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Convergence Challenges of Photonics with Electronics

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Why Convergence?

- **No Convergence By Competition With Silicon Electronics**
- **Convergence By Complimentary Functionality**
 - Higher Bandwidth
 - Lower Signal Latency
 - Lower Heat Dissipation
- **Must Be At Cost Point of Silicon Electronics**

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Convergence Applications

- **Communication**
Board-to-Board, Chip-to-Chip
- **Optical Clocking**
- **Cameras**
Camera Integration in Portables
- **Displays & Illumination**
Advances in LED Brightness, RGB
Thermal Packaging Challenges

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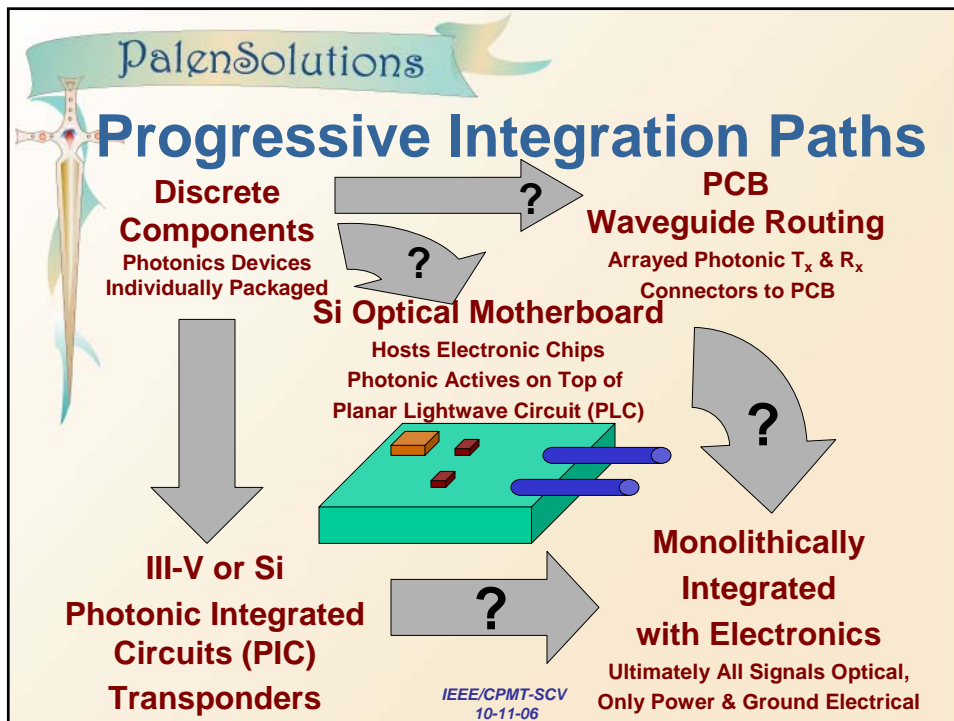
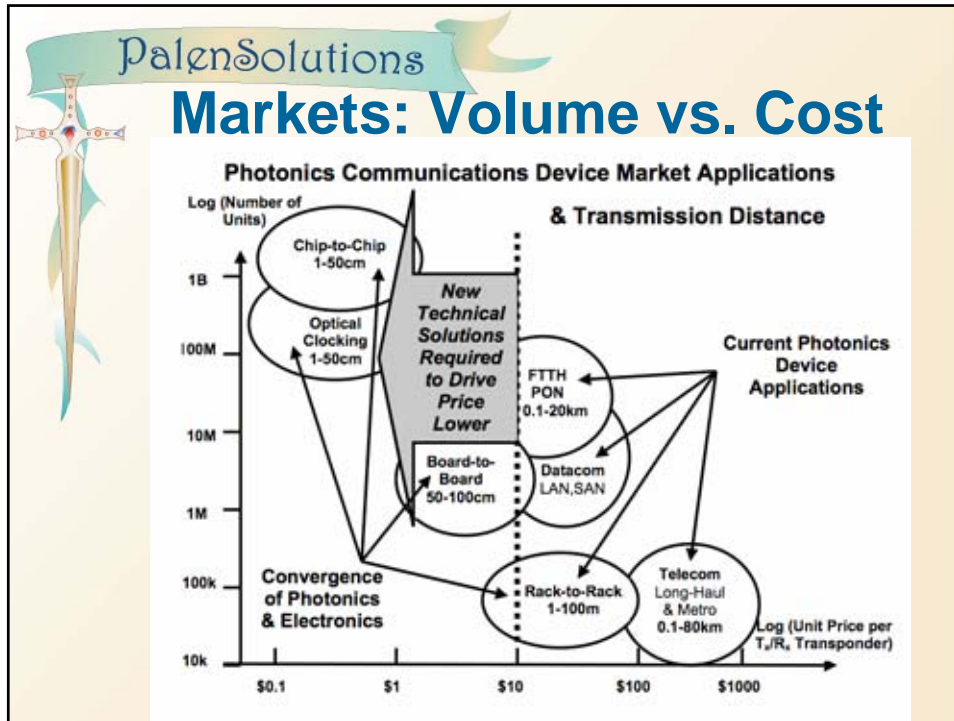
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Communications Convergence

