Optical Interconnects: A Viable Solution for Interconnection Beyond 10 Gbit/sec

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Introduction: Projection of Bandwidth

- Enterprise: Distance 0.1-10km
  - 10G
  - >= 40G

- Rack-Rack: Distance 1-100m
  - 3.125G
  - 10G
  - 20G

- Board-Board: Distance 50-100cm
  - 3.125G
  - 5-6G
  - 10G

- Chip-Chip: Distance 1-50cm
  - 3.125G
  - 5-6G
  - 10G

Transition driven by cost

Silicon Photonics?
Optical Tech
Copper Tech

Transition Zone
Potential Markets for UT’s IP Portfolio

- Optical backplane
- Optical PC Board
- Passive Waveguide Components
- Active Optical Components
- Optical Biosensor
Fully Embedded Board Level Optical Interconnection

- Unique Architecture for Optical PWB (Printed Writing Board)
  - All the optical components are interposed inside the PCB
  - Solve the package problem / Reduce Cost Effects

1x12 VCSEL

1x12 PIN Photodiode

12-channel Polymer Waveguide [109 cm]

VCSEL array

Micro-via

Cu Trace

45° micro-mirror

Optical PCB
12-Channel Polymer Waveguide & 45° Micro-Mirror

Cross Section View of Laminated Optical Layer

Cu Transmission Lines for VCSEL (or PD) Integration

- PSA (Pressure Sensitive Adhesive) Film : 100 / 200 μm
- Optical Waveguide Film Layer = ~ 170 μm
Fully Embedded Board Level Optical Interconnection

Micro-via

45° micro-mirror

Cu Trace

VCSEL array

Waveguide

Photodiode

Optical PCB

Cross section view of optical PCB

Physical Dimensions of Waveguide Structures

- No. of channels : 12
- Cross-Section : $50 \times 50 \ \mu m^2$
- Channel to channel separation : $250 \ \mu m$
- Total Length : $\sim 109 \ \text{cm}$
- Curvatures : $3.68 \ \text{cm} / 1.72 \ \text{cm}$

SEM image of $45^\circ$ Micro-mirror
Master Waveguide Structures for Mold

Channel waveguides

Mirror surface

PR Waveguide St.

Output

Input
Optical Bandwidth Measurement of the 51 cm Long Waveguide

The 3-dB optical bandwidth is determined to be **150GHz** for the 51cm long waveguide.
Polyimide Based 1-to-48 Fanout H-tree Optical Waveguide on Si-Substrate
Optical Signal Distribution in a Network Card
- Flatten Optical Layer to Facilitate Embedded Structure
- ~ 10 \( \mu \text{m} \) Thickness VCSEL Formation
  - Mechanical Lapping : ~ 50 \( \mu \text{m} \)
  - Chemical Wet-etching (Citric Acid : \( \text{H}_2\text{O}_2 \)) : ~ 10 \( \mu \text{m} \)

Original VCSEL
on GaAs Substrate

Substrate Removed
VCSEL (~ 10 \( \mu \text{m} \))
Design of Cu Transmission Lines for Flip Chip Integration

- Common P-contact Transmission Lines
- Separated 12 N-contact Transmission Lines
- Cu Plated Transmission Lines

2 mm
Integration of VCSEL and PIN Photodiode with Optical Waveguide Film

- Photolithography UV-Aligner
- UV-Curable Adhesive

1x12 VCSEL

12-channel Polymer Waveguide [109 cm]

1 x 12 PIN Photodiode
Speed Measurement of Substrate Removed 850 nm Wavelength VCSEL

- Eye-diagram

- BER/Q-factor/Jitter RMS
  \[
  \text{NRZ mode} \quad \text{PRBS} = 2^{31} - 1
  \]

- ** BER/Q-factor/Jitter RMS **
  - \( V_{\text{bias}} = 2.0 \, \text{V} \)
  - \( I_{\text{bias}} = 5.0 \, \text{mA} \)
  - Ampl = 0.5 V
  - Offs = 0 V
  - Freq. = 10 Gb

- Jitter RMS = 4.6 ps
- Q-factor = 5.18
- Eye width = 71.7 ps
Speed Measurement of Substrate Removed VCSEL and PIN Photodiode

- Frequency Response of 850 nm VCSEL
- Frequency Response of 850 nm PIN Photodiode

Graphs showing frequency response for different currents and powers, with a 3dB frequency $f_{3dB} = 10$ GHz.
Coupled Field Thermal-Electric Analysis for Heat Generation of Thin Film VCSEL

- 2-D Modeling of VCSEL for Coupled Field Analysis
  - Electrical Potential: \( \sigma_z \frac{\partial^2 V}{\partial z^2} + \sigma_r \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial V}{\partial r} \right) = 0 \)
  - Joule Heating In DBR: \( q = \sigma_z \left( \frac{\partial V}{\partial z} \right)^2 + \sigma_r \left( \frac{\partial V}{\partial r} \right)^2 \)

