A Monolithic 25-Gb/s Transceiver With Photonic Ring Modulators and Ge Detectors in a 130-nm CMOS SOI Process

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DARPA

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Migration of optical systems towards shorter reach communication
⇒ Silicon photonics become more and more important

But,

- Too many modulators and photo detectors on a circuit
- MZM requires high power consumption

Monolithic silicon photonic transceiver based on a PMR modulator
(operates at speeds greater than 25Gb/s)
**Ring Resonators**

- **Optical power transmission** $T_{opt}$ (reverse bias)

\[
T_{opt} = 1 - \frac{K_{ring}}{1 + 4 \left( \frac{\lambda - \lambda_0}{\Delta \lambda} \right)^2}
\]

- $\lambda$ = laser wavelength
- $\lambda_0$ = resonance wavelength
- $\Delta \lambda$ = linewidth of the resonance
- $K_{ring}$ = coupling coefficient of the PMR

Graph showing transmission as a function of wavelength with curves for $V_s = 0$ V and $V_s = 2$ V, indicating extinction ratio greater than 8 dB.
Ring Resonators

- Extinction Ratio

\[ P_o = P_{in} (1 - K_{ring}) \]

\[ P_1 = P_{in} \left(1 - \frac{K_{ring}}{1 + 4 \left(\frac{K_{\lambda}V_s}{\Delta \lambda}\right)^2}\right) \]

\[ E_r = \frac{1}{1 - K_{ring}} \left(1 - \frac{K_{ring}}{1 + 4 \left(\frac{K_{\lambda}V_s}{\Delta \lambda}\right)^2}\right) \]

Larger Voltage swing \(\uparrow\) ↔ Extinction ratio \(\uparrow\)

In constant Er ratio
Narrower linewidth ↔ voltage swing \(\downarrow\)

\[ \Delta \lambda = 0.1\text{nm} \]
\[ \Delta \lambda = 0.25\text{nm} \]
Ring Resonators

- **Optical quality factor**

\[ Q = \frac{\pi}{2\lambda_o} v_g n_e \tau_c \]

\( \tau_c = 26 \text{ ps (1550nm)} \)
- \( Q = 16000, \)
  \( BW = 12 \text{ GHz} \)

\( \tau_c = 13 \text{ ps (1550nm)} \)
- \( Q = 8000, \)
  \( BW = 24 \text{ GHz} \)

*in Reverse bias Photon lifetime is the limit of frequency response (Not the electric response)*

**Trade-off**

\[ BW = \frac{c}{Q\lambda_o} \]
Pre-Emphasis Driver

- Ring Modulator Driver
  - CMOS inverter structure
  - Get large swing from Low power
  - Swing V = Vdd-Vss

CMOS inverter structure
Pre-Emphasis Driver

- Pre-Emphasis for Ring Response

\[ V_S = V_C - V_A = D_k \cdot (V_{DD} - V_{SS}) + D_{k-1} \cdot 2\Delta V_H - D_{k-1} \cdot 2\Delta V_L \]

Rising Edge

\[ V_S = V_{DD} - V_{SS} + 2\Delta V_H \]

Steady State

\[ V_{DD} - V_{SS} \]

Falling Edge

\[ V_S = V_{DD} - V_{SS} - 2\Delta V_L \]
Pre-Emphasis Driver

- Pre-Emphasis for Ring Response
  - 20Gb/s
  - Bandwidth=12GHz
  - Left : Uncompensated
  - Middle : 125mV pre-emphasis
  - Right : 250mV pre-emphasis
  - Gray : Uncompensated
  - Black : 250mV pre-emphasis
Circuit Implementation

- **Waveguides**
  - 0.3 um wide (to support Single mode propagation)
  - Low-loss (a ~ 3dB/cm)
  - Over optical C- and L- bands (1520nm- 1570nm)

- **Ring modulator**
  - Radius 7.5 um
  - Critical coupling distance between ring-waveguide 450nm
  - Not thermally stabilized

- **On chip Germanium photodiodes**
  - 1.4um by 15um for the anode width and length
  - Responsivity = 0.8A/W at 1550 nm
  - C = 20pF, R = 460 Ohm
Circuit Implementation