- **Processing Challenges**
Compatibilities with Integration Level
Materials Platform
- **Cost Challenges**
Optical Interface Assembly
Integration Levels
Light Source
Market Size - # Units

Photonics is a Relatively Small # Units Market

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Cost Challenges - 1

- **Reduce Number of Optical Assembly Steps**
Historically Non-Planar Photonics Assemblies
- **Optical Alignment Tolerances**
Active vs. Passive Alignment
- **High Photonic Device BOM Cost**
- **Custom Assembly Equipment**
Large Labor Content
Off-Shoring of Manufacturing
Fiber Handling

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Cost Challenges - 2

- **Wafer Scale Integration**
Materials Platform
Waveguides & Photonic Elements
- **Processing Compatibility**
CMOS, III-V, SOB, Assembly
- **Light Sources**
Optical Coupling
Hermetic Seal & Reliability

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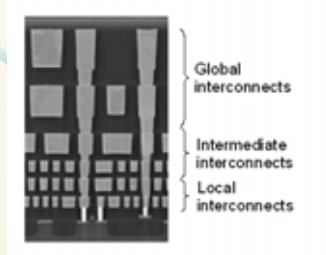
Dimensions Compatibilities

- **Si Feature Size Node**
130nm --> 90nm --> 60nm -->
- **Optical Waveguides**
0.2-0.5 μ m Core Planar Waveguides
9 μ m Core Single Mode Fiber
- **Wafer Size**
Si: 200mm & 300mm
III-V: 2", 3", 4"

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Si Monolithic Integration: Where Put Waveguide?



- **On Top of Chip**
Ridge Waveguides
- **In The Middle of Routing Layers**
Significant Process Interruption
- **Underneath Transistors**
Optical Ready Substrate Concept
US Patent 7,043,106

- **Side-By-Side**
Photonics & Electronics Blocks

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Waveguide Options

- **High Index Contrast**
 - Ridge Waveguides
 - Si Core, Silica Cladding
 - Sharp Turning Radii, down to 2 μ m
 - Materials: Si, Si₃N₄, SiO₂, + others
- **Low Index Contrast**
 - Large Turning Radii
- **Waveguide Roughness**
 - Dominates Optical Losses

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CMOS Integration Issues

- **Materials**
 - CMOS: no Au
 - Optical Properties of FEOL & BEOL Layers
- **Processing Temperatures**
 - FEOL: High Temperatures
 - BEOL: Routing Layers
- **Optical Coatings**
 - Wavelength Selective & AR Thin Film Dielectric Filters
- **Planarization**
 - CMP Compatibility
 - Larger Dimensions & Depths of Optical Components
 - Deep Etch Times

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Materials Platforms Si, SOI, SOB, III-V

