



An Economic Comparison of PSM4, PAM, and LR4

Brian Welch

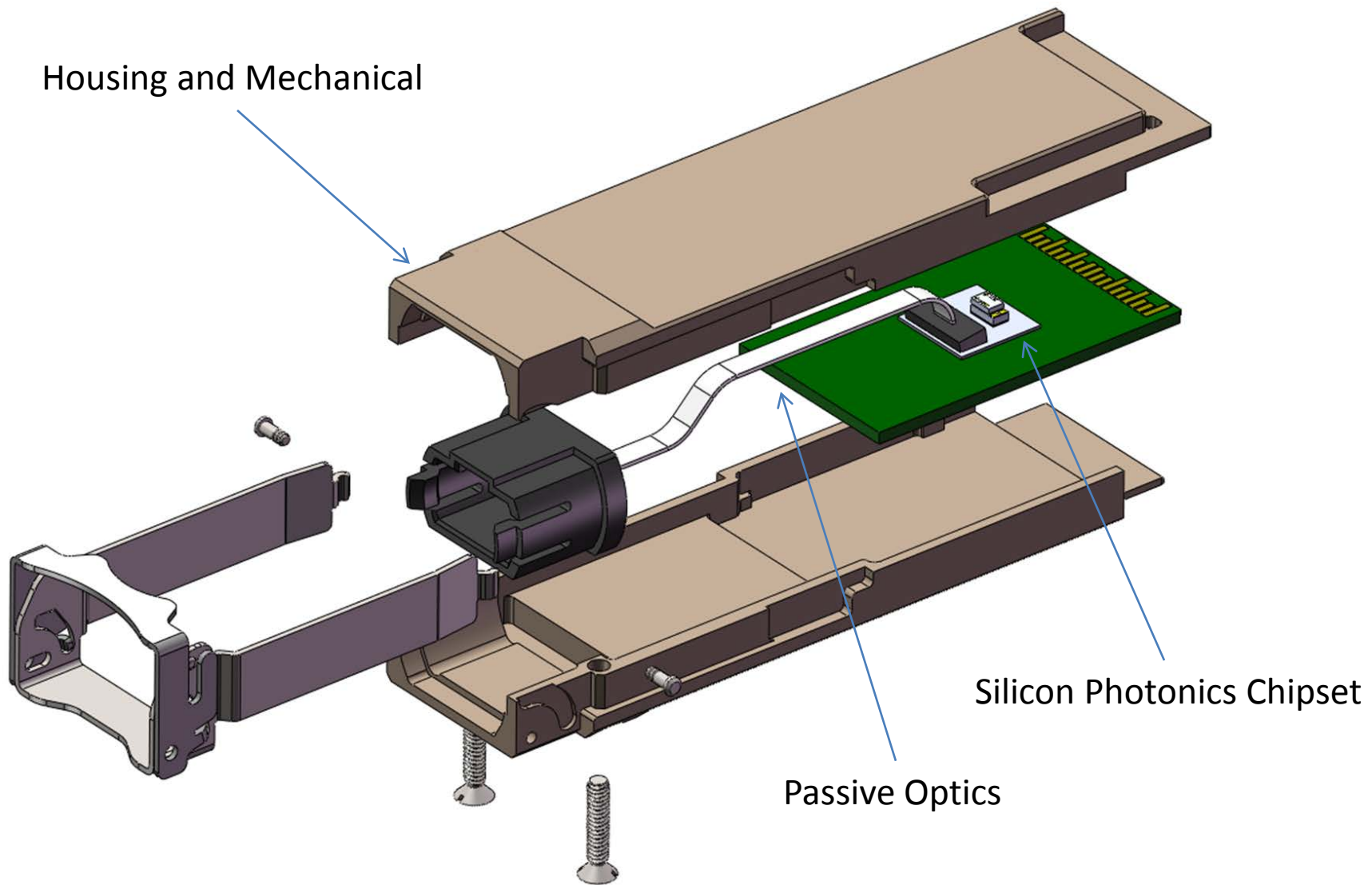
Supporters

- Chris Bergey – Luxtera
- Tom Palkert – Luxtera
- John Petrilla – Avago
- Jon Anderson – Oclaro
- Arash Farhood – Cortina
- Sudeep Bhoja – Inphi
- Scott Kipp – Brocade
- Brad Booth – Dell
- Oren Sela – Mellanox
- David Warren - HP

Overview

- Uses Silicon Photonics as a basis for all comparison.
- Compares costs for all critical components constituting a Silicon Photonics Chipset and module.
 - Silicon Photonics
 - CMOS
 - Light Source(s)
- Assumes equivalent total volume for either solution
 - Depends on market acceptance and chipset reuse in other markets
- Compares assembly processes and yields
 - And effects on product costs
- Comparison to contemporary solutions
 - SR10 and LR4
- Result: PSM4 and PAM solutions are approximately 1/5th the cost of LR4.

