Development of Low-Cost Manufacturing Methods for Volume Production of Optical Printed Circuit Boards

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IBM Symposium, 18-19 November 2009
T.J. Watson Research Center, Yorktown Heights, NY 10598, U.S.A
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- Implementation
  - R-stage (Research) projects & results
    - Waveguide polymers
    - Optical waveguides on cards and backplanes
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      - Optical layer integration
    - Optical coupling structures
      - I/O-1: Device-to-waveguide
      - I/O-2: Card-to-backplane
    - Demonstrator for 10Gbps chip-to-chip data link
  - D-stage (Development) projects & results
    - Process scaling from lab to LAP
    - Performance metrics and reliability
- Summary
Serve through People……Connect through Technology
R&D started 2003

Feasibility studies, White papers, Concept studies, Concept protos

Past projects

- Materials and manufacturing-1
- O/E-PCBs for datacom apps
- WGs for illumination
- 3D micro structuring
- Optical Backplane-1
- Low-cost Tx modules
- Univ. co-operation

PARTNERS

VTT, Finland
- Optical measurements
- Optical design, simulation and modelling
- Opto-mechanics
- O/E-pkg and assembly

MAIL
- R&D projects
- Customer projects
- Design qualification
- Process support

S. China
- Guangzhou, China

Proto Lab & S/V 2009

N. China
- Shanghai, China

Current projects

- Sample Protos, Design Guidelines, Test engines, Reliability tests

GME
- Materials development and testing center

SMST
- Proto-Lab team
- Design qualification
- DFM
- Waveguide characterization and testing

SME
- CAD/CAM
- OE-PCB mnf
- Reliability testing
- Production proto line (2010)

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Materials and manufacturing-2

Simulation + Modelling

Reliability

HDPUG - Opto interconnect

Meadville Confidential
Drivers for Optical Backplanes

• The continuing growth of data rates in servers, routers and high-bandwidth computing systems
• The trend in μ–processor architectures to many-core
  – Increase in chip-to-chip I/O bandwidth need at processor/memory interfaces and in multi-processor systems
• Challenges or gaps
  – CPU to memory latency
  – Mismatch of required and available bandwidth
  – Limited speed/physical line: 10-20 Gigabit/sec
  – Complex realization of thousands high-density lines at > 10 Gb/s
• Potentials of Optics
  – Higher interconnect density
  – Higher data rate per channel

Electrical
Complex circuits, high material cost, lower link length, signal integrity, increasing power consumption

Optical
Terahertz bandwidth, low loss, low cross-talk, low EMI/EMC, scalable architecture (10, 20, 40Gb/s), low weight
Channel Density – Optical vs. Copper

Optical polymer waveguides (25x50 µm channels at 100 µm pitch) for 12x 10+Gbit/s data transmission rate.

→ 100+ Gbit/s/ millimeter

<table>
<thead>
<tr>
<th>Core [µm]</th>
<th>Pitch [µm]</th>
<th>Density (Gbit/s/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50x50</td>
<td>250</td>
<td>40 Gbit/s/mm</td>
</tr>
<tr>
<td>50x50</td>
<td>100</td>
<td>100 Gbit/s/mm</td>
</tr>
<tr>
<td>35x35</td>
<td>62.5</td>
<td>160 Gbit/mm</td>
</tr>
</tbody>
</table>

Differential strip lines (80x7 µm lines at 460 µm pitch) for 2x 10Gbit/s data transmission rate.

→ 28.5 Gbit/s/ millimeter

(Source: IBM)

1D arrays, 10 Gbit/s/ch, crosstalk <-30dB
Applications

- Optical Backplanes
- OE-PCBs and Modules e.g daughter cards
- Optical and OE Flexes, including active signal cables
- O/E-package substrates (OE-BGA, OE-MCM)
- OE-SIPs (e.g. RF-over-fiber)
- Communication components, FTTx
- Illumination with waveguides – Touch screens and UI lightning
Optical Electrical Backplane – Card Concept

- Daughter card
- Transceiver module (Tx/Rx) with optical I/Os
- Optical (OE) Connector
- Optical Printed Circuit Board (OE-PCB)
- Coupling I/O
- Optical waveguides

