A 40Gb/s PAM-4 Transmitter Based on a Ring-Resonator Optical DAC in 45nm SOI CMOS

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HPC/Datacenters Interconnects

Demand for higher data-rates!

- **Within the Data Center Rack**
  10G → 25G → 50G

- **Between Data Center Racks**
  10/40G → 100G → 200/400G

- **Long Spans/Inter-Data Centers & WAN**
  40/100G → 400G → 1Tb/s

[Finisar]
Choosing The Right Modulation

NRZ vs. PAM4 @50Gb/s:

- Compare at fixed laser energy per bit
- PAM4 eye 2/3 of optical energy at Rx compared to NRZ
- Conversion to digital is not ideal ...!
Potential Solution: PAM4

• Considering non-idealities:
  – Noise
  – Samplers’ swing requirement
  – Non-linearity

• Trade-offs between NRZ & PAM4 energy-efficiency

• Proposed 400G long-reach standards:
  400G-DR4 (4x100G PAM4)
  400G-FR8 (8x50G PAM4 WDM)
  400G-LR8 (8x50G PAM4 WDM)

This work: How to efficiently generate PAM4 optical signals?
Prior Optical PAM4 Transmitters

- **Segmented Mach-Zehnder interferometer (MZI)**
  - Large footprint (~mm$^2$)
  - High optical insertion loss (>5dB)
  - Poor energy-efficiency (>1pJ/b)
  - Requires Mux/DeMux for WDM

[CISCO ISSCC 13]
Prior Optical PAM4 Transmitters

• Electrical DAC driven ring-modulator
  ✓ Small footprint and energy-efficient
  – Extra non-linearity/bandwidth limits of the DAC
  – Lateral PN junctions require custom photonics processes
  – Interconnect between CMOS and photonics diminishes efficiency!

[Image of electrical DAC driven ring-modulator]

[Roshan-Zamir OI 2016]
IBM/GF 12SOI (45nm) CMOS

- 300mm wafer, commercial process
- MOSIS and TAPO MPW access
- Advanced process used in microprocessors
- Photonic enhancement enables VLSI photonic systems
“Zero-Change” Optics in 45nm

- Photonics for free! (No modification to the process)
- Closest proximity of electronics and photonics
- Single substrate removal post-processing step

Monolithic photonics platform with the fastest transistors
Large Scale Integration

Millions of transistors + Hundreds of photonic devices

[C. Sun, Nature 2015]
Ring-resonator based Optical Links

- Ring-resonator Lorentzian transfer function
- Modulation Scheme:
  1. Deplete/Inject carriers using PN junctions
  2. $\Delta$free carriers $\rightarrow$ $\Delta$index of refraction
  3. On-Off Keying (OOK) modulation in frequency domain

[Courtesy of C. Sun]
“Spoked-ring” Resonators

- <100nm crystalline Silicon layer (MOS body layer)
- Interleaved planar PN junctions
- Enabled by advanced lithography of this process
- Spoked-shape contacts to avoid optical loss
- Q-factor > 10K

“Spoked-ring” 3D and 2D layouts [M. Wade, OFC 2014]
• Drive each segment independently
• Control resonance shift by depleting a portion of segments
• **PAM4 Transmitter**: Map each symbol to a different number of segments getting depleted
Transmission Characteristic

\[ \Delta N_e = \Delta N_h \alpha M \times \left( \sqrt{V + V_b} - \sqrt{V_b} \right) \]

\[ \Delta n = k_e \Delta N_e + k_h \Delta N_h \]

\[ \lambda_{\text{Shift}} \propto \Delta n \]

\[ T(\lambda) = 1 - \frac{A}{1 + 4 \left( \frac{\lambda - \lambda_{\text{Shift}} - \lambda_0}{\text{FWHM}} \right)^2} \]
Linearity Comparison

