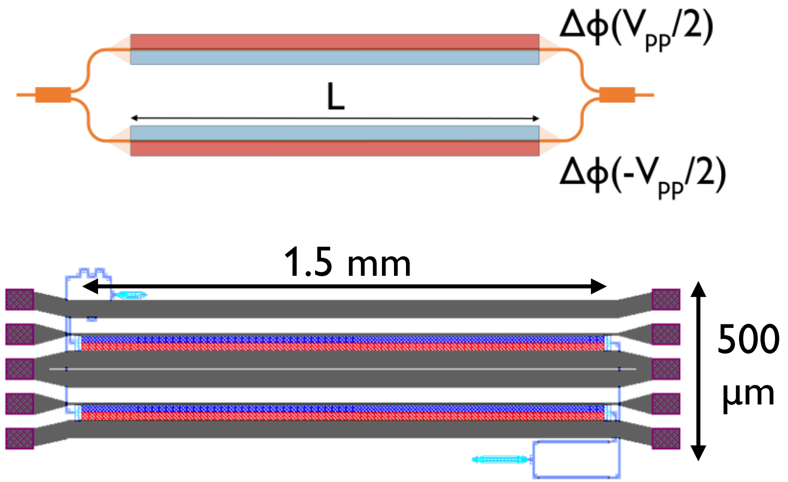

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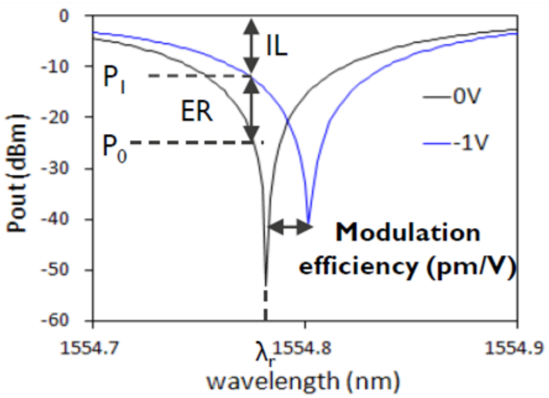
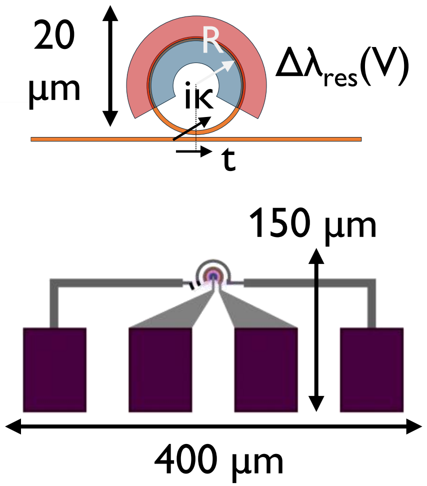


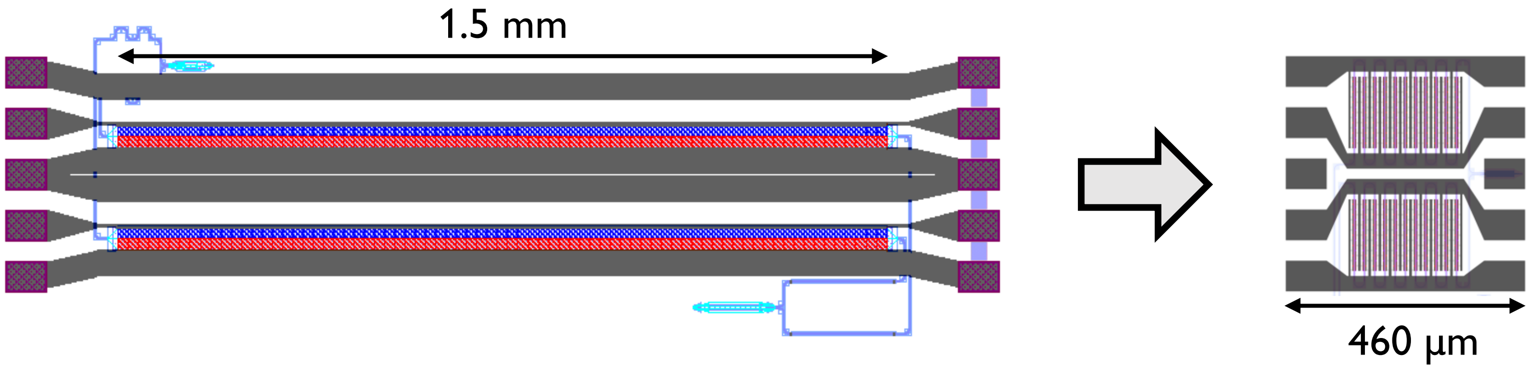


Metrics	**Mach-Zehnder Modulator**	**Ring Modulator**
Optical bandwidth	Broadband (if balanced)	Narrow-band (~ 1 nm)
Process/Temperature sensitivity	Robust	Active resonance control required
Footprint	Medium (**100 µm**-scale)	Small (**10 µm**-scale, **w/o pads!**)
Power consumption	Medium (only RF)	Small (RF: **10 fJ/bit**-scale)
Common driving condition	**Lumped-element**	Lumped-element

[2 images from Rakowski, "Silicon Photonics Platform for 50G Optical Interconnects", Cadence Photonics Summit and Workshop 2017]

Lumped-element MZM Description

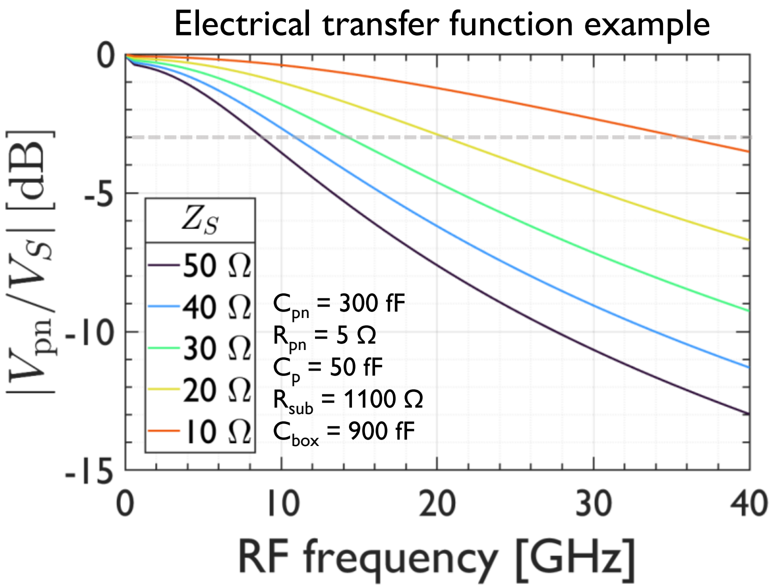
- Electrodes size should be much less than RF wavelength to avoid traveling-wave effects
- **Non-terminated** device: no DC power consumption and on-chip thermal dissipation



ref. B. Murray, C. Antony, G. Talli, P. D. Townsend, "Predistortion for high-speed lumped silicon photonic Mach-Zehnder modulator," IEEE Photonics Journal, vol. 14, no. 2, 2022

Lumped-element MZM Description

- Electrodes size should be much less than RF wavelength to avoid traveling-wave effects
- **Non-terminated** device: no DC power consumption and on-chip thermal dissipation
- **Optical** bandwidth limit: optical transit time
- **Electrical** bandwidth limit: RC charge-discharge