Silicon Photonics Module Design



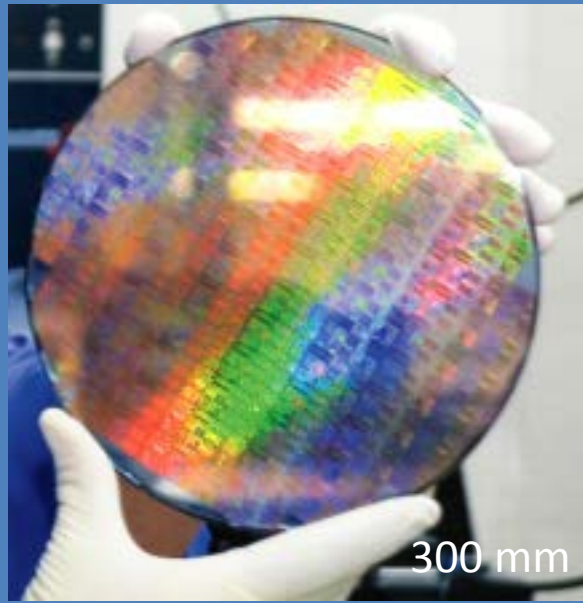
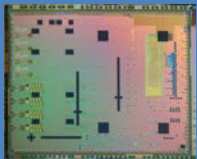
Note: QSFP Shown. Power Consumption of LR4 would likely mandate larger form factor

