Silicon based integrated optical switching technology for telecom application

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Outline

| 1. Application to optical path switches for next generation ROADM |
| Ultrafast network currently being upgraded will enable and also require optical layer flexibility with optical path switches. |
| Our approach to optical switches with silicon photonics |
| Demonstration on optical switch circuits based on silicon photonics device integration |
Evolution toward next generation CDC-ROADM

ROADM: Reconfigurable Optical Add Drop Multiplexer

Conventional ROADM

- Static connection between transponders and lines
- 2-degree transmission lines
- AWG
- Transponders

Next generation ROADM

- Higher flexibility in optical layer
- Reconfigurable or dynamic connection between transponders and lines
  - Color-less
  - Direction-less
  - Contention-less
- Multi-degree transmission lines
- "Optical switching"
- Many transponders for advanced modulation format

(CDC)
CDC-ROADMs

**Configuration**

- Cut-through part with WSS
- Transponder aggregator part

**Functions**

- Colorless
- Directionless
- Contentionless

**Benefits**

- Any transponders can be used for setting up path at any wavelength for any direction.
- Each transponder can be used for multiple purposes. Multiple transponders can be used for single purpose.
- Increase in transponder usage efficiency. Reduction in transponder number.
- Shared backup scheme leading to highly reliable and cost-effective failure recovery
- Higher reconfigurability corresponding to unexpected traffic change

Several proposals for transponder aggregator

**Configuration of CDC-ROADM**

- Cut-through part with WSS
- Transponder aggregator part

**Examples of transponder aggregator using silica waveguide devices**

**Split & Select**


**AWG & Matrix Switch**

Ultra-compact optical switch based on silicon photonics

Configuration of CDC-ROADM

Mach-Zehnder TO switch element

8x8 split & select switch

Sharply bended waveguide

Efficient thermo-optical effect

Basic expectation for optical switch
Our approach to optical switches with silicon photonics

- Conventional discrete optical devices
- Design rules for their integration
- Use of sophisticated CMOS process

Silicon photonics

- Cost effectively developing high density, large scale optical device integration
- Ultra-small, low-power optical devices

Conventional discrete optical devices

- Switching element
- AWG
- Photo-detector
- Modulator

Large silicon wafer
Ultra-small optical devices using Si waveguides

**Strong light confinement into small core with high index contrast, thus sharp waveguide bending**

<table>
<thead>
<tr>
<th>Conventional SiO₂ waveguide</th>
<th>Si waveguide</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂ core Dimension: 5~7 um</td>
<td>Si core Dimension: 0.3~1 um</td>
</tr>
<tr>
<td>SiO₂ cladding</td>
<td>SiO₂ cladding</td>
</tr>
</tbody>
</table>

Large core dimension
Small index contrast
Weak light confinement
Gentle waveguide bending
(Curvature radius: 1~10 mm)

Small core dimension
Large index contrast
Strong light confinement
Sharp waveguide bending
(Curvature radius: 10~100 μm)

Comparison of AWG size
10~50 mm
100~500 μm

What generation of process technology is applied?

**Silicon photonics application**

- NW equipment
  - Optical path switch for wide area network
  - Cost 1/10
  - Size 1/10
- IT equipment
  - Optical transceiver for interconnect
  - Chip-to-chip/on-chip optical interconnect
  - Power 1/10

Small volume
Large volume

Si CMOS Process technology

Progress under Moore’s law

Rakesh Kumar, “Fabless Semiconductor Implementation,” 2008
Selecting waveguide structure compatible with process

Si CMOS process technology
Parameters representing size fluctuation
- Roughness
- Uniformity

Si waveguide technology
Size fluctuation influences waveguide properties
- Propagation loss
- Polarization dependence
- Phase error in interference devices

Option in silicon optical waveguide cross section

Contrast of effective refractive indexes at rib and slab
\[ \Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \]
AWG: Arrayed waveguide grating

Structure

Optical spectra

Silicon thermo-optical (TO) switch element

Sharply bended waveguides
- Si core with cross section dimensions of 0.3~1.5 um
- SiO₂ cladding