- Improved linearity compared to electrical DAC drive
- Eliminates the need for high-speed electrical DAC
- Higher Q-factor \( \Rightarrow \) More nonlinearity

Wavelength Shift = 20pm/V

\[ Q = 7.5K, \ \text{ER}_i = 10\text{dB} \]
Transmitter Data-path

- 16 Anode Segments (Shared cathode connected to $V_{\text{bias}}$)
- Thermometer Coding (equivalent to 4-bit binary DAC)
- Extra 2 bits used to pre-equalize ring non-linearity

![Diagram showing data path from PAM4 Symbols to Anode[i]]

- **Binary Symbols** → **2b**
- **Thermometer Codes** → **16b**
- **Programmable LUT**
- **16 x Final Serializer and inverter-based driver slice**
- **Slice[i]** → **Anode[i]**
Thermal Sensitivity

- **10GHz/K** resonance thermal sensitivity!
- Temperature variation sources:
  - Circuits, Optical power inside the ring, ...
- **Necessity of having thermal tuning feedback**
Thermal Tuning for PAM4

- Optimizes eye-opening and tune the ring constantly
- Modified controller equations for PAM4
- Symbol-Statistical (Independent of data encoding)
- Potentially can be used to adaptively set DAC codes

[C. Sun, JSSC 2016]
Clocking Scheme

- Fully digital loop [J. Crossley, CICC 2010]
- Custom designed inductor to adjust for the substrate removal
- Measured locking range: 16-22 GHz
Full Transmitter Architecture

Direct Digital-to-Optical Conversion!
Packaging & Test Setup

- Flip-chip packaged
- Single step post-processing
  - Substrate removal
- Grating coupler loss: 3.5dB
DAC Static Measurement

- Measured spectrum at low optical power ($P_L=-15\text{dBm}$)
- Measured $Q=7.5\text{K}$ (over-coupled @1280nm)
40Gb/s PAM4 Transmit-eye

- Extinction ratio (ER): 3dB, Insertion loss (IL): 5.5dB
- Laser Power: 5.5dBm
- PAM4 coding used: (0,5,10,15)
- \(42fJ/b\) driver energy efficiency
Area/Energy Breakdown

**Area Breakdown**
Total Transmitter Area = 0.06 mm²

- Photonics: 16%
- Dig. Backend (PRBS, Serializers, Thermal Tuning): 46%
- DPLL: 35%
- Modulator Drivers and LUT: 2%
- Thermal Tuning: 1%

**Energy Breakdown (in fJ/b)**
Total Transmitter Energy = 685fJ/b

- DPLL: 375
- Serializers & Backend: 250
- Thermal Tuning: 18
- Modulator Drivers: 42
# Performance Summary

<table>
<thead>
<tr>
<th>Reference</th>
<th>Wu ISSCC 13</th>
<th>Xiong OI 15</th>
<th>Roshan-Zamir OI 16</th>
<th>This Work</th>
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<td>Integration</td>
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<td>Driver Supply (V)</td>
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<td>ER/IL (dB)</td>
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<td>3/5.5</td>
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<td>PAM4 Data-rate (Gb/s)</td>
<td>20</td>
<td>56</td>
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<tr>
<td>Modulator and Driver</td>
<td>0.29</td>
<td>4.8</td>
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<td>Energy Efficiency (pJ/b)</td>
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<td>Photonics Area (mm²)</td>
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<td>Driver Area (mm²)</td>
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<td>Modulator and Driver</td>
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<td>3.6</td>
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<tr>
<td>BW Density (Tb/s/mm²)</td>
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</table>
Conclusion

- “Zero-change” 12SOI platform provides low cost & energy-efficient solution for silicon photonic links

- A 40Gb/s PAM-4 transmitter based on segmented ring-resonator optical DAC demonstrated

- 42fJ/b driver energy-efficiency (100x improvement over MZI-based PAM-4 transmitters!)

- This approach can be extended for higher order modulations (PAM-8/16)
Acknowledgment

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