Silicon Photonics Chipset

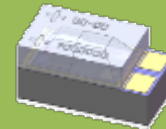
BOM Comparison

Silicon Photonics Building Blocks

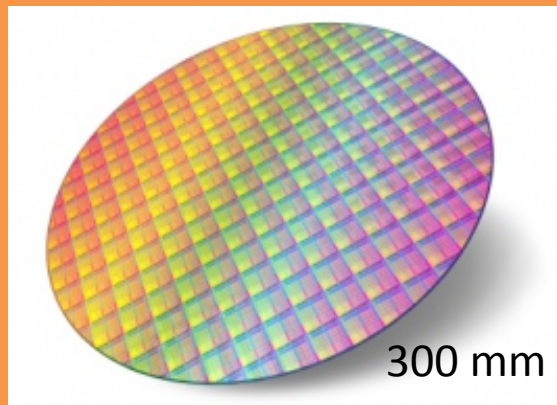
Silicon Photonics



Packaged Light Source

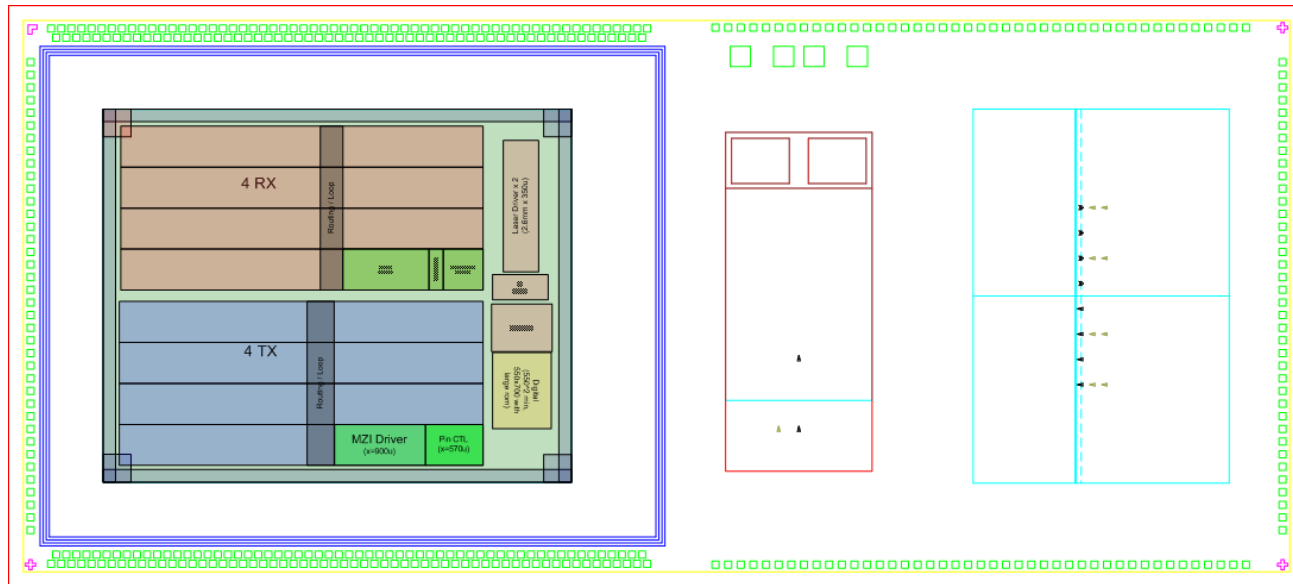


CMOS



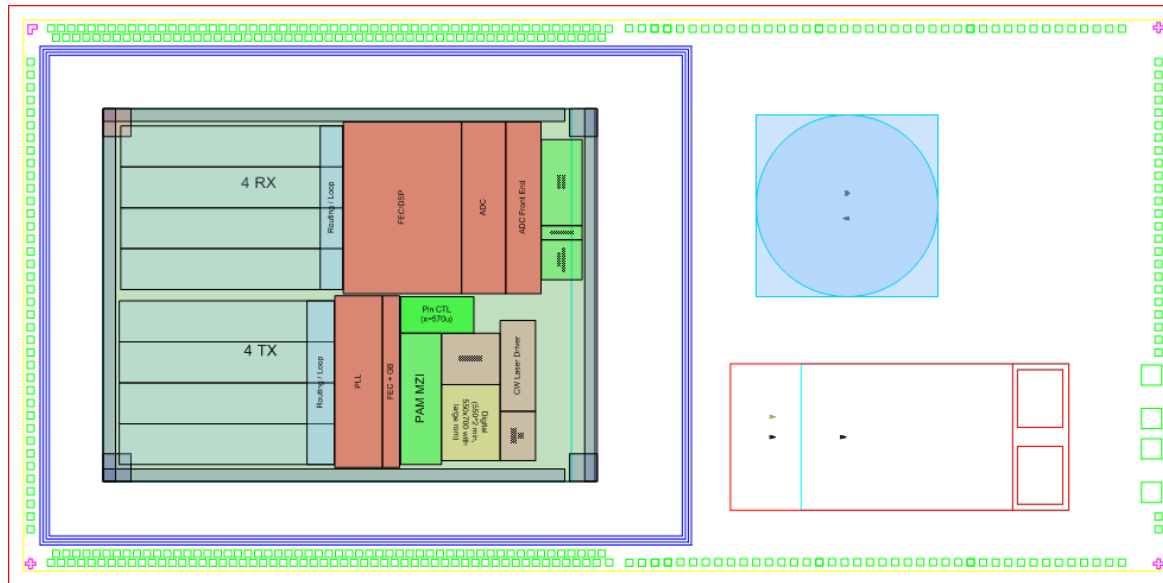
PSM4

| | Area / Count | per Wafer |
|------------------------|--------------------|-----------|
| Silicon Photonics Area | 68 mm ² | 880 |
| CMOS Area | 17 mm ² | 3576 |
| Light Source(s) | 1 | 3000 |