**Copper layers** for power, control signals and low speed signals

**Optical channels** for high speed serial signals between cards
Specifications – Cards and Backplane

- Cost: few $/Gbit/s per link
- Board-to-board data link length: ~1 m
- Channel data rate: > 10 (15, 20) Gbit/s
- Number of channels: 24, 32, 48 → Aggregate data rate > 200 Gbit/s
- Channel density: 250 µm pitch (4 ch/mm), 62.5 µm pitch (16 ch/mm)
- Bi-directional data
- 2D WG arrays with multiple optical layers
- Power consumption: < 12.5 mW/Gb/s for Tx-Rx pair
- Passive O/E hybrid backplane
  - Core dimensions: Ø < 50 µm
  - Core & Clad height/width control: < 5 µm
  - Passive alignment of parts
  - Power budget: < 13 dBm
    - Tx-to-WG loss: < 2 dB
    - Channel loss: ~0.05 dB/cm
    - Card-to-BP: < 2 dB
    - WG-to-Rx: < 3 dB
- Wavelength: 850 nm, 1300 nm
Implementation
A feasibility test vehicle with different concept alternatives
Physically separated build to allow testing
Optical-PCB with
- Polymeric 2D channels on FR4
- Various NA, WG L/S and component designs
- Integrated out-of-plane couplers

Optical subassemblies with
- VCSEL/PD arrays with driving ICs assembled on LTCC modules
- OE-modules with micro-optic couplings assembled on HF-substrates

→ Feasible WG materials, process and O/E-PCB design
→ Feasible coupling concept
Fabricated Polymer Waveguides for Optical Backplanes

- **Waveguide Material**
  - UV curable acrylic polymer
  - Propagation loss @ 850nm: 0.04 dB/cm
  - Temperature resistance: up to 350°C

- **Waveguide Properties**
  - Size: 50x50 µm
  - Index contrast $\Delta$: 0.03, NA=0.3

- **Components and Arrays**
  - Linears, splitters, crossings
  - Arrays with fiber-pitch: 250µm
  - Up to 32 channel high density arrays
Waveguide Core Shape Control – UV Cure Kinetics

- Kinetics of Photoinitiated Radical Polymerization
  - Chain Length
  - Chemical structure of oligomers
  - Initiation efficiency
  - Influence of light intensity
  - Influence of atmospheric oxygen

- In UV curable systems
  - Initiation rate and the cure depth is controlled by photoinitiator

- To achieve a deep-through cure by frontal polymerization
  - Use of initiator with highest initiation efficiency to result fast photobleaching during UV exposure
Characterization – Channel Propagation Loss

• Experimental results
  – Propagation loss for commercial acrylate and epoxy waveguide polymers
  – Losses independant of channel width (25, 50 and 70 µm)
  – Losses increased significantly in 1.3 µm and 1.55 µm (2nd and 3rd) telecom windows
  – Highly sensitive to process defects & sidewall roughness
Channel Loss of Waveguides (L=79.5cm)

- Acrylate-based waveguide material
- Waveguide loop
  - Total length L=79.5cm
  - 6x180° turns and 2x90° S-turn
  - 6x over crossings
  - Minimum bending radius $R_{\text{min}} = 14.5$ mm
- Loss at 840 nm
  - Insertion loss 11.5 – 13.5 dB
  - Waveguide transmission loss $\sim$0.08 - 0.1 dB/cm
Side Wall Roughness vs. Channel Loss

\[ \lambda = 850 \text{ nm}, \text{ Core } 100\mu\text{m} \times 100\mu\text{m}, n_{\text{core}} = 1.56, n_{\text{clad}} = 1.49 \ (\text{NA} = 0.46) \]

Source: IT-Information Technology 45 (2003), 79-86

Core "Micro" roughness : < 5 nm

Cladding "Macro" roughness (L=240 µm)

Core "Macro" roughness (L=300 µm)

White light interferometer (Wyko NT 2000)

LSCM, Solarius LT 8010, step 50 nm

Ra < 25 nm

Ra < 30 nm

Surface Statistics:
- Ra: 3.57 nm
- Rq: 4.53 nm
- Rz: 51.88 nm
- Rt: 75.47 nm

Tool Options:
- Mag: 51.3 X
- Mode: VSI

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1st Level Coupling – Concepts & Analysis

Indirect coupling with micro-optics
- SMT packaged OEs
- 90-deg beam turn
- Loosest tolerance
- "Chip-like approach"
- Complex I/O
- Low loss μ-optics and beam turn
- No comm.OE- pkgs