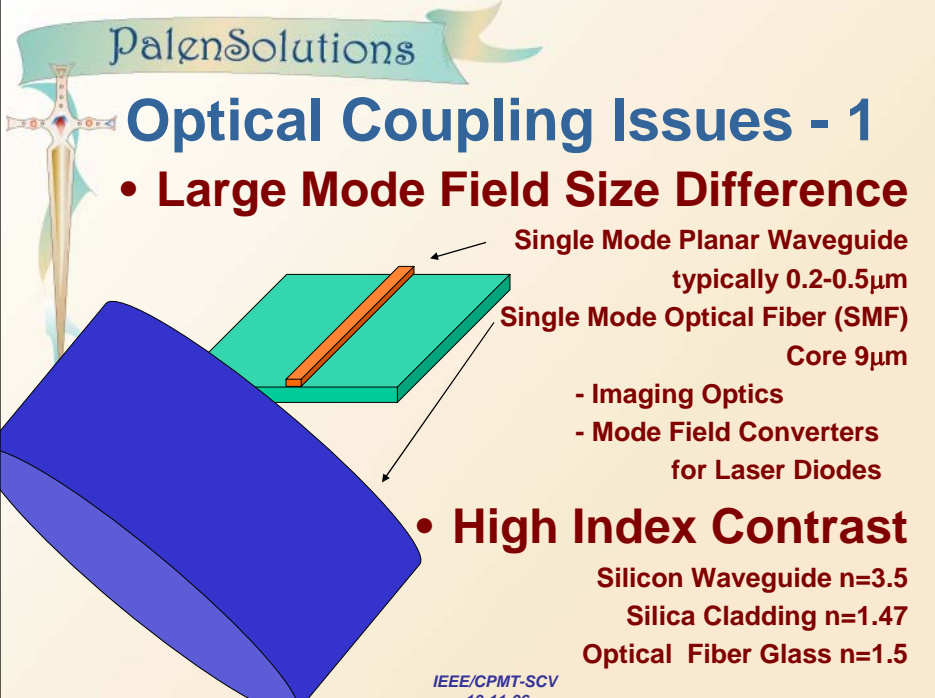
- **Si & SOI**
All Photonic Elements Except Light Source
- **Silicon Optical Bench (SOB)**
Anisotropic Wet KOH Etch of <100> Si
Platform of Precision Pedestals for
Laser and Photodetector Mounting
Precision V-Grooves for Passive Fiber Alignment
Integrate with Waveguides of PLC
- **III-V**
All Photonic Elements
Integrate High Speed Electronics?

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Optical Coupling Issues - 1

- **Large Mode Field Size Difference**
Single Mode Planar Waveguide typically 0.2-0.5 μ m
Single Mode Optical Fiber (SMF) Core 9 μ m
- Imaging Optics
- Mode Field Converters for Laser Diodes
- **High Index Contrast**
Silicon Waveguide n=3.5
Silica Cladding n=1.47
Optical Fiber Glass n=1.5



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Optical Coupling Issues - 2

- **High Coupling Efficiency**
- **Low Cost Requirements**
 - Compatibility with Surface Mount Assembly
 - Alignment Tolerances
 - Passive Align & Attachment Processing
- **Solutions:**
 - Grating Couplers, PDL Sensitivity
 - Spot Size Converter (SSC) & Tapered Waveguides
 - Silicon Optical Bench (SOB) Configurations,
V-Groove Fiber Butt Couple to PLC Waveguide
 - Pluggable Ferruled Fiber into Injection Molded TOSA


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Optical Coupling Issues - 3

- **Optical Alignment Tolerances**
 - <1 μ m Custom Photonics Equipment, Slow & Very Expensive
 - 1-5 μ m Flip-Chip, Expensive
 - 10-20 μ m Standard Pick & Place Equipment, Low Cost
- **Scalability for High Volume**
 - Low BOM
 - Fast Assembly Times
 - Cost of Assembly Equipment
 - Ability to Use Industry Infra-Structure
of Standard Electronics Assembly Equipment
- **Innovative Solutions Needed**
 - To Meet Lower Cost Points
for Integration with Electronics


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Coupling Developments

- **Injection Molded TOSA**
 - Pluggable Transponders to Ferruled Fiber
 - Widespread Implementation
- **Surface Mount Photonics**
 - Evanescent Coupling to Laser Converter
 - Turning Mirrors to PD
 - Laser on SOB Pedestal Coupled to Fiber in V-Groove
 - Laser Spot Size Converter Options
- **Grating Couplers**
 - Lithographic Fabrication
 - Waveguide and Grating Lithographic Alignment
 - Polarization & Wavelength Sensitivity



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Integration Components

- **Actives**
 - Lasers, Amplifiers
 - Modulators
 - Photodetectors
- **Passives**
 - Waveguides, Splitters & Couplers
 - WDM Multiplexers: Add/Drop, AWG, Switches
- **Interface Optical Couplers**
 - To Fiber or Waveguides