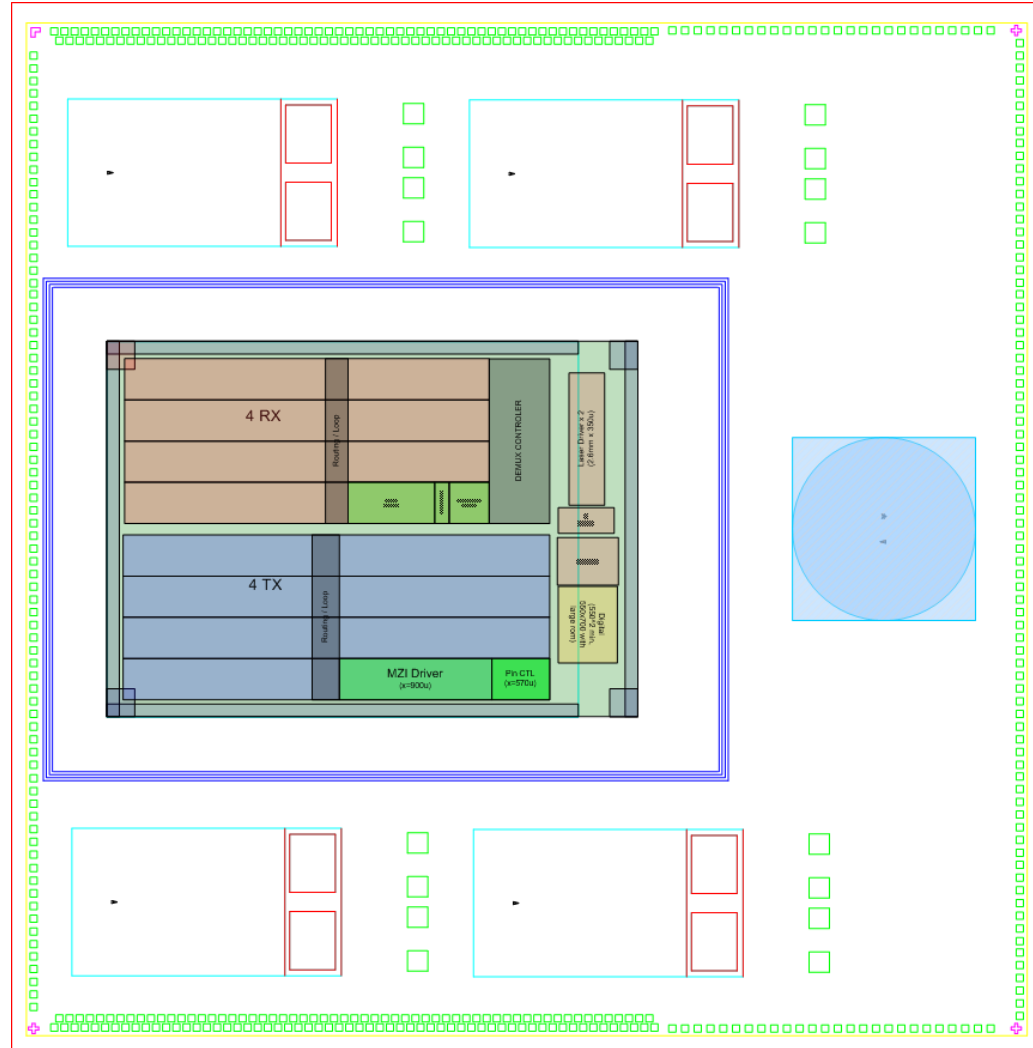
PAM

| | Area / Count | per Wafer |
|------------------------|--------------------|-----------|
| Silicon Photonics Area | 62 mm ² | 976 |
| CMOS Area | 18 mm ² | 3395 |
| Light Source(s) | 1 | 3000 |



LR4

| | Area / Count | per Wafer |
|------------------------|--------------------|-----------|
| Silicon Photonics Area | 98 mm ² | 612 |
| CMOS Area | 19 mm ² | 3180 |
| Light Source(s) | 4 | 750 |