- Material Properties (thermal/electrical) & Physical Dimensions

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<thead>
<tr>
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<tbody>
<tr>
<td>P-DBR</td>
<td>( \sigma_r = 496 )</td>
<td>( k_r = 1.2 \times 10^{-5} )</td>
<td>3.30</td>
</tr>
<tr>
<td></td>
<td>( \sigma_z = 6.6667 )</td>
<td>( k_z = 1.0 \times 10^{-5} )</td>
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<tr>
<td>N-DBR</td>
<td>( \sigma_r = 24.8 )</td>
<td>( k_r = 1.2 \times 10^{-5} )</td>
<td>3.497</td>
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<tr>
<td></td>
<td>( \sigma_z = 3500 )</td>
<td>( k_z = 1.0 \times 10^{-5} )</td>
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<tr>
<td>GaAs sub.</td>
<td>( \sigma_r = \sigma_z = 30 )</td>
<td>( k_r = k_z = 4.5 \times 10^{-5} )</td>
<td>10 ~ 200</td>
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<tr>
<td>Au</td>
<td>( \sigma_r = \sigma_z = 2.2 \times 10^{-2} )</td>
<td>( k_r = k_z = 3.15 \times 10^{-1} )</td>
<td>0.2</td>
</tr>
<tr>
<td>Copper</td>
<td>( \sigma_r = \sigma_z = 1.7 \times 10^{-2} )</td>
<td>( k_r = k_z = 3.98 \times 10^{-1} )</td>
<td>0 ~ 200</td>
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<tr>
<td>Polymer</td>
<td>( \sigma_r = \sigma_z = 10^{18} )</td>
<td>( k_r = k_z = 2.0 \times 10^{-7} )</td>
<td>30 ~ 100</td>
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- Coupled Field Analysis
  - Electric Field Analysis
    - Electrical Potential
    - Current Density
  - Thermal Analysis
    - Joule Heating in DBR
    - Heat Generation in Active Region
Experimental & Simulation Results
Thermal Resistances ($R_{th}$) of Thin Film VCSEL

中存在的Thin Film VCSEL

- **Temperature Distribution inside Thin Film VCSEL**

- **Thermal Resistances of Thin Film VCSEL as a Function of Substrate Thickness**

Simulation & Experimental Parameters
- Bias Conditions: 5 mA / 2 V
- Thickness of VCSEL = 10 µm ~ 200 µm
- Substrate Cooling Condition by TEC (25 °C)

Substrate Thinning (200 µm $\rightarrow$ 10 µm)

40 % Thermal Resistance Reduction
Effects of Thermal-Via Structures for the Fully Embedded Thin Film VCSEL

- Temperature Distribution of Thin Film VCSEL with Thermal Via

- Thermal Resistances of Thin Film VCSEL as a Function of Substrate Thickness

![Diagram of VCSEL with thermal via structures](image)

Fabricated via-hole on the optical film layer
(D = 200 mm, Aspect ratio = 0.5)

Optimized VCSEL Thickness
= 44 μm ~ 72 μm
Silicon Thin Film
Photonic Crystal Waveguide Modulator
Opal, the best known periodical structure in nature.
Schematic of Fully Embedded External Modulator for Analog Signal Transmission

- EO Waveguide Modulator
- Vias
- Driving Electrode
- CW Laser Diode
• In-plane structure: Photonic crystal waveguide

• High dispersion enhances modulation efficiency, up to 100 times
# Key Performance Improvement

<table>
<thead>
<tr>
<th></th>
<th>Conventional Mach-Zehnder Modulator</th>
<th>Proposed Si PCW Modulator</th>
<th>Improvement Factor</th>
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<tbody>
<tr>
<td><strong>Size</strong></td>
<td>~ 4mm</td>
<td>~ 40 um</td>
<td>100 X reduction</td>
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<tr>
<td><strong>Power consumption</strong></td>
<td>~ 0.3 W</td>
<td>~ 0.01 W</td>
<td>10X to100X reduction</td>
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<td><strong>Integration</strong></td>
<td>No integration potential</td>
<td>Potential for high density integration</td>
<td>N/A</td>
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* Conventional Mach-Zehnder modulator performance represents typical specifications.
Rough sidewall without post-etching oxidation

Focus Ion Beam (FIB) nano-polished endface

High smoothness, exact round shape

2-D Image

3-D Image

JEOL JBX-6000FS/E E-Beam Nano-Lithography

FEI Strata DB235 Dual Beam SEM/FIB Nano-characterization System

Plama-Therm 790 Si and SiO₂ Reactive Ion Etching (RIE)
Micrographs of Mach-Zehnder (MZ) modulator: electrodes, pads, and photonic crystal waveguides (in lighter color)

Y-junction of the MZ modulator, the rib waveguide splits as it extends up. Two 4μm wide air-trenches (etched through the entire upper silicon layer) separate the rib waveguides from the surrounding silicon.
Photonic Crystal MZI Modulator
- more SEM micrographs
High-speed measurement set-up
Switching characteristics: Modulation traces

\( \lambda = 1541 \text{ nm} \) and \( I_{tr} = 7.1 \text{ mA} \)

Modulation depth = 92%

Operating wavelength: \( \lambda = 1541 \text{ nm} \)

Applied voltage: \( V_{on} = 2 \text{ V} \), \( V_{off} = -1 \text{ V} \)

1 Gbit/sec