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Light Sources

- **Cost Challenge**
Lower Cost FP vs. Lower Yield, Higher Cost DFB
- **Modulation**
Directly Modulated <4Gbps, External Modulation 10GBps
Integrated EAM on Laser Chip, Power Limitations
- **Edge vs. Surface Emitters**
Wafer Scale Testing of VCSEL
High Cost Edge Emitters More Power & Performance
Beamshape: VCSELS Easier to Couple to Fiber
Than Asymmetric Beam of Edge Emitters

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Light Sources Hermetic Packaging

- **Packaging Cost**
Individually Packaged vs. Arrayed Configurations
Hermetic Packages: Low Cost TO-Can to High Cost Butterfly
- **Surface Mount Photonics - Xponent**
Sealed Optical Path
of Adiabatic Coupling Method
- **SOB Solution**
Hymite Hyshell™ Small Footprint SOB Cavity
with Hermetically Sealed Top Window
& High Speed Electrical I/O
Through SOB Backside



Fig. 1. Cross section of a hermetically sealed p-on



L18 for Hermetic enclosure
400 micron
Laser and receiver module
mounted to the PCB carrier



Fig. 1. Cross section of a hermetically sealed p-on

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Integrated Light & Amplification Sources - 1

- **Si BandGap Limitation**
- **III-V Light & Amplification Sources**
GaAs & InP Lasers, SOA
III-V Processing Unique, Not CMOS Compatible
- **Raman Amplification Development in Si Platform**
Still Needs Pump Light Source Optical Coupled to Chip
- **Low Cost Solutions**
Package Integration of Mature III-V Lasers
Isolator Requirements Contribute to Costs
Innovative Solutions Needed

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Integrated Light & Amplification Sources - 2

- **Hybrid Silicon Laser - Intel/UCSB**
InP Light Source at Wafer or Die Level "Glass-Glued" Heat Bonded to Pre-Patterned Si Wafer
Using Low Temperature Oxygen Plasma to Grow 25 Atom Thick Oxide Layer for Bonding
Claim "No Bonding Alignment" Required
Evanescent Optical Coupling through Oxide to Waveguide on Si
Waveguide External Cavity Define Wavelength
Scaleable Solution Potential with High Density & Small Footprint
Note: No Laser Performance Data Released




Figure 1. Cross-section schematic of a hybrid silicon laser.



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2x2 hybrid silicon laser array



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Modulators

- **Discrete Modulators Too Expensive**
- **Mach-Zehnder Interferometer**
 - Intel Developments in Si , 2-10Gbps
 - Potential Integration in Optical Motherboard
 - Large Footprint
- **MicroRing Resonators**
 - Small Footprint
- **Electro-Absorption in III-V**
 - On Laser Chip, DFB-EAM

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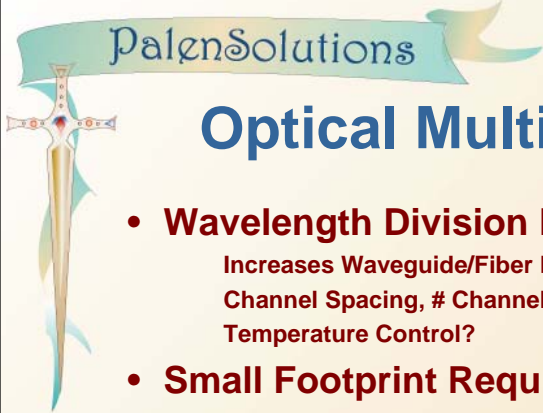


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Photodetectors

- **Discrete Photodetectors Mounted on Optical Motherboard**
 - Low Tolerance Alignment to PLC Waveguides
 - BOM & Assembly Cost
- **Wavelength & Speed**
 - SiGe, Ge, III-V for: 850nm, 1310nm, 1550nm
 - PIN Lower Cost, APD More Sensitive
- **Integrated Solutions**
 - Si Platform: SiGe or Ge
 - III-V Platform PIC

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Optical Multiplexers

- **Wavelength Division Multiplexing (WDM)**
Increases Waveguide/Fiber Bandwidth
Channel Spacing, # Channel, Cross-Talk Isolation
Temperature Control?
- **Small Footprint Requirement**
For Monolithic Integration with Electronics
- **Arrayed Waveguide Gratings (AWG)**
Silica on Silicon AWGs Implemented
for High Channel Count DWDM Multiplexers
- **Wavelength Tunability?**

