A 3.9 ns 8.9 mW 4×4 Silicon Photonic Switch Hybrid-Integrated with CMOS Driver


IBM T.J. Watson Research Center, Yorktown Heights, NY
Outline

• Motivation
• Silicon photonics technology overview
• Integration strategies: full monolithic and hybrid
• 4×4 switch hybrid-integrated with CMOS driver
• Conclusion
Motivation

• **Goal:** develop photonic device process compatible with CMOS
  – enables high-speed, high-density interconnects for lower power, lower cost, long reach communication
  – opens up a number of new applications (biomedical, sensor, etc)

• Hybrid integration (flip-chip or wirebond) of Si photonic devices and electrical circuits:
  – ideal for early prototyping
  – important step towards full integration
  – either hybrid or monolithically integrated could be commercialized

• A 4×4 switch requires the development of all key components, highlights the advantages of the silicon photonic technology:
  – data stays in the optical domain
  – multiple data streams routed in the same device (WDM)
Outline

• Motivation
• Silicon photonics technology overview:
  – Waveguides ("SOI photonic wires"), other passive devices
  – Modulators, detectors
  – Fiber coupling
• Integration strategies: full monolithic and hybrid
• 4×4 switch hybrid-integrated with CMOS driver
• Conclusion

http://www.research.ibm.com/photonics
Silicon Photonic Waveguide

Waveguide cross-section color-coded with intensity of electric field ($\lambda = 1.55 \, \mu m$)

- Undoped Si and SiO$_2$ are transparent for $\lambda = 1.2 \, \mu m - 6.5 \, \mu m$ (this range covers the long haul optical communication C-band)
- Si surrounded by SiO$_2$ forms a dielectric waveguide (similar to single mode fiber, but much smaller due to high contrast ratio)
- Losses (2 $\mu m$ BOX) : $\sim 2 \, dB/cm$ and $\sim 0.01 \, dB/bend$ (R $\sim 5 \, \mu m$)
Silicon Photonic Passive Devices

Y-junction:

Directional coupler:

- IN$_1$ → $T_{11}$
- $T_{12}$

- Coupling length: 0.3 µm

Ring resonator:

- IN → THRU
- DROP

- Ring resonator can be used as add/drop for WDM
Mach-Zehnder Interferometer Based Modulator

- Mach-Zehnder interferometer (MZI) splits the signal into two arms, adds relative phase and then merges the arms again.
- One MZI arm contains a p-i-n diode that implements an optical phase shift through charge injection.

\[
\frac{P_{OUT}}{P_{IN}} = \frac{1 + \cos(\Delta\phi)}{2}
\]

- 50% directional couplers

- Mach-Zehnder interferometer (MZI) splits the signal into two arms, adds relative phase and then merges the arms again.
- One MZI arm contains a p-i-n diode that implements an optical phase shift through charge injection.
MZI Modulator with Integrated p-i-n Diode

Cross section of one MZI arm shows the partially etched rib waveguide with p-i-n diode

The p-i-n diode injects charge into the core of the waveguide, resulting in optical phase shift without significant loss of signal

W. Green, et al. (2007); J. Van Campenhout, et al. (2009)
Waveguide Coupled Germanium Detector

Cross section

Performance: 40 Gb/s (at 2 V bias)

Die photo

- Ge photodetector in CMOS compatible process
- Speed: 40 Gb/s
- Size: 20 µm long (~10 fF)
- Avalanche gain demonstrated at 1.5 V

S. Assefa, et al. (Nature 2010)
Edge Coupling to Standard Fiber

SiON couplers over tapered Si waveguides help mitigate the cross-section mismatch:

- Si waveguide (0.2 \(\mu\)m \(\times\) 0.5 \(\mu\)m)
- SiON waveguide (1 \(\mu\)m \(\times\) 3 \(\mu\)m)
- Single mode fiber core (9 \(\mu\)m diameter)
- Parallel fiber array (250 \(\mu\)m pitch)
- Si waveguide array (20 \(\mu\)m pitch)

Optical Coupling to Parallel Waveguides: 640 Gb/s: 4$\lambda$ in 4 waveguides at 40 Gb/s

<table>
<thead>
<tr>
<th>Input</th>
<th>WG 1</th>
<th>WG 2</th>
<th>WG 3</th>
<th>WG 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1531 nm</td>
<td>1537 nm</td>
<td>1543 nm</td>
<td>1549 nm</td>
<td></td>
</tr>
</tbody>
</table>

- Multichannel tapered coupler interfacing Si waveguides (20 $\mu$m pitch)
- 8 Tb/s/mm bandwidth density at chip edge

- Less than 1 dB coupling loss obtained from tapered glass waveguide (through SiON coupling structure) to Si waveguide

B. G. Lee, *et al.* (OFC 2010)
Outline

• Motivation
• Silicon photonics technology overview
• Integration strategies: full monolithic and hybrid
  – Monolithic integration technology announced (SEMICON 2010)
  – 15 Gb/s detector hybrid-integrated with CMOS receiver (CLEO 2011)
  – 8 Gb/s ring modulator hybrid-integrated with CMOS driver (OFC 2011)
• 4×4 switch hybrid-integrated with CMOS driver
• Conclusion
CMOS Integrated Nanophotonics

Fully integrated 6-channel WDM transceiver project (2008):

- 130 nm design rules for CMOS circuits
- 65 nm design rules for photonic devices
- CMOS FEOL integrated (Ge-first prior to activation)
- Small lithographic variations
- 0.5 mm² per transceiver channel
- Current focus: transfer to next-generation CMOS