Indirect coupling without micro-optics
- Flip chip OEs
- 90-deg beam turn
- Simple I/O
- FC OEs available
- High accuracy critic.
- Low loss beam turn

Direct coupling
- OE-chip in cavity or plugg-in rod
- No beam turn
- Simple I/O
- Low loss I/O
- WG end face critic.
Characterization of O-PCBs

- Path Losses and Optical Alignment Tolerances, using
  - Precision translation stages for fibre-to-waveguide coupling
  - Fibre-coupled (850 nm) light source; match fiber NA and core diameter with waveguides
  - Power meter coupled to step-index fibre; fibre NA and core diameter a bit larger than of waveguide

- Data transmission: Eye Patterns and Bit-Error-Rate; using PRBS data generator (and high-speed optical Tx & Rx)
On-Card Link Tests – Eye Diagrams at 10 Gb/s

**Electrical transmission on FR4**

**Electrical test line**
L=8.2cm, FR4

10Gbit/s

**Optical data transmission on FR4**

**Sender test**  
Tx-MMF

4Gbit/s  
10Gbit/s

**Optical waveguide**  
MMF-WG-MMF

10Gbit/s  
5Gbit/s

**Full link**  
Tx-MMF-Rx

10Gbit/s  
10Gbit/s

The 10Gbps $2^7-1$ PRBS signal was generated by Maxim MAX3952 evaluation kit. Eye diagrams were measured by HP3480 Digital Communications Analyzer (DCA). The reference signal was measured by connecting the generator cables and analyzer cables directly by SMA bulk connector. The reference signal is depicted in Figure 57.
Two Separate Microlens Arrays – BGA Alignment Tolerance

Loss increases only <1 dB, when module-to-board distance increased to 1 mm (i.e. good collimation between microlenses)

Waveguide width 75 µm

Waveguide width 50 µm
Link Loss Analysis

- Source power: 0 dBm (Target), 0 dBm (Measured)
- Coupling loss at transmitter: 0.5 dB (Target), 2 dB (Measured)
- Coupling I/O: Lens2-mirror-WG: 3 dB (Target), 5 dB (Measured)
- Waveguide loss: 4 dB (Target), 4 dB (Measured)
- Coupling I/O: WG-Mirror-Lens3: 3 dB (Target), 5 dB (Measured)
- Coupling loss at receiver: 0.5 dB (Target), + (Measured)
- Received power: -11 dBm (Target), -15 dBm (Measured)

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Coupling...1 – Integrated 45° μ-Mirrors

Optical coupling from/to waveguides

- Integrated 45° beam couplers for VCSEL-WG interface
- Short optical path for direct coupling without micro-optics with flip chip VCSELs
- Angle accuracy 45° ± 0.5°
- Surface roughness: Ra < 30 nm
- Coupling loss
  - 1.6 dB (TIR, measured)
  - < 0.5 dB (HR coat, simulated)
- Fiber-fiber test with MMF in Ø 50µm for 50 µm WG, lower loss expected by SMF
Coupling...2 – Curved μ-Mirrors

Optical coupling from/to waveguides
- Integrated parabolic/circular shaped micro mirrors for beam down-turns
- Multiple optical functions: 90° turn, focus/collimation (in/out)
- Low tolerance for geometric inaccuracies
- Surface roughness: Ra < 25 nm
- Coupling loss
  - 0.33 dB (TIR [1])

[1] ETRI 2004
Volume Scale O/E-PCB Manufacturing

**Targets**
- Volume manufacturing of small size OE-PCBs and optical backplanes
- Panel size up to 500 x 600mm

**Challenges**
- Fabrication of low-loss waveguides
  - Channel length $L_{\text{typ}}$ 15-75 cm – defects vs. loss vs. yield
  - Loss spec. $< 0.1$ (0.05) dB/cm *with curves and crossings*
  - Roughness $< 50$ nm in sidewalls
  - Thermal stability: Pressing conditions & Lead-free compliance
  - Chemical stability: Alkaline and acid solutions, contamination, absorption, moisture,..
  - High sensitivity to process errors
- I/O end face and beam turns $< 1$-3 dB per I/O
- Large board size
  - Deposition and patterning with high uniformity & accuracy
  - Bending of PCB – stress-induced errors to RI & loss
  - Adhesion strength
  - Material cost in development
# Waveguides & I/O’s: Features and Specifications