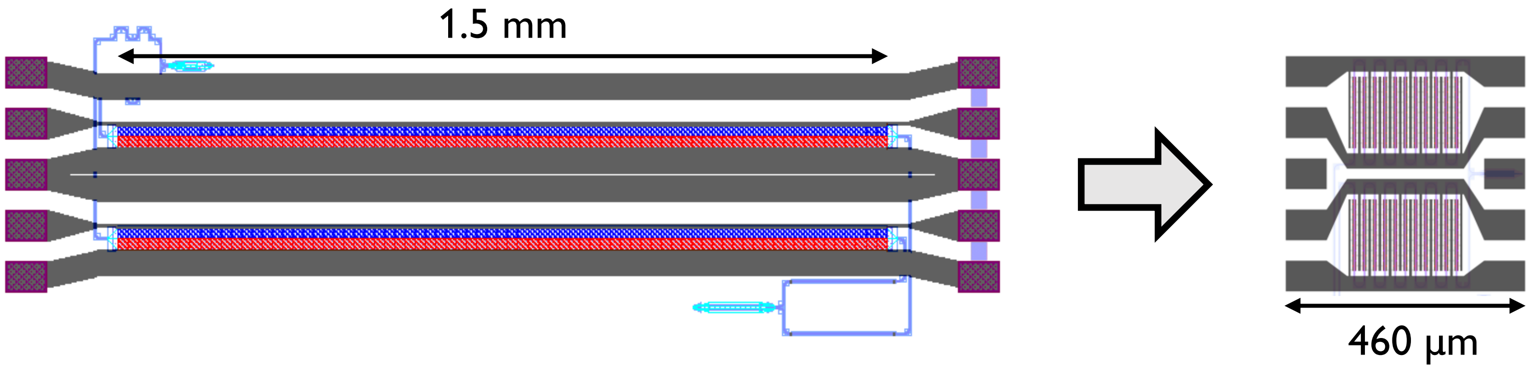


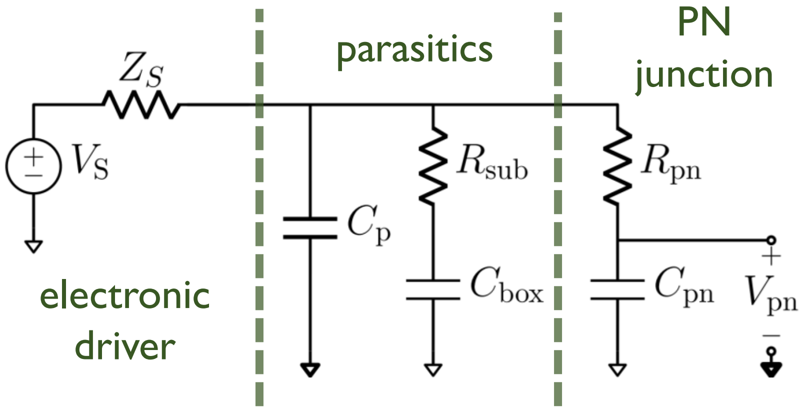
$$f_{3dB,opt} \approx \frac{0.44 \cdot c}{n_g L}$$

group index (n_g), optical length (L)

$$f_{3dB,ele} \approx \frac{1}{2\pi Z_S C_{pn}}$$

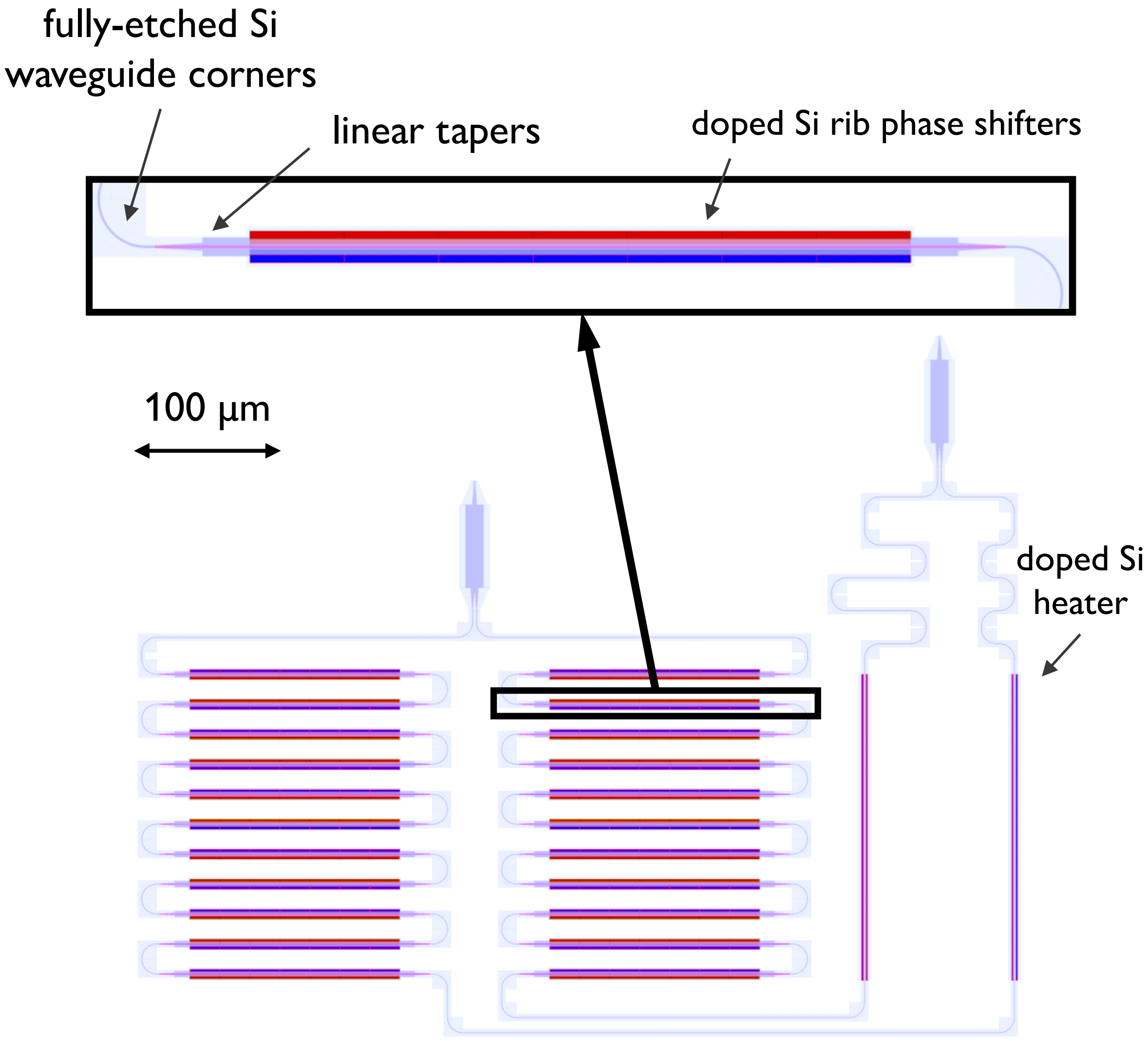
PN junction capacitance (C_{pn}), driving impedance (Z_S)





Folded MZM Device Design

- Technology: Imec's iSiPP50G
- MZM with **meandered** phase shifters:
  - **1.5 mm**-long active length per MZM arm ($f_{3dB,opt}$ ~ 15 GHz)
  - Unbalanced arm lengths: operating point tunable changing wavelength



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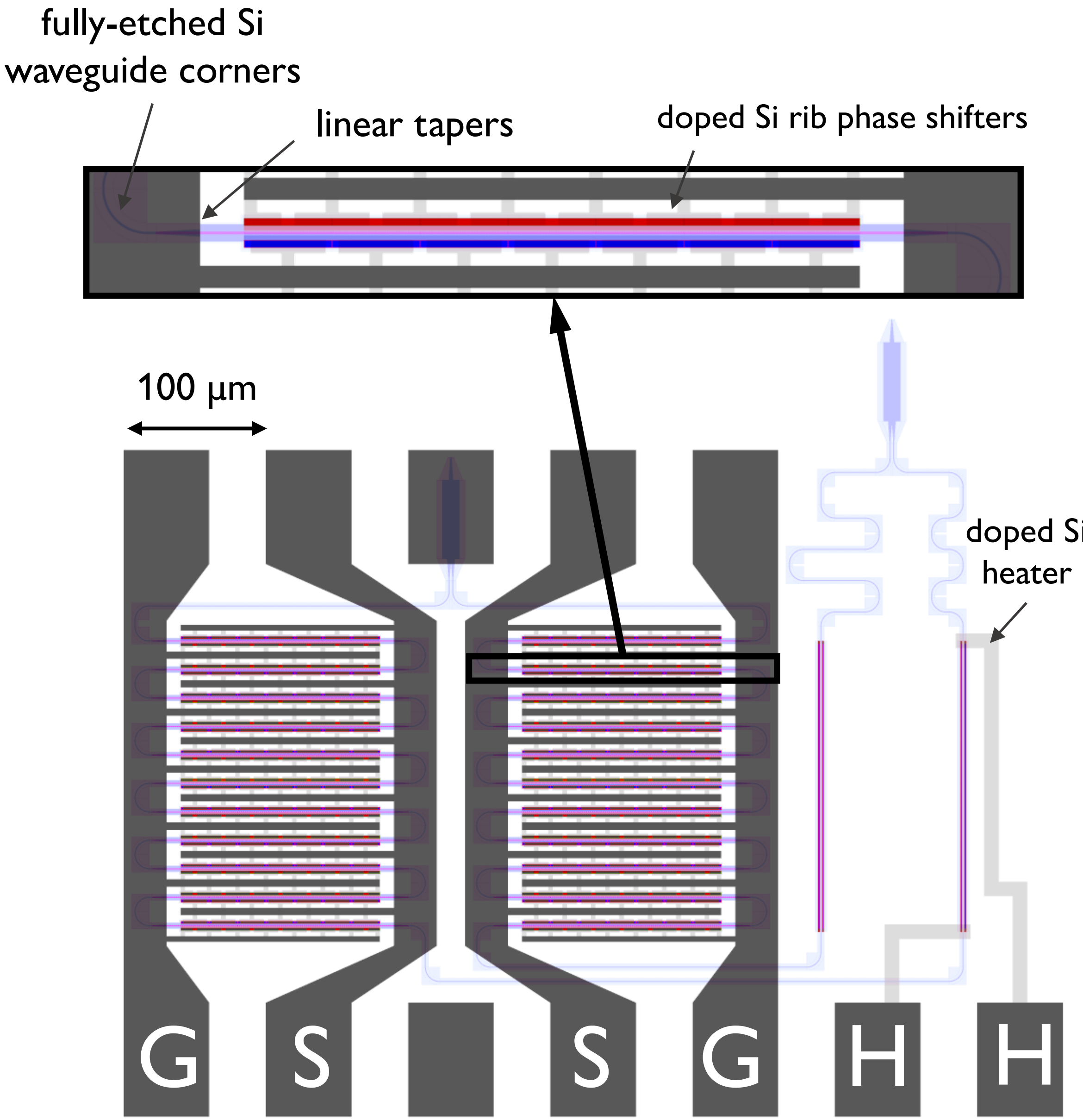
  - Interdigitated electrodes: 460 µm x 240 µm footprint per MZM arm