W. Green, et al. (SEMICON 2010)
S. Assefa, et al. (talk OMM6 at OFC 2011)
http://www.research.ibm.com/photonics
15 Gb/s Germanium Photodetector Hybrid-Integrated with 90 nm CMOS Receiver

Measured 15 Gb/s eye diagram BER < 10^{-12} at -8 dBm, 1310 nm

• Both the PD and the CMOS RX are faster than 15 Gb/s
• Slowdown attributed to packaging parasitics

B. G. Lee, et al. (CLEO 2011)
8 Gb/s Ring Modulator Hybrid-Integrated with 90 nm CMOS 1-tap FFE Driver

8 Gb/s operation

(only 1 Gb/s without equalization)

FFE Driver Block Diagram:

<table>
<thead>
<tr>
<th></th>
<th>Ring Modulator</th>
<th>MZI Modulator (2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>50 µm</td>
<td>200 µm</td>
</tr>
<tr>
<td>Power</td>
<td>1.8 pJ/bit</td>
<td>5 pJ/bit</td>
</tr>
<tr>
<td>Drive voltage</td>
<td>50 mVpp</td>
<td>7 Vpp</td>
</tr>
<tr>
<td>FFE design</td>
<td>fully integrated</td>
<td>discrete components</td>
</tr>
</tbody>
</table>

J. Rosenberg, et al. (talk OWQ4 at OFC 2011)
Outline

• Motivation
• Silicon photonics technology overview
• Integration strategies: full monolithic and hybrid
• $4 \times 4$ switch hybrid-integrated with CMOS driver
  – $2 \times 2$ switch performance
  – $4 \times 4$ switch architecture
  – Circuit and package considerations
  – Testing results
• Conclusion
MZI Based 2×2 Switch

p-i-n diode phase shifter

IN$_1$ ON/OFF T$_{11}$

50% directional couplers

IN$_1$ ON/OFF T$_{12}$

30 nm

-18 dB

1.4 1.5 1.6

wavelength (µm)

transmission (dB)

ON T$_{11}$ OFF

ON T$_{12}$ OFF

J. Van Campenhout, et al. (2010)
Measured Optical Switching Times of a CMOS Driven 2×2 MZI switch

B. G. Lee, et al. (CLEO 2010)
4x4 Switch and CMOS Driver Block Diagram
4×4 Switch Configuration States

Of the $2^6=64$ possible states of the 2×2 switches, only 9 are unique. The equivalent states of the 4×4 switch differ by static power dissipation (number of 2×2 switches “ON”).

In all 9 configuration states, worst case crosstalk between channels is less than -10 dB, insertion loss ~6 dB, off chip coupling loss ~1 dB.

<table>
<thead>
<tr>
<th>State</th>
<th>MZI1</th>
<th>MZI2</th>
<th>MZI3</th>
<th>MZI4</th>
<th>MZI5</th>
<th>MZI6</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Area: 300 × 1600 µm² (relaxed layout)
Digital 90-nm CMOS Driver

- Electrical model of the p-i-n diode includes contact resistance, non-linear charge-dependent capacitance and carrier lifetime-dependent current source
- Designed to drive a wide range of capacitive loads and steady state currents with ample speed for switch applications
4x4 Switch and CMOS Driver Die Photos

Drivers with predrivers

Serial Interface

150 µm
Hybrid Packaging of CMOS and Photonics

Ni-Au Pad Metallization:

Flux-Free Solder Process:
- eutectic SnPb solder (260-300°C) plus forming gas
- ~25-30 g/bond obtained

Solder Transfer
- 75 µm pads, 150 µm pitch
- ~50 µm tall
- ~30 µm tall
- solder reflowed again to collapse columns into balls
Infrared Images of Static Optical Switching

East Input → West Output

All 6 MZI’s OFF — West Output

East Input → West Output

MZI 6 ON (1.02V) — North Output

East Input → West Output

MZI 2 ON (1.05V) — South Output

West Output
North Output
East Output
South Output

East Input

North Output
East Output
South Output

West Output
North Output
East Output
South Output

West Output
North Output
East Output
South Output
Measured routing of 40 Gb/s data

40 Gb/s modulator 4×4 Photonic Switch

1531 nm

North Input South Input East Input West Input

North Output

South Output

East Output

West Output

No U-Turn

No U-Turn

No U-Turn

No U-Turn

λ att RX

Measured routing of 40 Gb/s data
Measured routing of $3 \times 40 \text{ Gb/s}$ WDM data

1531 nm 1537 nm 1543 nm

East Input

North Output

South Output

West Output

40 Gb/s modulator

4×4 Photonic Switch

RX

EDFA

EDFA

$\lambda$

att
Measured Power Sensitivity Curves

All wavelength channels, all output configurations of the 3 × 40 Gb/s signal tested, showing ~0.5 dB spread at 10^{-12} BER
Conclusion

• Full set of CMOS compatible photonic devices:
  – waveguides, splitters, couplers, crossings, WDM structures, etc.
  – waveguide coupled integrated Ge photodetectors
  – MZI and ring based switches, modulators

• High-density, low-loss edge fiber coupling demonstrated
  – 8 parallel fibers coupled to on-chip waveguides on 20 µm pitch

• Monolithically integrated technology announced in December 2010

• Recent CMOS driven hybrid-integrated results include a 15 Gb/s receiver and a ring modulator based 8 Gb/s transmitter

• Hybrid-integrated packaging process developed

• Hybrid-integrated CMOS driven 4×4 switch fully tested

The authors gratefully acknowledge support from DARPA under contract HR0011-08-C-0102.