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Light Routing

- **Optical Waveguides**
Insertion Loss, Etch Roughness
- **Splitters**
Optical Power Budget
- **Spot Size Converters**
Facilitates Coupling to Larger Waveguide of Fiber
Horizontal Features Lithographically Defined
Vertical Dimension Features Limited

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Transponder Markets

- **FTTH PON**
 - Lower Cost Transponder Market Need
 - Bidirectional, 1310nm Upstream Time Multiplexed
 - Biplexers (Asia) 1490nm, Triplexers (N. America) 1550nm
 - High Channel Optical Isolation Requirements
- **Server Routers**
 - High Density, High Data Rate
 - Smaller & Lighter Weight Cable Harness
 - Lower Heat Dissipation
- **Short Reach**
 - Small Form Factor (SSF), SOB Integrated Packaging
 - TOSA/ROSA Packaging
- **Telecom**
 - Price Compression Since Telecom Bubble Burst
 - Assembly Manufacturing Off-Shored

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Application: Optical Clocking

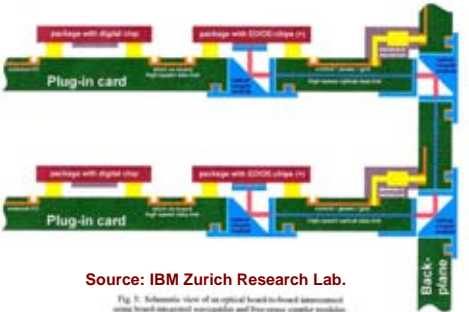
- **Why?**
 - Cost of Impedance Matched & Ground Planes of High Speed Routing In CMOS Chip
 - Heat Dissipation in Routing
- **Challenges**
 - Low Cost Low Jitter Light Source
 - Optical Distribution & Optical Power Budget
 - Very Low Cost Optical Coupling System
 - Paradigm Shift in Electronics for Implementation

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PCB Waveguide Solutions - 1

- **Polymeric Waveguides in PCB**
 - ~50µm Core Multimode Waveguides in FR4
 - Turning Mirror in PCB or Coupling Mount
 - 10x-100x Easier Coupling Alignment Tolerances to Multimode than to Single Mode Waveguides on Chip
 - Coupled To Arrayed VCSELs and Arrayed Photodetectors on PCB
 - Free-Space Optical Coupler of PCB Waveguides to Back-Plane Board Waveguides



Source: IBM Zurich Research Lab.

Fig. 1. Schematic view of an optical board-to-board interconnect using board-integrated waveguides and free-space coupler modules.

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PCB Waveguide Solutions - 2

- **Challenges:**
 - Low Cost Optical Coupler Solutions with Passive Alignment Connectors
 - Fabrication Process Integration of Waveguides in PCB
 - Routing of Thicker Waveguide & Cladding Layers in PCB
 - PCB Reliability Issues Related to Polymeric Waveguide Layers
- **Market Space Need?**
 - Need For PCB Photonic Routing Solution vs. Electronic PCB Routing?
 - Will Developments in PIC Transponders Fill The Need of Photonic PCB Solution?

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Developments: Xponent

- 


• **Planar Lightwave Circuit**
 Silica on Silicon Multiplexer Waveguides
 Fiber in V-Groove Butt Coupled to PLC Waveguide
- 

• **Surface Mount Photonics (SMP)**
 Laser Adiabatic Coupling to PLC Waveguide
 $\pm 2.5\mu\text{m}$ Passive Alignment,
 Sealed Optical Interfaces
 Photodetector with Turning Mirror
 $>\pm 10\mu\text{m}$ Passive Alignment
 Thin Film WDM Filter
 on Vertical Si Membrane in Narrow Etched Slot of PLC
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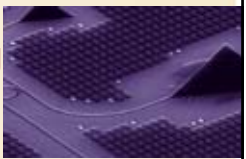
Solder Attachment



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Developments: Luxtera

- 

• **Surface Mount Optical Coupling**
 Holographic Lens, $\pm 1\mu\text{m}$ Alignment
 Laser & Fiber Surface Mounted to Si Chip
- **Small Footprint Optical Blocks**
 Integrated Ge Seed on Si High Speed Photodetectors
 MicroRing Modulators $30\mu\text{m}$ Diameter, & MZ Modulators
 MicroRing Resonator Wavelength Add/Drop
 Electrically Tunable AWG Multiplexers
- **Integrated Electronics**
 CMOS Fabricated, Freescale 130nm SOI Process
 Electronics Side-By-Side to Waveguides & Optics
- **High Density Transponders**
 10 x 10Gbps Channel T_x & R_x
 Router Harness Application: Sun Microsystems