Chipset BOM Comparison

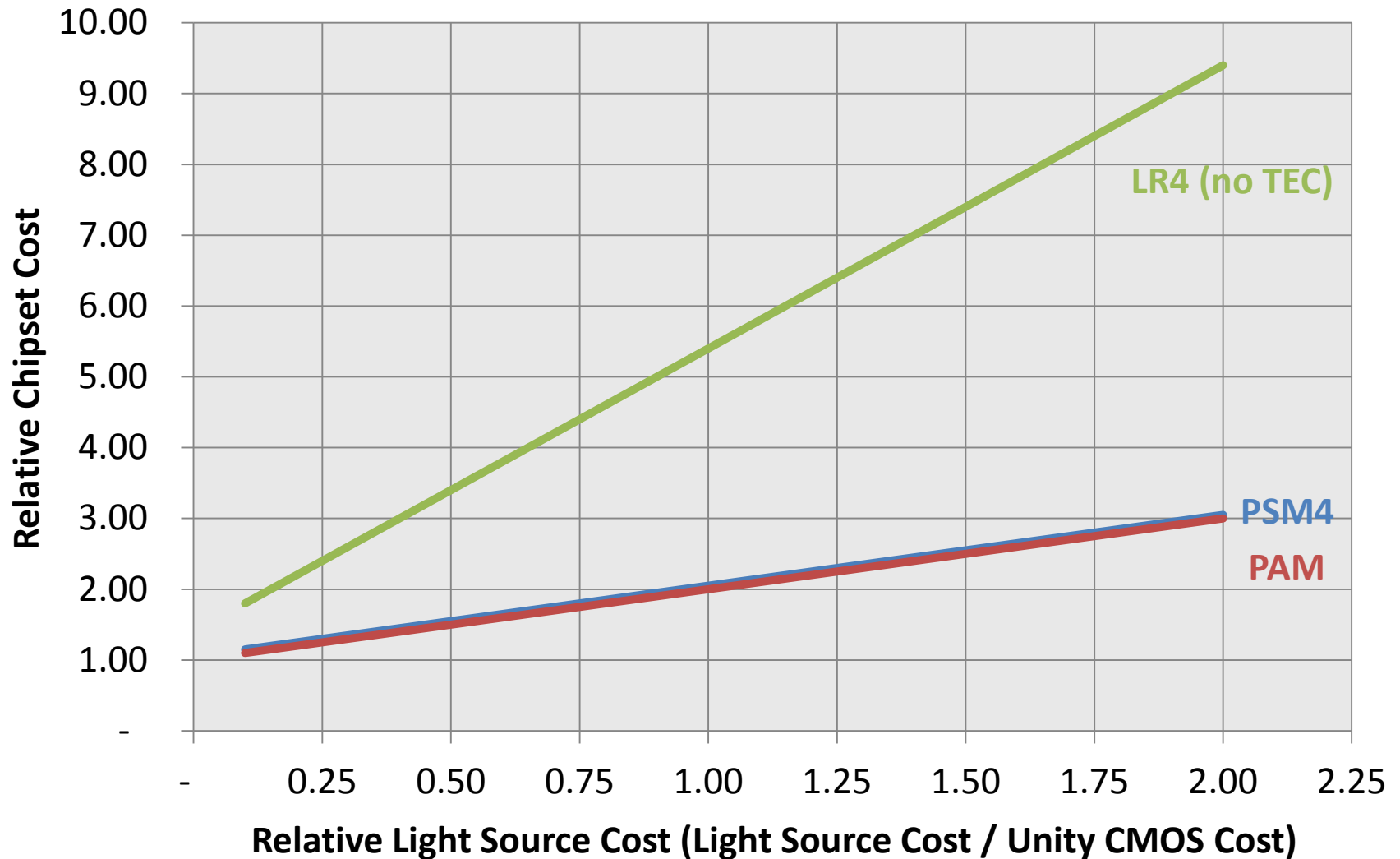
| DPW | PSM4 | PAM | LR4 |
|----------------------|------|------|------|
| Silicon Photonics IC | 880 | 976 | 612 |
| CMOS IC | 3576 | 3395 | 3180 |
| Light Source(s) | 3000 | 3000 | 750 |

| Relative Cost | PSM4 | PAM | LR4 |
|-----------------------------------|-------------|----------------------|-------------|
| Silicon Photonics IC [†] | 0.70 | 0.63 | 1.01 |
| CMOS IC | 0.35 | 0.37 | 0.39 |
| <i>CMOS Total Area</i> | <i>1.05</i> | <i>1[‡]</i> | <i>1.63</i> |
| Light Source(s) | 1 | 1 | 4 |