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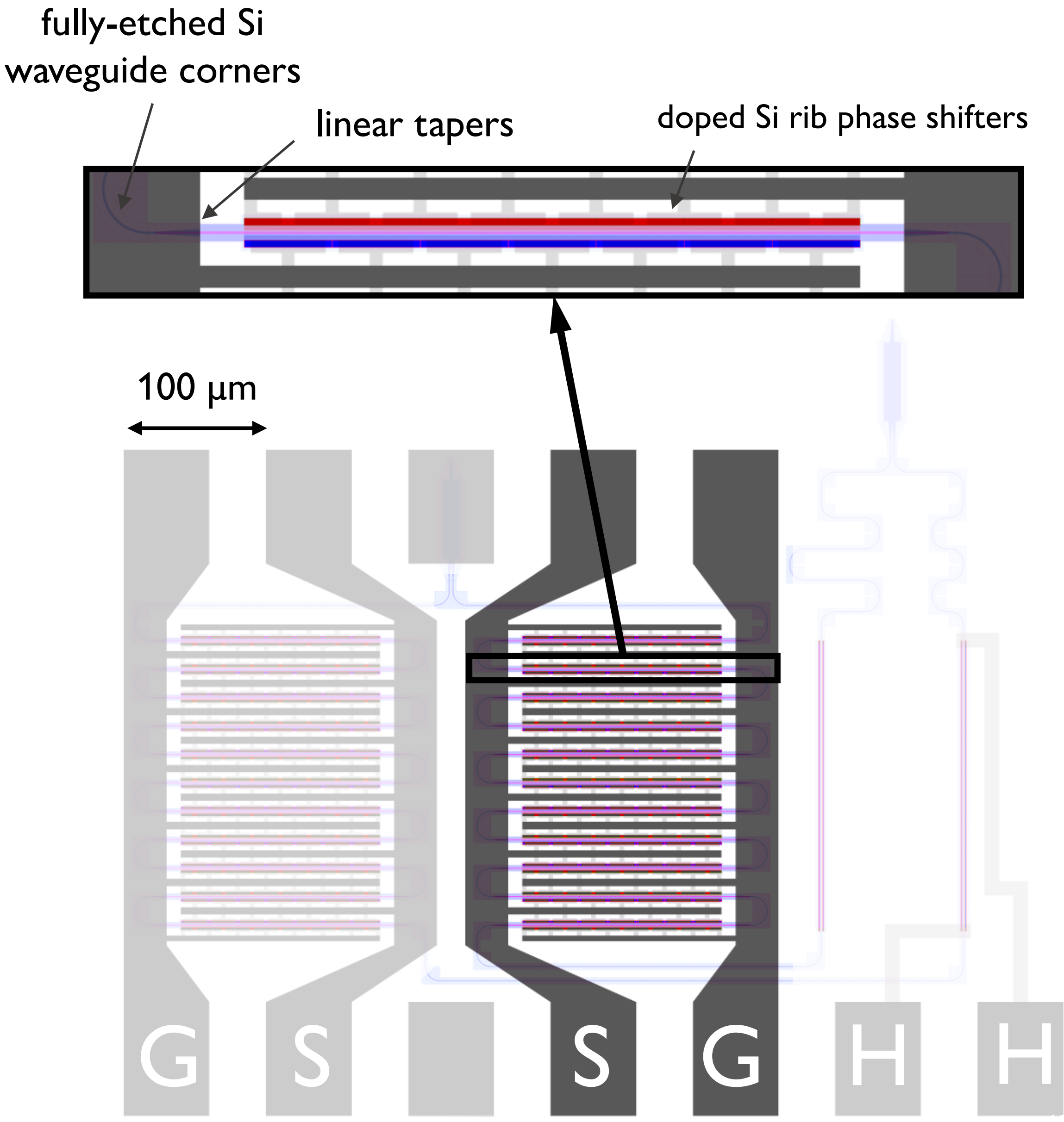
  - Unbalanced arm lengths: operating point tunable changing wavelength
  - Interdigitated electrodes: 460 µm x 240 µm footprint per MZM arm
- Test conditions:
  - **Single-arm driving**
  - No external 50 Ω termination

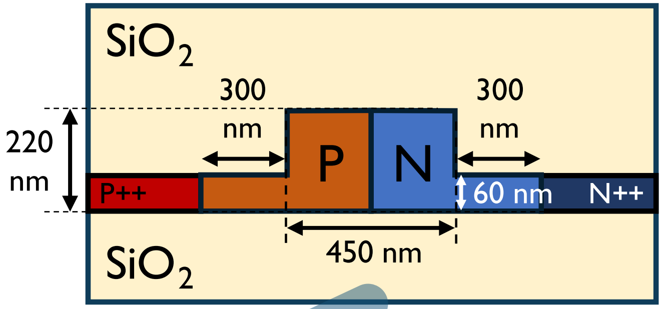


P conc. ~ 1x N conc.
P+ conc. ~ 10x P conc.
P++ conc. ~ 50x P conc.
N++ conc. ~ 50x N conc.

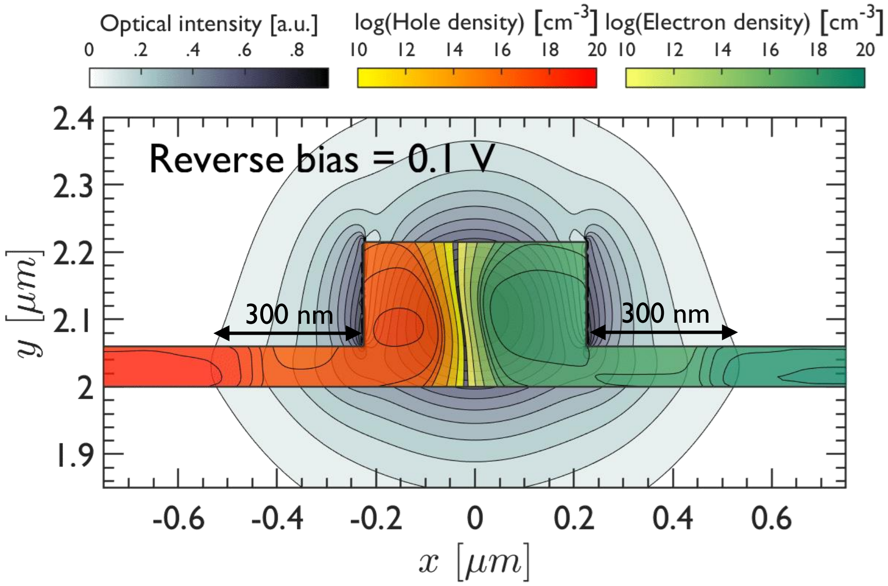
Folded MZM PN Phase Shifter Cross-sections

- Effective index change via charge carriers movement (PN-junction in SOI waveguide)

Convential design



Standard design

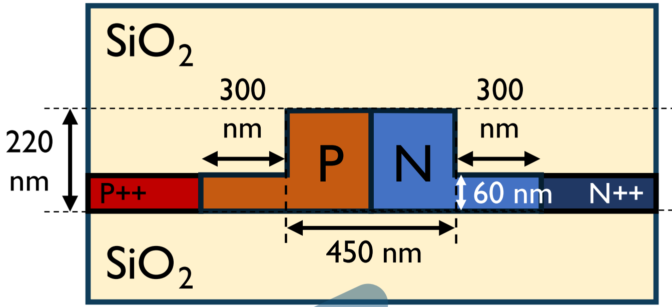


Folded MZM PN Phase Shifter Cross-sections

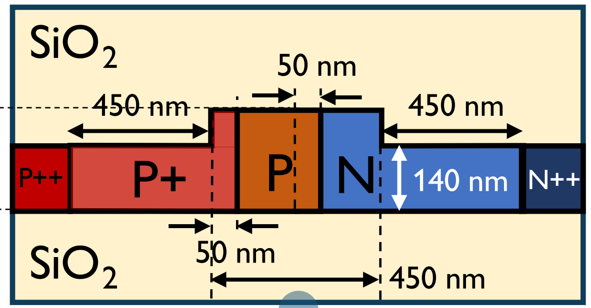
P conc. ~ 1x N conc.
P+ conc. ~ 10x P conc.
P++ conc. ~ 50x P conc.
N++ conc. ~ 50x N conc.