<table>
<thead>
<tr>
<th>Unit or criteria</th>
<th>Target Spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Straights</strong></td>
<td></td>
</tr>
<tr>
<td>[dB/cm]</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Curves</strong></td>
<td></td>
</tr>
<tr>
<td>[dB] per 180° bend, R=20mm</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>R\textsubscript{min} [mm]</strong></td>
<td></td>
</tr>
<tr>
<td>for 0.5 dB per 180° bend, Flex-WGs</td>
<td>&lt;2.5</td>
</tr>
<tr>
<td><strong>Crossings</strong></td>
<td></td>
</tr>
<tr>
<td>[dB]</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Splitter</strong></td>
<td></td>
</tr>
<tr>
<td>[dB] per 50-50 split</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Dispersion</strong></td>
<td></td>
</tr>
<tr>
<td>[Gb/s] Open eye</td>
<td>≥10 (&gt; 1m)</td>
</tr>
<tr>
<td><strong>Coupler (1\textsuperscript{st}), chip-to-WG</strong></td>
<td></td>
</tr>
<tr>
<td>[dB] per turn (out-of-plane)</td>
<td>&lt; 1</td>
</tr>
<tr>
<td><strong>Coupler (2\textsuperscript{nd}), WG-to-conn</strong></td>
<td></td>
</tr>
<tr>
<td>[dB] per interface</td>
<td>&lt; 2</td>
</tr>
<tr>
<td><strong>Substrate</strong></td>
<td></td>
</tr>
<tr>
<td>Rigid, flex</td>
<td></td>
</tr>
<tr>
<td><strong>Channel length</strong></td>
<td></td>
</tr>
<tr>
<td>[m] OE-PCBs, O-flex, BPs</td>
<td>0.1- 1</td>
</tr>
<tr>
<td><strong>Core dimensions</strong></td>
<td></td>
</tr>
<tr>
<td>[µm] Multimode, 35-70</td>
<td></td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td></td>
</tr>
<tr>
<td>[ch/mm] (pitch, L/S)</td>
<td>16 (62.5, 35/27.5)</td>
</tr>
<tr>
<td><strong>Layer count</strong></td>
<td></td>
</tr>
<tr>
<td>Optical layers</td>
<td>2-4</td>
</tr>
</tbody>
</table>

Numbers at \( \lambda = 850\text{nm} \)
Table 1.B.1. Commercial polymers. Photoimageable liquid/ dry films OWG/WR materials for multimode WGs on PCBs. Excluding non-photoimageable (e.g. RIE), moldable or ink-jet materials

<table>
<thead>
<tr>
<th>Type</th>
<th>Loss [channel]</th>
<th>RI (Nco)</th>
<th>RI (Ncl)</th>
<th>Δ (%)</th>
<th>NA</th>
<th>L/F</th>
<th>APPL</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>0,04</td>
<td>NA</td>
<td>NA</td>
<td>1,586</td>
<td>1,543</td>
<td>2,7</td>
<td>0,37</td>
<td>FILM MM</td>
</tr>
<tr>
<td>Siloxane</td>
<td>0,08</td>
<td>0,24</td>
<td>0,50</td>
<td>1,510</td>
<td>1,490</td>
<td>1,3</td>
<td>0,24</td>
<td>LIQ SM,MM</td>
</tr>
<tr>
<td>Acrylate</td>
<td>0,04</td>
<td>NA</td>
<td>NA</td>
<td>1,550</td>
<td>1,520</td>
<td>1,9</td>
<td>0,30</td>
<td>LIQ SM,MM</td>
</tr>
<tr>
<td>Siloxane</td>
<td>0,05</td>
<td>0,20</td>
<td>0,60</td>
<td>1,555</td>
<td>1,534</td>
<td>1,4</td>
<td>0,25</td>
<td>LIQ SM,MM</td>
</tr>
<tr>
<td>Acrylate</td>
<td>0,08</td>
<td>0,35</td>
<td>1,60</td>
<td>1,510</td>
<td>1,490</td>
<td>1,3</td>
<td>0,24</td>
<td>FILM SM,MM</td>
</tr>
<tr>
<td>Epoxy</td>
<td>0,10</td>
<td>NA</td>
<td>NA</td>
<td>1,587</td>
<td>1,572</td>
<td>0,9</td>
<td>0,22</td>
<td>LIQ SM,MM</td>
</tr>
<tr>
<td>BCB</td>
<td>0,80</td>
<td>0,80</td>
<td>1,50</td>
<td>1,550</td>
<td>1,500</td>
<td>3,2</td>
<td>0,39</td>
<td>LIQ SM</td>
</tr>
<tr>
<td>Siloxane</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>LIQ SM,MM</td>
</tr>
<tr>
<td>PNB</td>
<td>0,03</td>
<td>-</td>
<td>-</td>
<td>1,54</td>
<td>1,50</td>
<td>2,6</td>
<td>-</td>
<td>LIQ MM</td>
</tr>
<tr>
<td>Epoxy</td>
<td>0,10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>FILM MM</td>
</tr>
<tr>
<td>Polysilane</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>LIQ MM</td>
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<tr>
<td>Epoxy</td>
<td>0,10</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>FILM MM</td>
</tr>
<tr>
<td>Polyimide (-F)</td>
<td>0,18</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>FILM MM</td>
</tr>
</tbody>
</table>
Optical Evaluation Card Designs