- **Transmitter**
  - **DFF (D-type flip-flop)**
    : symbol spaced delay
  - **Level shifter**
    : Changes swing voltage
    : 300mV $\Rightarrow$ 1V
  - **Pre-emphasis**
    : which we looked at before
Circuit Implementation

- Receiver

- **TIA**
  : Variable transimpedance stage
  : current to voltage

- **MA**
  : Major amplifier

- **50 Ohm**
  : Output buffer

- **TIA response**
  : 3dB BW = ~25GHz
  : group delay = +/- 12.5 ps
Measurements

- Static ring
- Transmitter
- Receiver
Measurements

- Static ring

- Laser
  - Agilent 8164A Laser source with 81600 tunable module
  - 1560nm
  - output power = 6dBm
  - “0” : 0V
  - “1” : 2.4V
  - $K = 32 \text{pm/V}$
  - $Er$ ratio = 8dB
Measurements

- Transmitter measurements
  - Eye diagram (Uncompensated)

- Eye diagram (Compensated)
Measurements

- Transmitter measurements

Min BER => under $10^{-12}$
Measurements

- **Receiver measurements**
  - Jitter added by receiver
    
    $t_{J,RX} = \sqrt{t_{J,measured}^2 - t_{J, TX}^2}$

    \[
    \sqrt{(3.7 \text{ ps})^2 - (2.6 \text{ ps})^2} = 2.6 \text{ ps}
    \]

  - Comparison with “Photline receiver”

- Eye diagram (Compensated)
## Measurements

### Comparison to Reported 10-20GB/s Optical transceivers

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Process</th>
<th>$\lambda$ (nm)</th>
<th>Modulator</th>
<th>Modulator Supply (V)</th>
<th>Extinction Ratio (dB)</th>
<th>Receiver Sensitivity at BER = $10^{-12}$ (dBm)</th>
<th>Bit Rate (Gb/s)</th>
<th>Power (mW)</th>
<th>Area ($mm^2$)</th>
<th>Link Efficiency (pJ/bit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[34]$^1$</td>
<td>130nm CMOS</td>
<td>990</td>
<td>off-chip VCSEL</td>
<td>3.3</td>
<td>N/A</td>
<td>N/A</td>
<td>14</td>
<td>140</td>
<td>N/A</td>
<td>10</td>
</tr>
<tr>
<td>[35]$^1$</td>
<td>80nm CMOS</td>
<td>850</td>
<td>off-chip VCSEL</td>
<td>1</td>
<td>6</td>
<td>-13.5</td>
<td>4x10</td>
<td>100</td>
<td>N/A</td>
<td>2.5</td>
</tr>
<tr>
<td>[11]$^2$</td>
<td>130nm SOI</td>
<td>1550</td>
<td>on-chip MZM</td>
<td>5</td>
<td>5-6</td>
<td>-19.5</td>
<td>2x10</td>
<td>2500</td>
<td>8x5.6</td>
<td>125</td>
</tr>
<tr>
<td>[36]$^2$</td>
<td>90nm CMOS</td>
<td>850</td>
<td>off-chip VCSEL</td>
<td>20</td>
<td>N/A</td>
<td>N/A</td>
<td>10 to 18</td>
<td>99.5 to 171.6</td>
<td>5x1.25</td>
<td>10 to 9.6</td>
</tr>
<tr>
<td>This work$^2$</td>
<td>130nm SOI</td>
<td>1560</td>
<td>on-chip PMR</td>
<td>2</td>
<td>6.9</td>
<td>-6</td>
<td>25</td>
<td>256</td>
<td>1x2</td>
<td>10.2</td>
</tr>
</tbody>
</table>

*1: off-chip modulator/photodetectors/lightsource, *2: off-chip lightsource power consumption not included, N/A: not available
Conclusion

• Fully integrated optical transceiver
  – demonstrated based on a photonic ring modulator and Ge photodiode implemented in a 130 nm SOI process

• Transmit pre-emphasis
  – compensate for the electrical and optical frequency response of the photonic ring resonator
  – can continue to be used to boost data rates for PMSs to 40Gbps

• High speed modulation
  – Operation from 20 to 25Gb/s