- Effective index change via charge carriers movement (PN-junction in SOI waveguide)
- Radiation-hardening by design:
  - Shallower etch
  - P-side doping increase

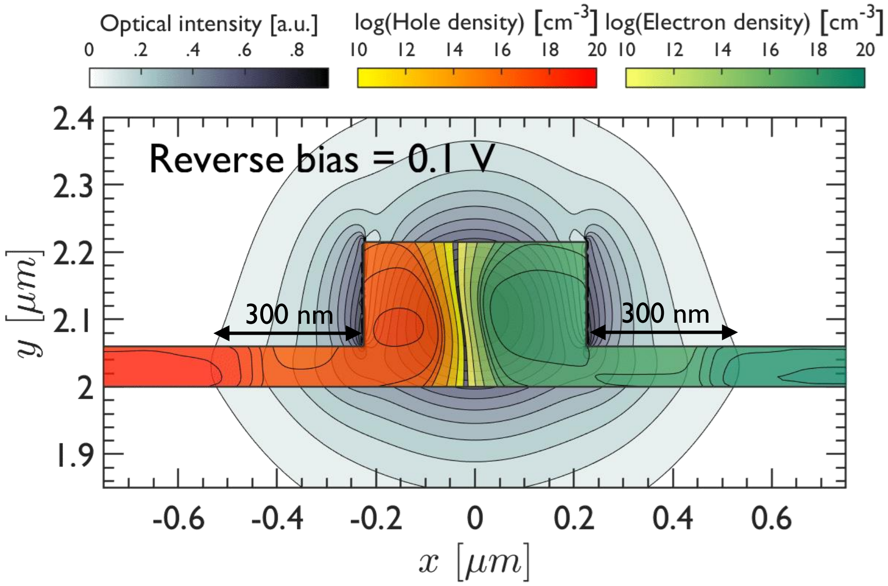
Conventional design



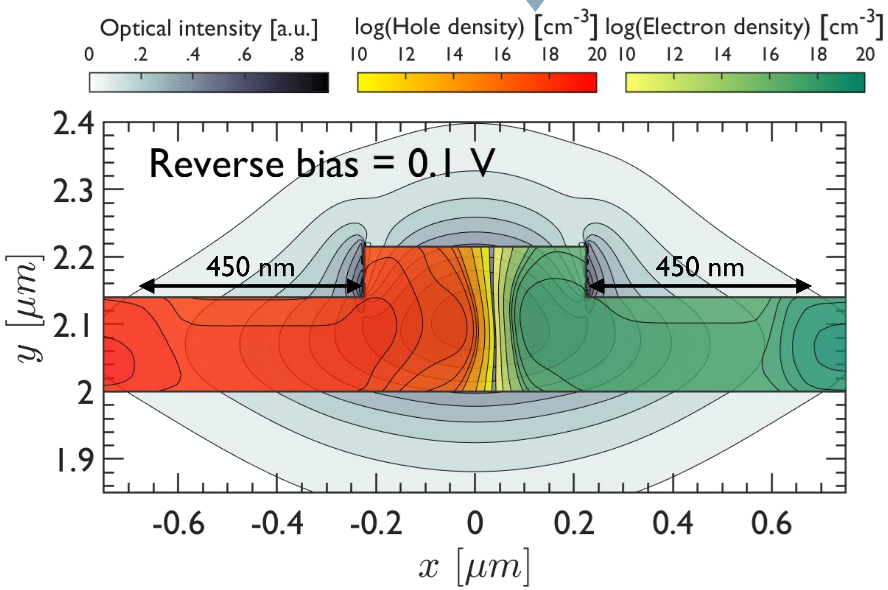
Rad-hard design



Standard design



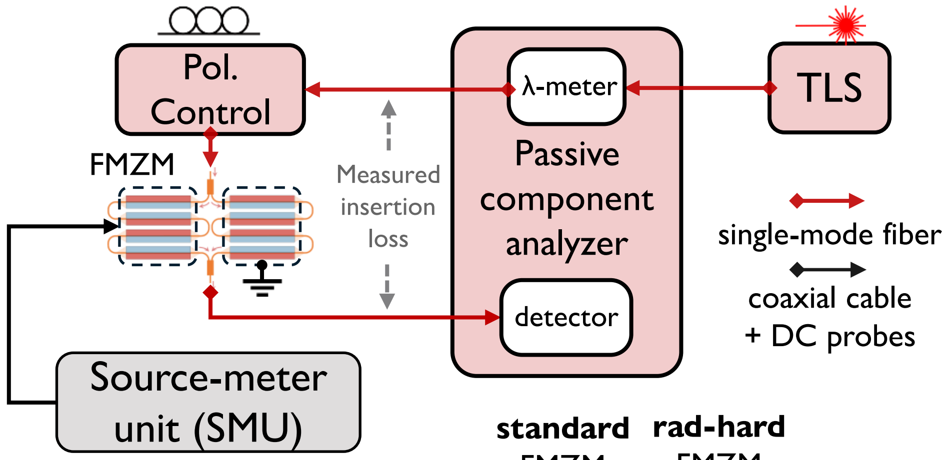
Rad-hard design

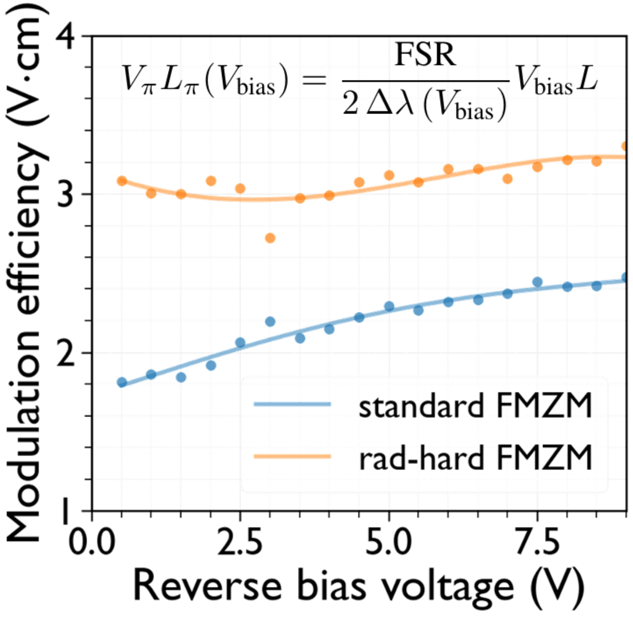


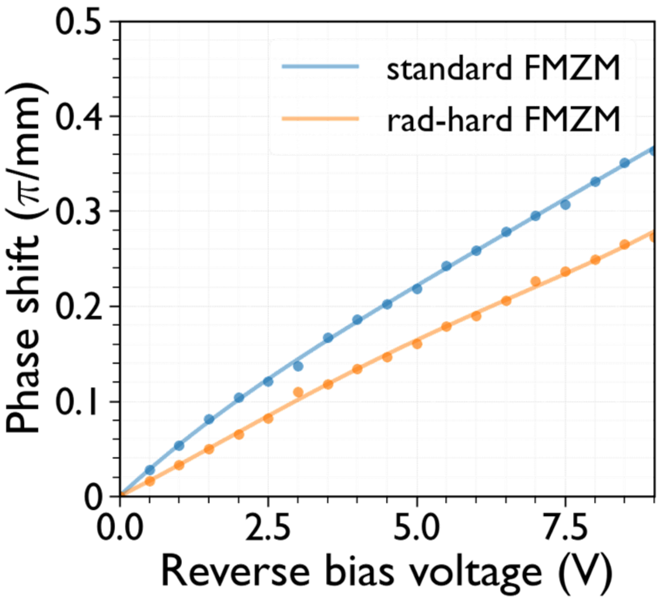
DC Electro-optic Characterization

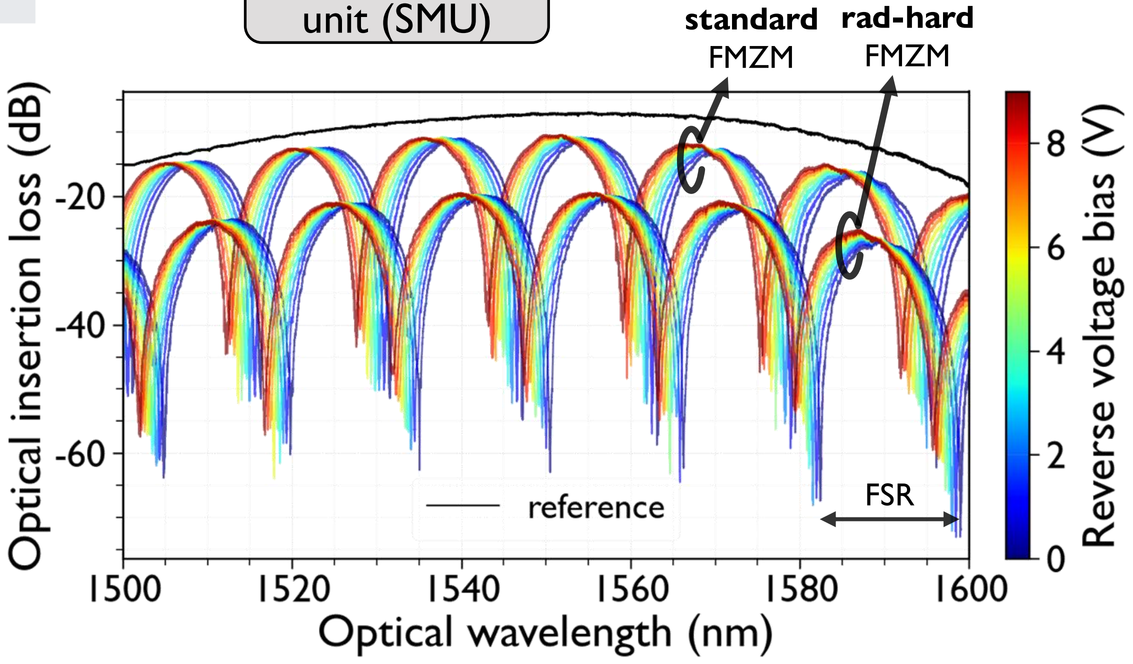
- Tunable laser swept across C-band to capture performance metrics dependance on PN junction bias