Lower cladding (clad-1)

Core

Top cladding (clad-2)

50 µm

50 µm

100-250 µm

25-70 µm

50 µm
Base Materials for Opto-Electronic PCBs

$T_g$ vs. $T_d$

<table>
<thead>
<tr>
<th>Material</th>
<th>Layer Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hitachi HE-679G</td>
<td>High Layer Count</td>
</tr>
<tr>
<td>Doosan DS-7402H</td>
<td>High Layer Count</td>
</tr>
<tr>
<td>Shengyi S-1165</td>
<td>Low Layer Count</td>
</tr>
<tr>
<td>Doosan DS-7402</td>
<td></td>
</tr>
<tr>
<td>Panasonic R-1566W</td>
<td></td>
</tr>
<tr>
<td>Panasonic R-1566V</td>
<td></td>
</tr>
<tr>
<td>Hitachi BE-67GJ</td>
<td></td>
</tr>
</tbody>
</table>
Base Materials for Opto-Electronic PCBs

$D_k$ vs. $D_f$

![Graph comparing dielectric constant and insertion loss for various materials.](Image)
Optical PCB (2+W), Optical Buildup, Side-to-Side O-VIAs

- 2+W
- Rigid OE-CB, FR4
- Thickness 0.95 mm
- Optical layer thickness: 275 µm
- Polymer waveguides
- NA=0.18, $\alpha \sim 0.1$ dB/cm at 850 nm
- Integrated 45-deg beam couplers
- Optical vias from side-to-side
- Channel width/pitch: 100µm/1mm
- Large core and loose pitch for fast characterization e.g. in reliability tests
Optical PCB (2+W+2), High Density Multichannel Array in Optical Inner Layer

- 2+W+2
- Rigid OE-CB, FR4
- Thickness 2.0mm
- Optical layer thickness: 115 µm
- Channel width: 25-70µm
- Standard fiber pitch: 250 µm
- High density pitch: 100 µm
- Polymer waveguides
- NA=0.18, α ~ 0.1 dB/cm at 850nm
- Integrated 45-deg beam couplers
- Aggregate bandwidth: 125 Gbit/mm (12.5 Gb/s source)

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Optical PCB (2+W), High Density Small Feature WGs in Optical Buildup

L/S 12/88 µm, 25/75, 50/50 µm

- 2+W
- Rigid OE-CB, FR4
- Thickness 0.4 mm
- Optical layer thickness: 125 µm
- Channel width: 6, 12, 25, 50 µm
- High density pitch: 100 µm
- Polymer waveguides
- NA=0.18, α ~ 0.1 dB/cm at 850 nm
- Aggregate bandwidth: 125 Gbit/mm (12.5 Gb/s source)
2nd Level Coupling – Concepts & Analysis

**90°-in-optics**
- Connector at card edge
- 90-deg beam turn inside conn.
- With or without micro-optics
- WG end face critical
- Near commercial connectors

**Butt coupling**
- Connector at card edge
- Direct coupling, no beam turn
- No waveguides on cards
- Potentially low loss
- Manufacturing tolerances criticals
- WG end face critical
"EcoSystem" for Optical Board-Level Communication

TECHNOLOGY

- Board-level waveguide technology
- Devices + Pkgs with E/O/E conv. and optical I/Os
- Optical coupling techn. – 1st & 2nd level
- Computer / system architectures
- Simulation and design tools
- Techn. standards