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Developments: Infinera

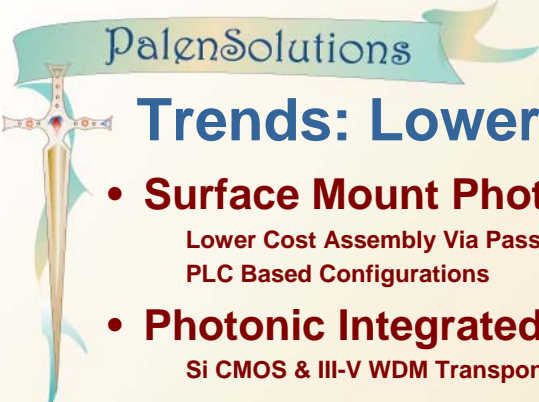
- **InP Platform**

Photonic Integrated Circuit (PIC)
 Integrated Arrays of Tunable DFB, OPM, EAM, VOA, PD
 Integrated DWDM AWG Multiplexers
 Edge Coupled to SMF
- **High Data Rate Transponders**

10 x 10GBps Transponders T_x & R_x
- **Market Success**

25% Market Share of 10Gbps Long-Haul Transponders in Q4, 2005

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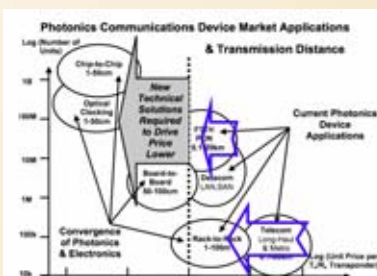


Trends: Lower Costs By


- **Surface Mount Photonic Configurations**

Lower Cost Assembly Via Passive Alignment
 PLC Based Configurations
- **Photonic Integrated Circuits**

Si CMOS & III-V WDM Transponders



The graph plots Log(Number of Devices) on the y-axis (ranging from 10⁰ to 10¹⁰) against Log(Price per Device) on the x-axis (ranging from \$0.1 to \$1000). It shows various market applications: Chip-to-Chip (1-10km), Board-to-Board (1-100m), Rack-to-Rack (1-100m), and Long Haul (1-10000km). Annotations include 'New Technical Solutions Required to Drive Price Lower' and 'Convergence of Photonics & Electronics'. A note at the bottom right specifies 'Current Photonics Device Applications' and 'Long Haul (Unit Price per TxA Transponder)'.

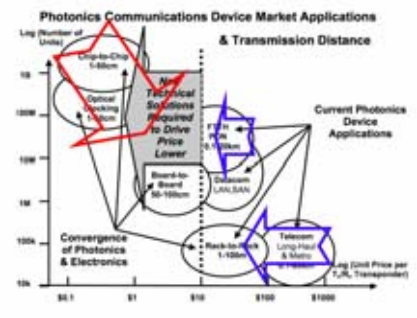


Predictions

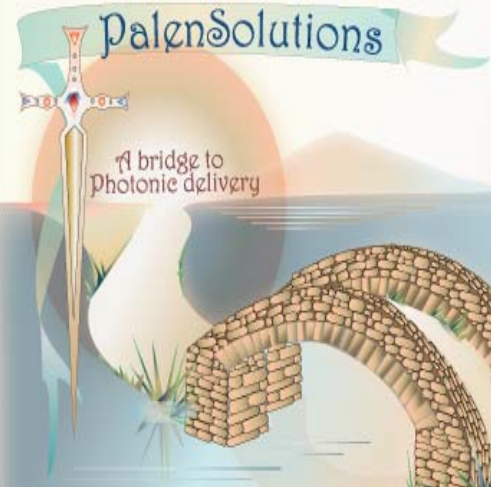
- **Some Time Before Photonics Convergence**
Convergence Pushed Out Further Until;
- **Much Lower Cost Integrated Solutions**
Backfill Market Space

Enabled by:


- (1) Very Low Cost Optical Interconnects
- (2) Future PIC Implementations
- (3) Low Cost Light Sources



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A bridge to Photonic delivery



A leader in innovative process technology solutions, bridging over development & manufacturing risks, protecting investments by forging a path to delivering photonic products and services.