Metrics @ 0 V_{bias}	Standard FMZM	Rad-hard FMZM
Optical propagation loss @ 1550 nm	~ 15 dB/cm	~ 61 dB/cm
Modulation efficiency $V_\pi l_\pi$	~ 1.8 V·cm	~ 3 V·cm



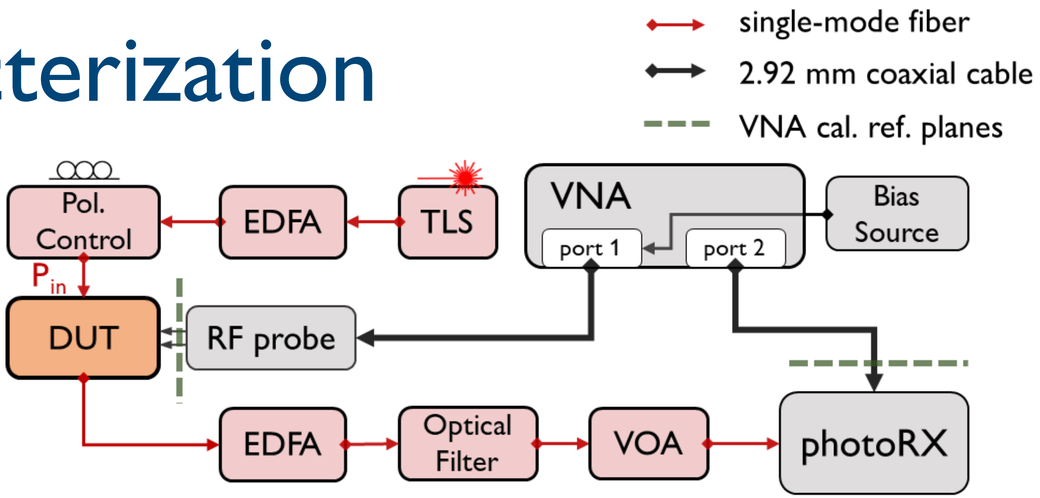


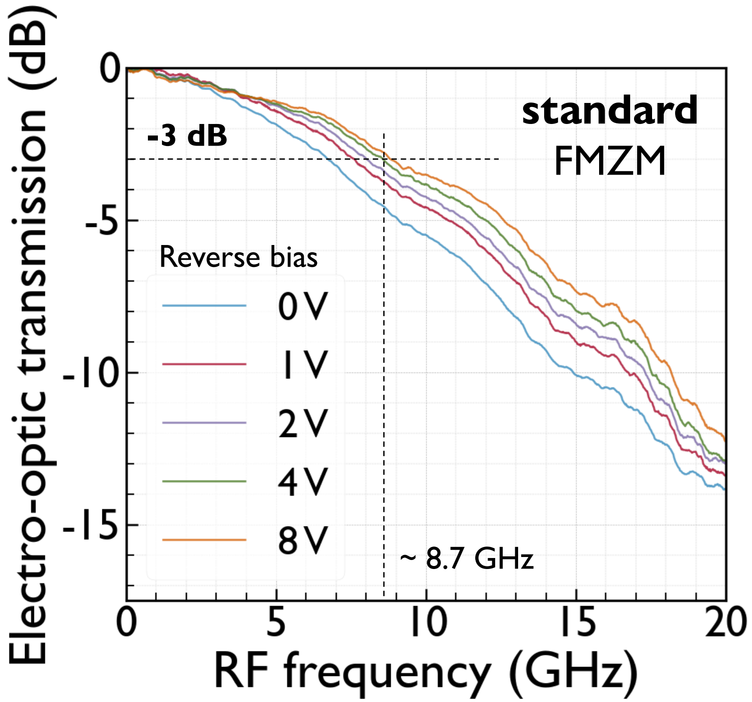


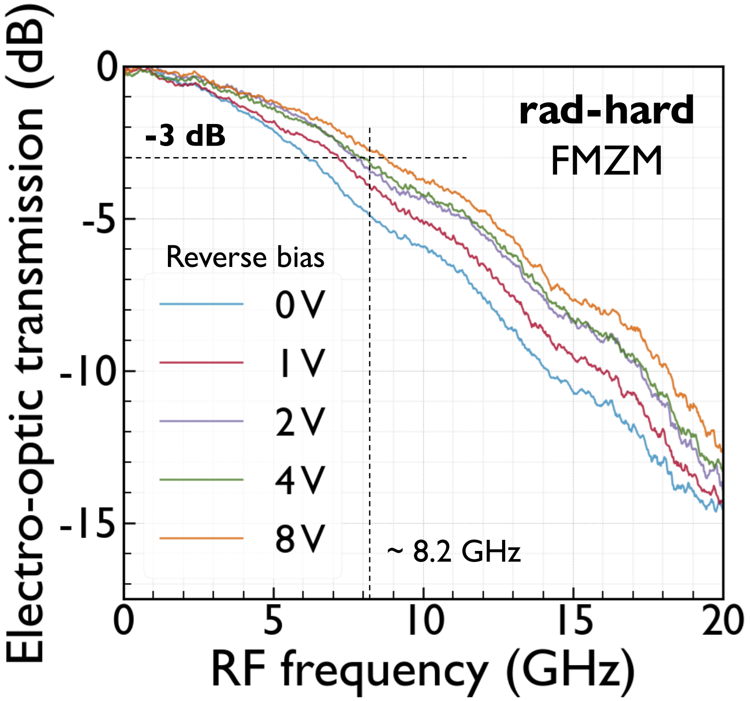


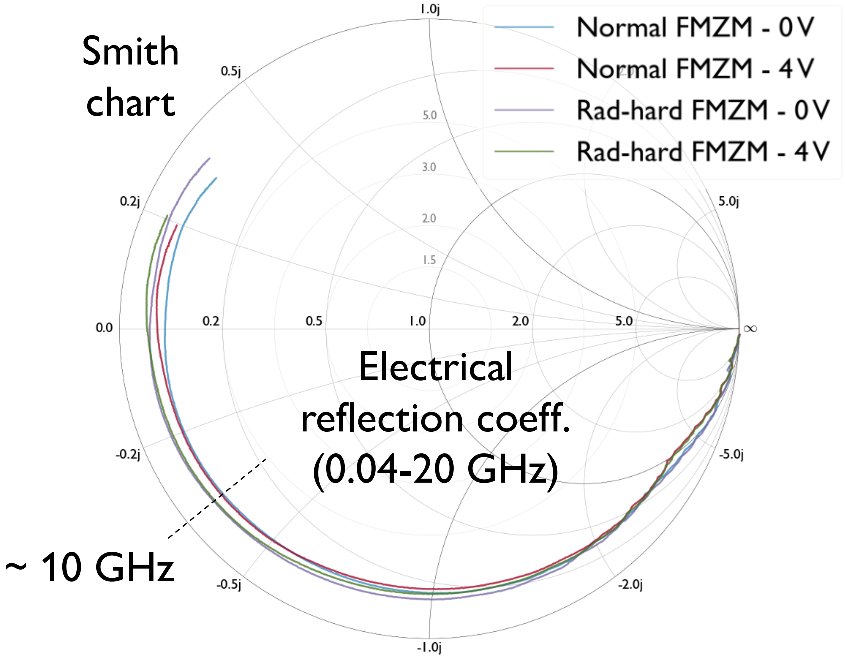
Small-signal Electro-optic Characterization

- Electro-optic -3dB bandwidths ranging from 6.5 to 8.5 GHz for both devices (bias-dependent)
- Test conditions: laser wavelength in C-band at MZM quadrature + optical amplification to recover from coupling optical losses