INFRASTRUCTURE

- Mass-production and asse. techniques and tools
- Supply chain, multiple sources

Commercial viability
Summary

- High channel density over copper is one of the key drivers for embedded optical waveguides on PCBs
- Manufacturing of waveguides, out-of-plane couplers and optical vias on PCBs on panel scale boards challenging, yet possible
- Coupling and alignment accuracies are the most challenging parts in realization of full optical card-backplane data link
- Reliability of materials and waveguides proven, – need for system-level tests and specified performance targets – Telcordia, IPC, LF
- To meet cost target for opto
  - Volume scale high yield manufacturing of optical PCBs and backplanes
  - Applications and first-entry products
Meadville value proposition / Business strategy

Your truly One Stop Solution Partner!

- Continual Investment in Technology
- Increased Capacity for High-End and Complex PCBs
- Capitalising on High Margin, Strong Growth Products
- Early Involvement in Product Development
- Strategic Partnership with Key Accounts

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Thank You!
Additional Data: Optical Design and Modelling
OPTICAL DESIGN WITH ALIGNMENT TOLERANCE ANALYSIS

Optimization of design for assembly

- Based on non-sequential ray tracing (using ASAP software)
  - 3-D optomechanical system model
  - Multimode VCSEL beam (measured profile)
  - Ray-trace propagation through waveguide

1) Sensitivity analysis => Most critical tolerances are found
2) Monte Carlo analysis => Statistical information about performance (≈yield)
   - Input parameters: fabrication & assembly tolerances
   - All variables are simulated simultaneously
   - Large number of randomly chosen perturbed systems

Example:
- Fiber coupling
- Optical interconnect on circuit board

Measured VCSEL beam
### Example: OPTICAL DESIGN WITH ALIGNMENT TOLERANCE ANALYSIS

<table>
<thead>
<tr>
<th>Tolerance parameter</th>
<th>Lens arrays</th>
<th>VCSEL &amp; PD</th>
<th>Tx &amp; Rx modules</th>
<th>Mirrors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shift x, y, z</td>
<td>± 10 / 15 µm</td>
<td>± 5 / 8 µm</td>
<td>± 20 / 60 µm</td>
<td>± 10 µm</td>
</tr>
<tr>
<td>Tilt x &amp; y</td>
<td>± 0.1° / 2°</td>
<td>± 1°</td>
<td>± 1°</td>
<td>± 0.5°</td>
</tr>
<tr>
<td>Tilt z</td>
<td>± 0°</td>
<td>± 0°</td>
<td>± 1°</td>
<td>± 0.5°</td>
</tr>
</tbody>
</table>

**Distributions of Monte Carlo systems with alternative tolerance parameter sets**

![Graph showing coupling loss in dB vs. number of M.C. systems for different tolerance parameter sets.](image)
SIMULATION OF MICROLENS SCHEME

Optimization by sensitivity analysis

Model of full optical channel

VCSEL

Detector

Microlenses

Lightguide

Mirror

Coupling loss [dB]

VCSEL-lens distance (nm)

Lens-mirror distance (nm)
TOLERANCE ANALYSIS OF MICROLENS SCHEME

<table>
<thead>
<tr>
<th>Tolerance parameter</th>
<th>VCSEL &amp; detector</th>
<th>Individual lenses</th>
<th>Stacked lens pairs</th>
<th>Transmitter &amp; receiver modules</th>
<th>Mirrors</th>
<th>Receiver module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shift x,y</td>
<td>± 5 µm</td>
<td>± 10 µm</td>
<td>± 5 &amp; 10 µm</td>
<td>± 15 µm</td>
<td>± 10 µm</td>
<td>± 15 µm</td>
</tr>
<tr>
<td>Shift z</td>
<td>± 5 µm</td>
<td>± 10 µm</td>
<td>± 10 µm</td>
<td>± 15 µm</td>
<td>± 10 µm</td>
<td>± 15 µm</td>
</tr>
<tr>
<td>Tilt x,y</td>
<td>± 1°</td>
<td>± 0.1°</td>
<td>± 0.5°</td>
<td>± 1°</td>
<td>± 0.5°</td>
<td>± 1°</td>
</tr>
<tr>
<td>Tilt z</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
</tbody>
</table>

Distribution of 1000 Monte Carlo systems