Mach-Zehnder type TO switch element
- 100 um
- Heater
- Electrode pads

Compact & low power
- Compact
- Low driving power
- Transparent
- Highly suitable for integrated functional devices
Basic properties of Si TO switch element

**Structure**

- Si rib waveguide
- SiO₂ cladding
- 100 μm
- TE
- TM
- 8 inch wafer
- 248-nm lithography process

**Output on-off contrast**

- Cross port
- Bar port
- ~25 dB

**Time response**

- Switching time ~15 μs

**Easily controllable**
- Cross state without heating
- Bar state with heating

**Polarization independence**

**Demonstration on optical switch circuits based on silicon photonics device integration**
Silicon optical switch using split & select configuration

8 x 8 split & select switch

Silicon optical circuit including 152 switch elements is formed within the area of 16 x 12 mm.

TO switch element

1 x 8 selector switch

Requirements

- Small footprint
- Low power
- Low loss
- Polarization independent
- Wide wavelength range
- High on-off contrast
- Ambient temperature independent
- ... 

Light propagation in silicon TO switch element

- Mach-Zehnder is symmetric.
- Without heating one arm

Ambient temperature insensitive

Destructive at bar port

Constructive at cross port

- With heating one arm

Index increase

Destructive at bar port

Constructive at cross port

Ambient temperature sensitive
Temperature characteristics of Si TO switch element

- Mach-Zehnder is symmetric, the arm lengths of Mach-Zehnder are the same. We still need to consider temp. characteristics when one arm is heated.

Refractive index change in Si when heated

\[ \Delta n = \frac{dn}{dT} \Delta T = \frac{dn}{dT} \cdot \rho \cdot P = \frac{dn}{dT} \cdot \rho \cdot \frac{V^2}{R} \]

\[ \frac{dn}{dT} \cdot \rho \cdot \Delta R \]

Temperature dependence of Si thermo-optic coefficient (dn/dT)

Temperature dependence of heater resistance (R)

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Measured temperature characteristics

Output (Bar port)

As a function of heater power

As a function of heater voltage

As a function of heater current

- 75°C
- 50°C
- 25°C
- 0°C
Light propagation in silicon TO switch element

- Mach-Zehnder is symmetric.
- Without heating one arm
  - Constructive at cross port
  - Destructive at bar port

- With heating one arm
  - Index increase
  - Constructive at bar port
  - Destructive at cross port

Ambient temperature insensitive

Mach-Zehnder is symmetric.
Without heating one arm

Ambient temperature insensitive

Without heating one arm

With heating one arm

Index increase

Adding gate part and using configuration that light blocking is done by two-stage gate elements, 1x8 selector switch part becomes tolerant to ambient temperature change

1 x 8 selector switch part

Configuration of 1 x 8 selector switch
Temperature independent, high extinction switching

**Measured transmission spectra showing on-off contrast**

For different polarization

- TE
- TM

40dB

At different ambient temperature

- 75°C
- 25°C
- 0°C

40dB

High extinction ratio (>40 dB)
Wide wavelength range (>50 nm)
Polarization independent
Ambient temperature independent under constant current drive


Toward silicon optical switch module

1 x 8 selector switch

Optical switch circuit part

Optical in/out part

8 x 8 split & select switch

8x8 optical paths can be set up using 152 TO MZ switch elements, which are integrated in the area of 12 mm x 16 mm.

Conclusion

- Silicon thermo-optical switch element
- Integration of silicon thermo-optical switches toward next generation ROADM's
- Using a devised configuration of 1 x 8 selector switch, high extinction, temperature independent optical switching is achieved.

- 8 x 8 split & select type optical switch
  - Small & Low power
  - Polarization independent (less than 0.8 dB)
  - Wide wavelength range (over 50 nm)
  - High on-off contrast (over 40-45 dB)
  - Ambient temperature independent (over the range of 0 - 75 °C)
  - Low loss
    - Internal loss excluding splitter loss (less than 5 dB)
    - Coupling loss - In progress
  - Packaging - Near future