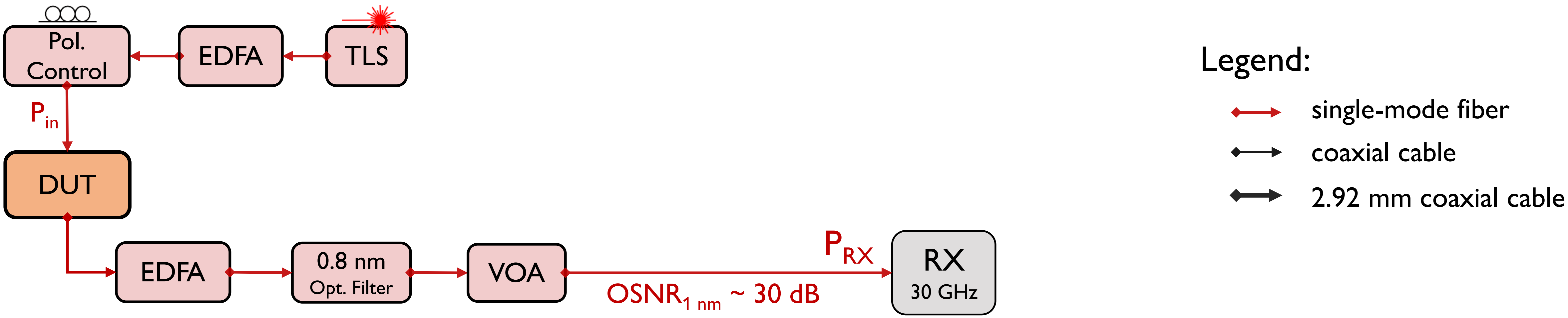






Large-signal Electro-optic Measurement Setup

- **Goal**: capture time-domain performances via eye diagrams and bit-error-rate (BER) analysis with respect to:
  - received optical power P_{RX} (constant OSNR)
  - bit-rate
- **NRZ** transmission system



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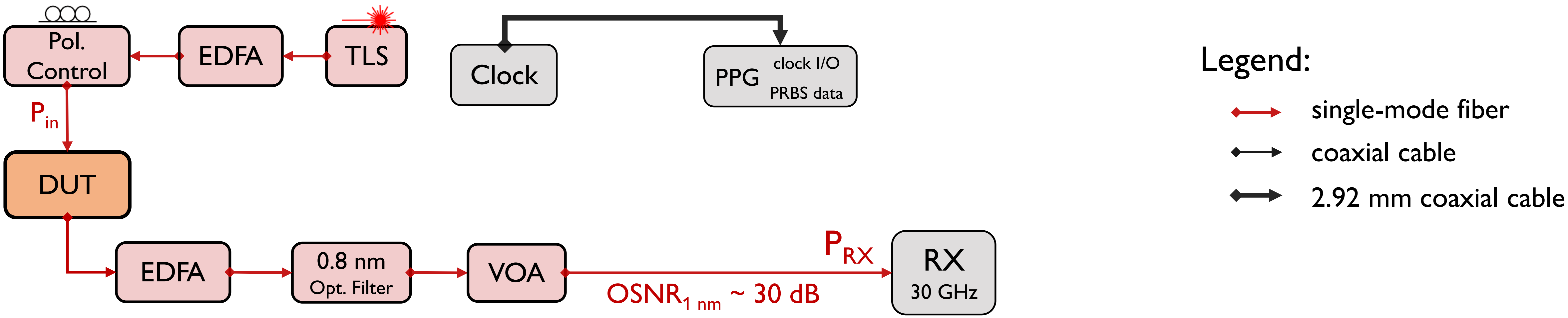

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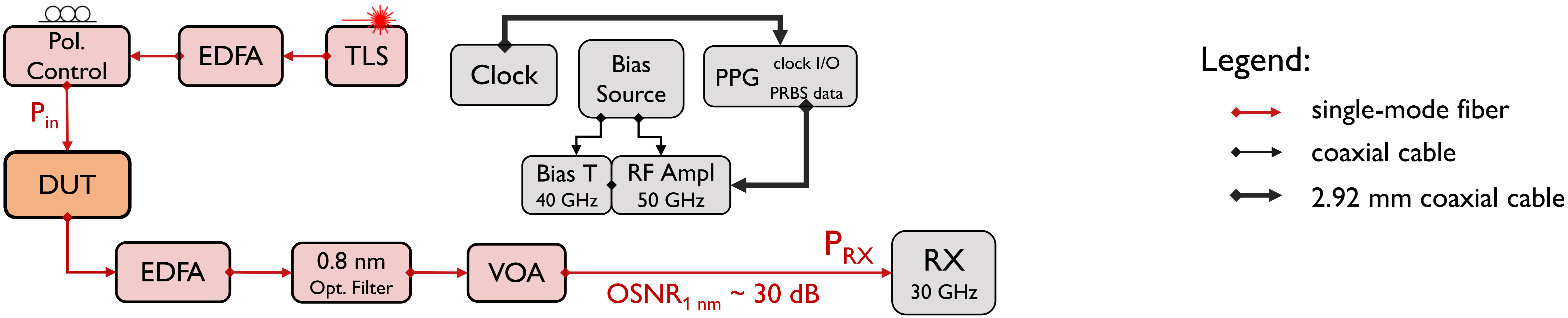
- **NRZ** transmission system: PRBS 2^7-1 pattern, RF amplification



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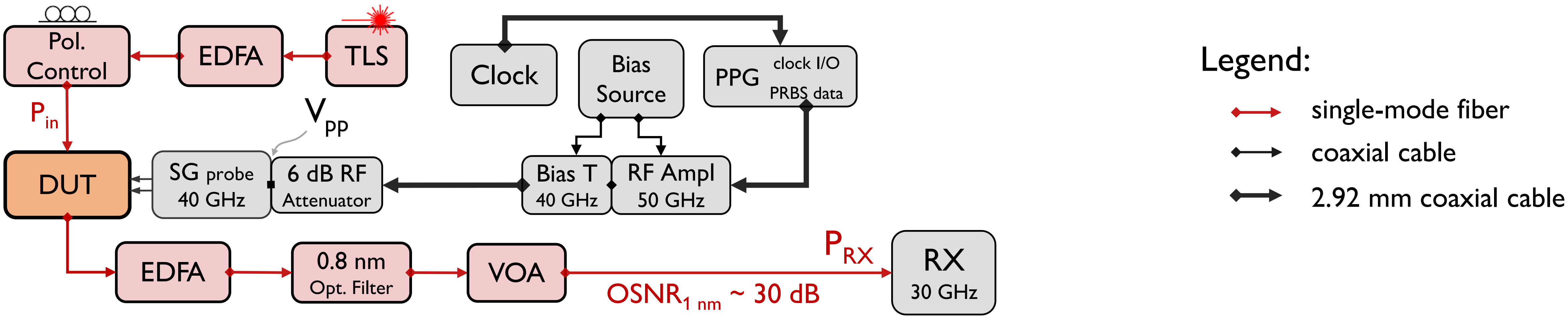
- **NRZ** transmission system: PRBS 2^7-1 pattern, RF amplification and on-chip probing with in-line RF attenuator