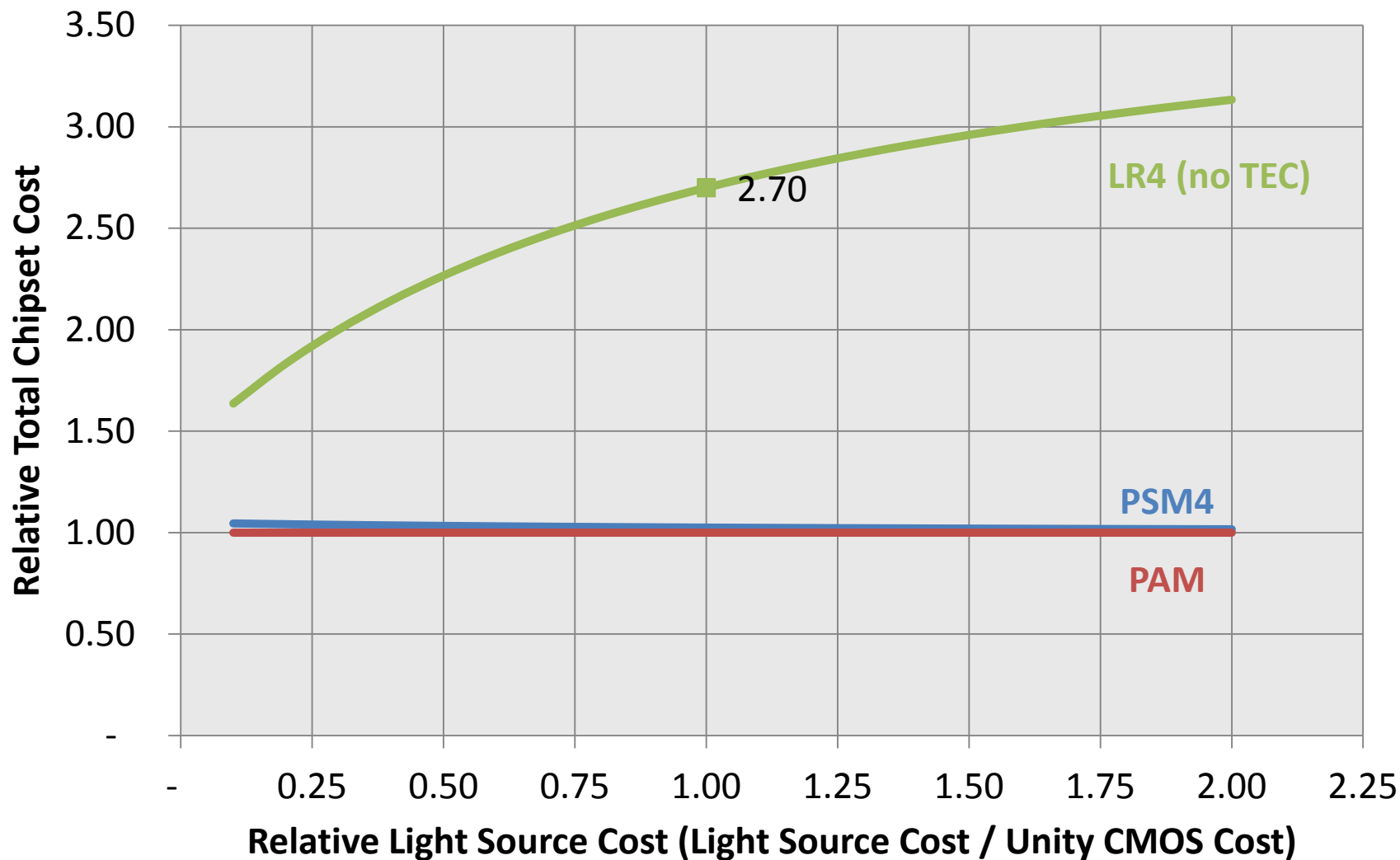
† Uses ½ the number of process steps as full flow CMOS process

‡ Hereafter defined as 'Unity CMOS Cost'