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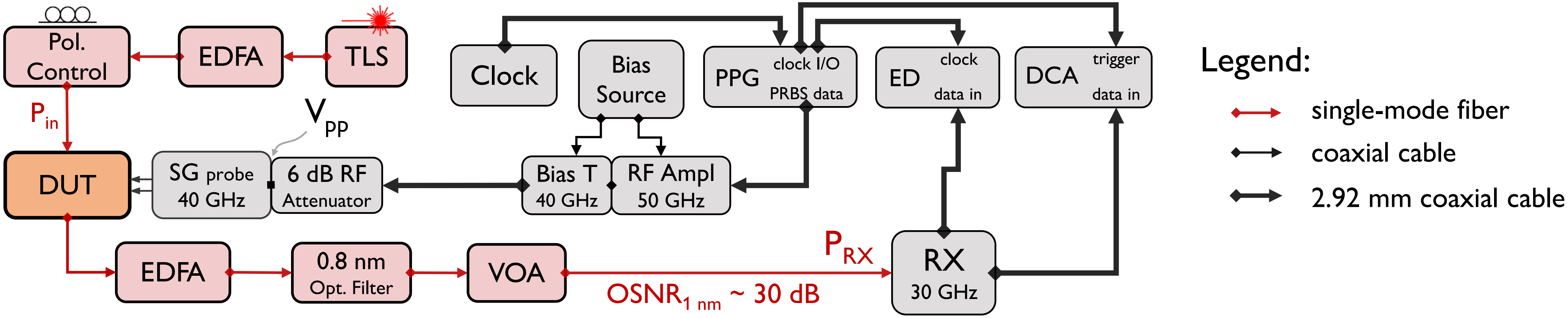
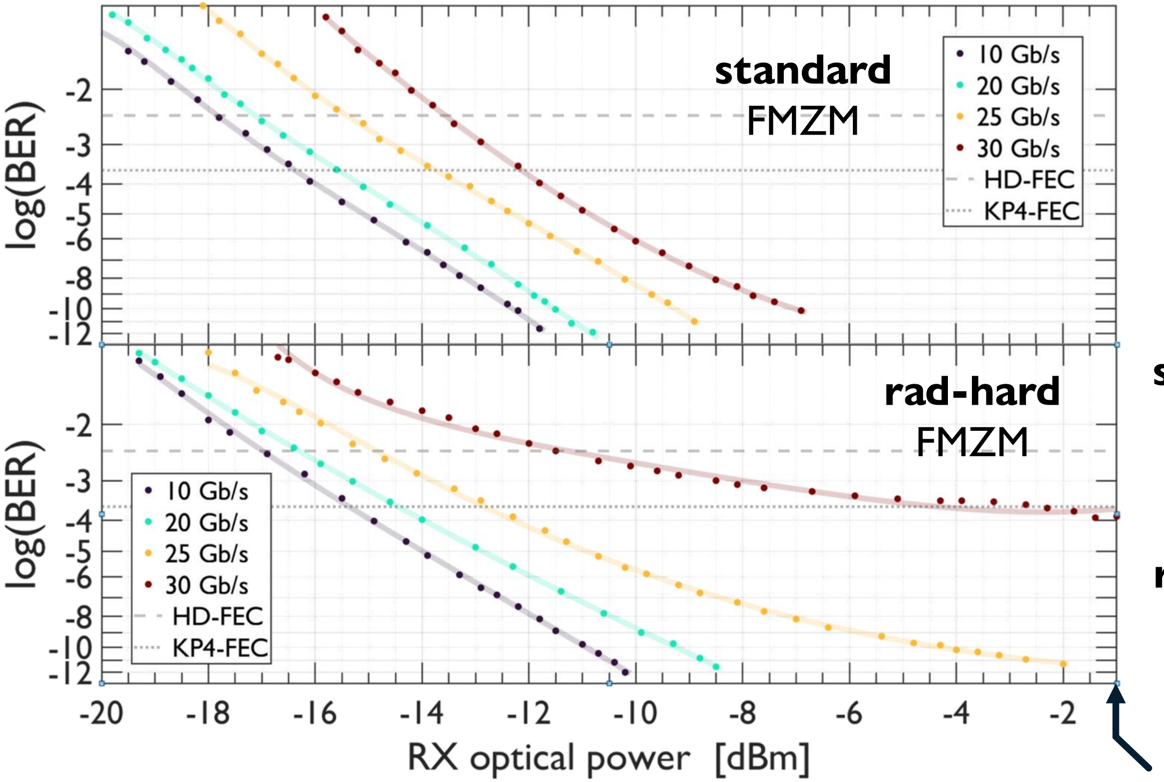
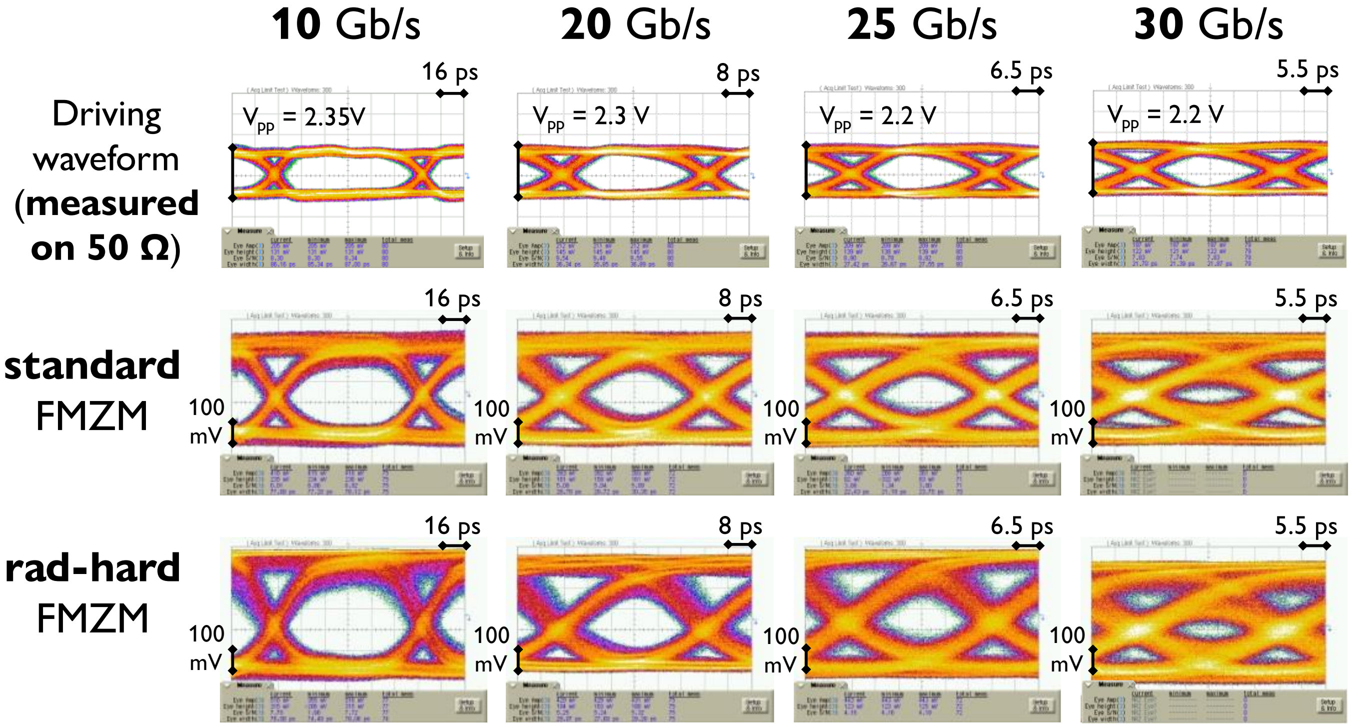


Large-signal Results Standard vs. Rad-hard FMZMs

- 30 Gb/s error-free transmission with conventional design, while BER floors start to appear in rad-hard FMZM at 25 Gb/s due to comparatively higher $V_\pi L_\pi$
- Test conditions: ~ 4.4 V_{pp} (4 V_{bias}) driving on modulator pads, laser wavelength in C-band





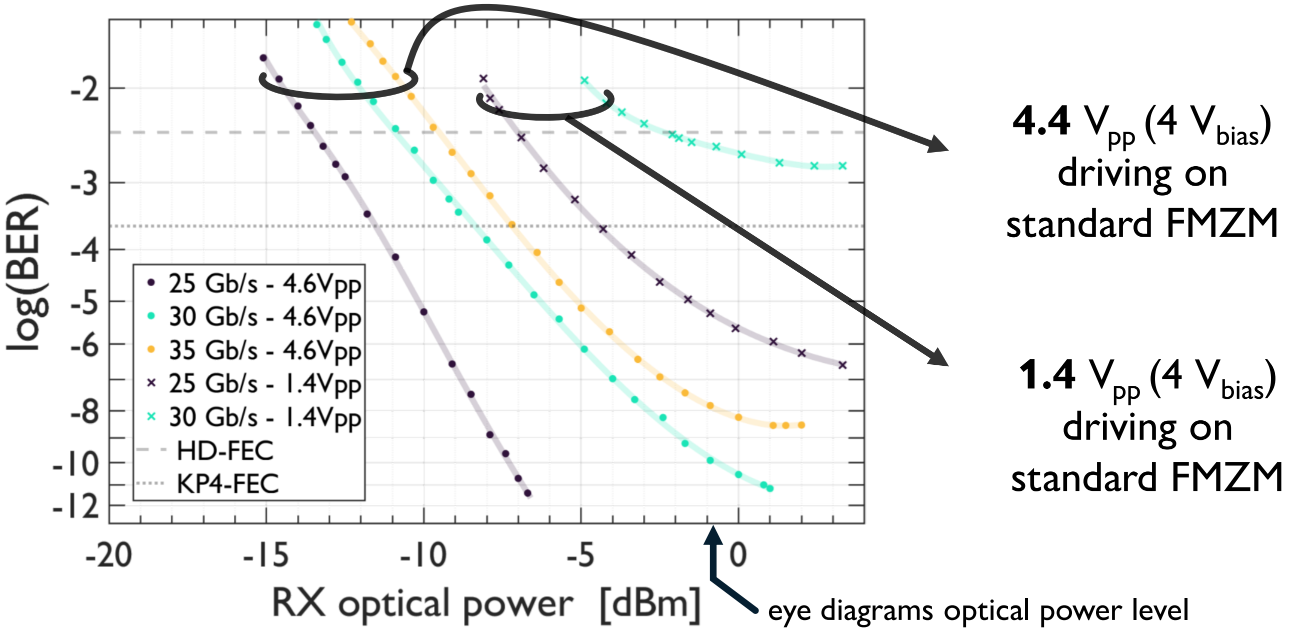
eye diagrams optical power level

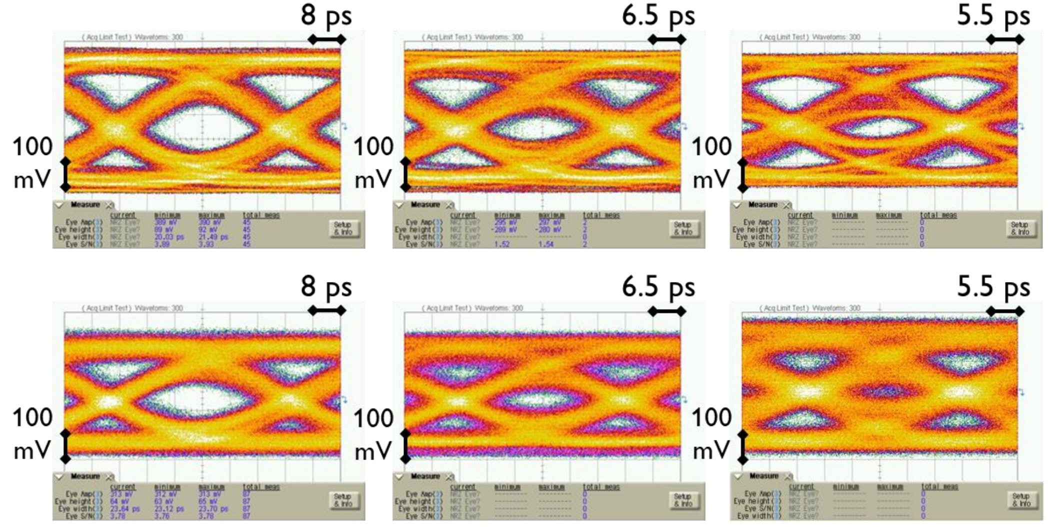
Large-signal Results Low-voltage FMZM Operation

- Standard FMZM at **25 Gb/s** (operated in **quadrature**):
  - **7 dB** optical power penalty at KP4-FEC between 4.4 V_{pp} and 1.4 V_{pp} driving conditions
  - Energy consumption estimation at **25 Gb/s** :
    - **~ 120 fJ/bit** for 1.4 V_{pp} driving
    - **~ 1.3 pJ/bit** for 4.4 V_{pp} driving

$$E_{\text{bit}} = \frac{1}{4} C_{\text{pn}} V_{\text{pp}}^2$$

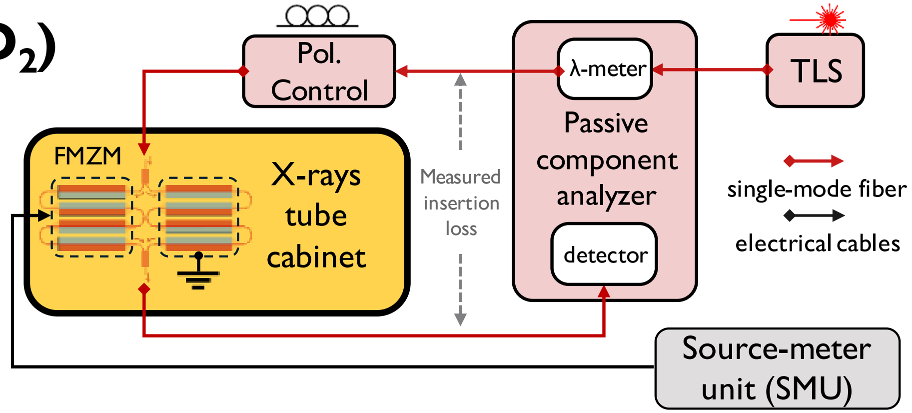
$C_{pn}(4\ V_{bias})$ ~ 250 fF

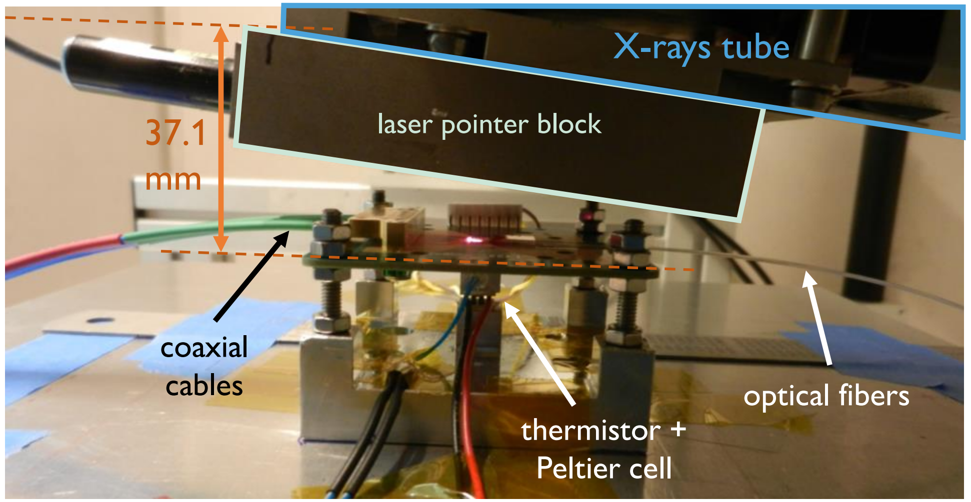


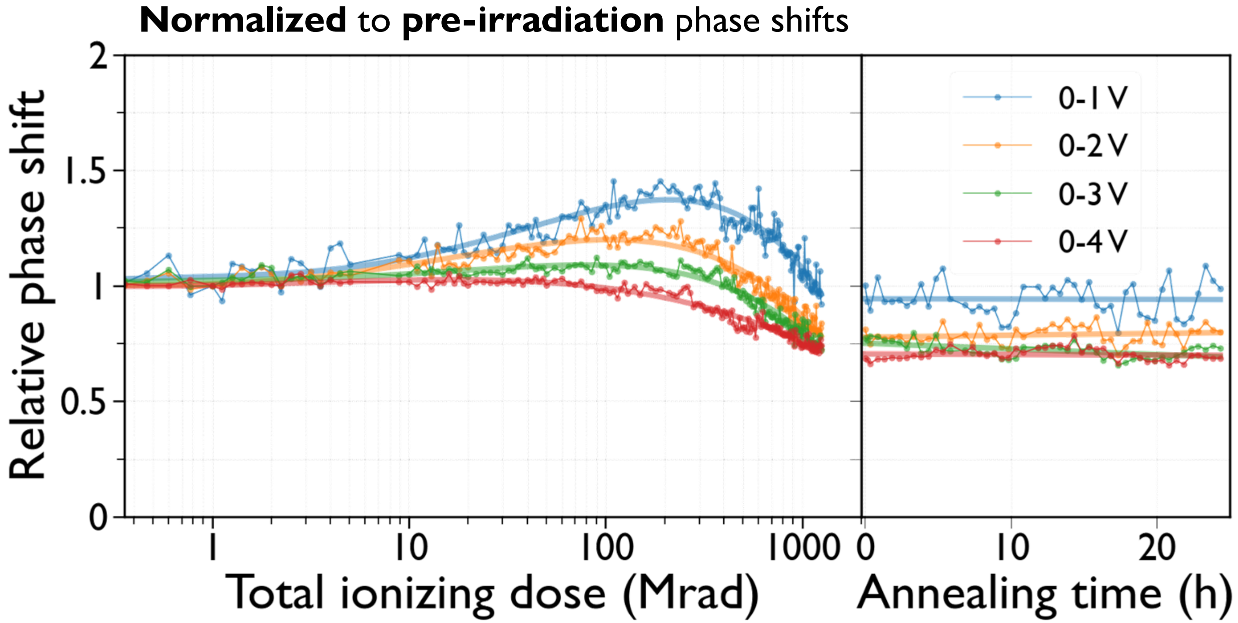


TID Irradiation Results Rad-hard FMZM

- Rad-hard FMZM irradiated with 10 keV X-rays to **1.25 Grad(SiO_2)** at 1 V reverse bias
- Phase shift versus TID extracted from optical spectra: phase shift enhancement followed by slow degradation
- No changes captured during room-temperature annealing







Conclusions

- Meandered-layout lumped-element-driven MZMs introduced for HEP applications
- Two device flavors presented:
  - **Standard FMZM**: deep-etch phase shifter design
  - **Rad-hard FMZM**: shallow-etch phase shifter design with reinforced P-side doping
  - Rad-hard version shows higher optical propagation losses and reduced modulation efficiency (trade-off with radiation hardness)
- **> 25 Gb/s** NRZ transmission validated for:
  - Both standard and rad-hard FMZM designs with **4.4 Vpp** driving with **$< 1 \cdot 10^{-9}$** BER
  - Standard FMZM with **1.4 Vpp** driving with **$< 2.4 \cdot 10^{-4}$** BER, i.e., KP4-FEC threshold
- Rad-hard design proved to be radiation-tolerant till **1.25 Grad(SiO_2) TID** with DC electro-optical testing

Thanks Stefano!

dedicated to Stefano Faralli

(Scuola Superiore Sant’Anna and INFN Pisa)

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