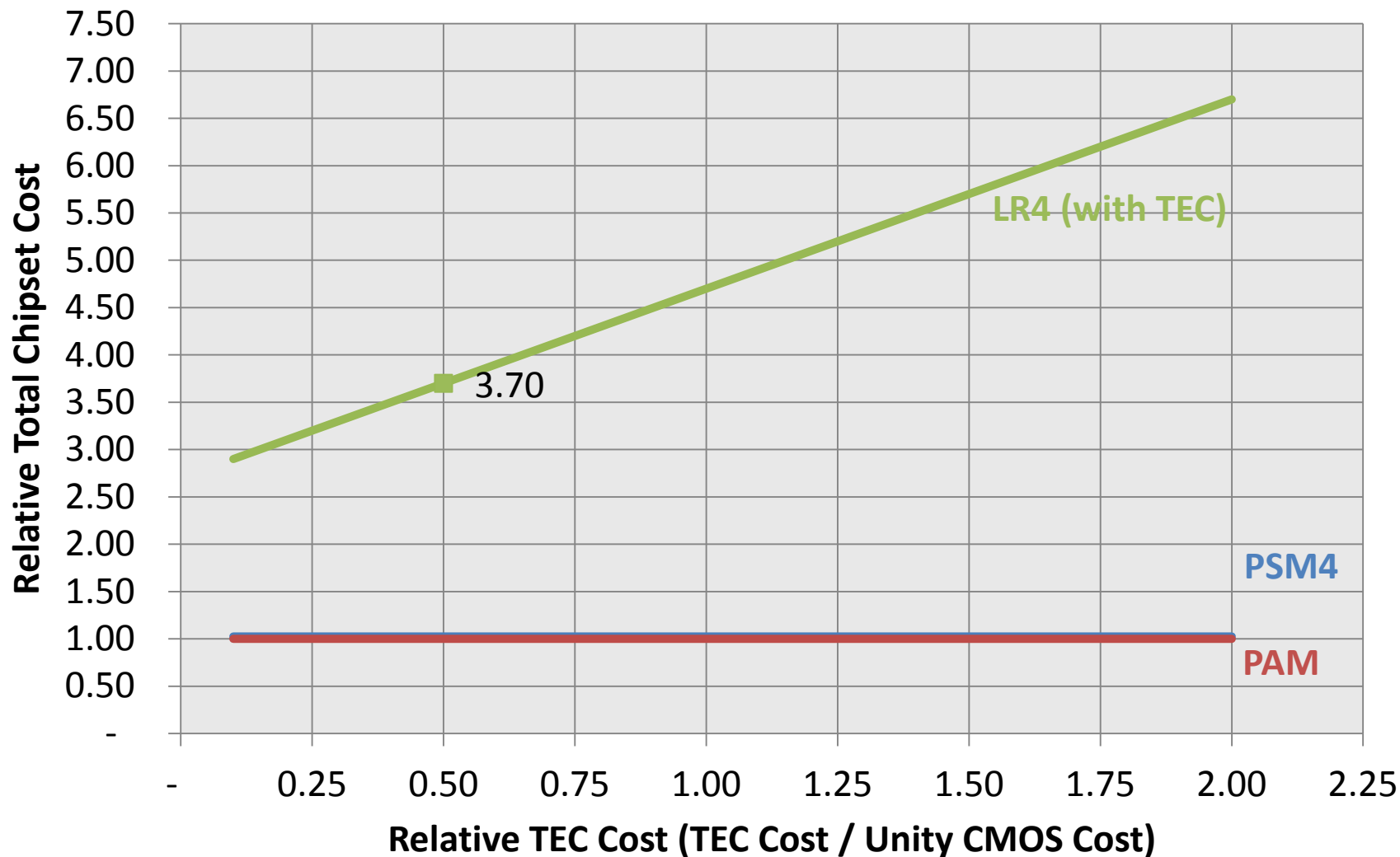
Chipset BOM Comparison



Chipset BOM Comparison - Normalized



Chipset BOM Comparison with TEC - Normalized



Silicon photonics Modules

Assembly Comparison

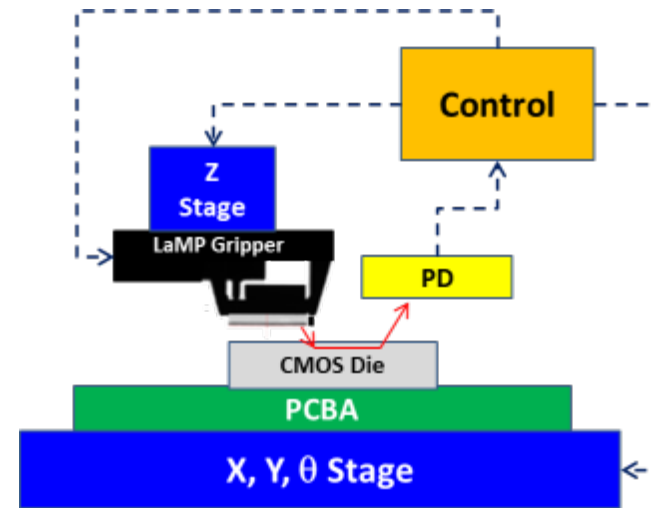
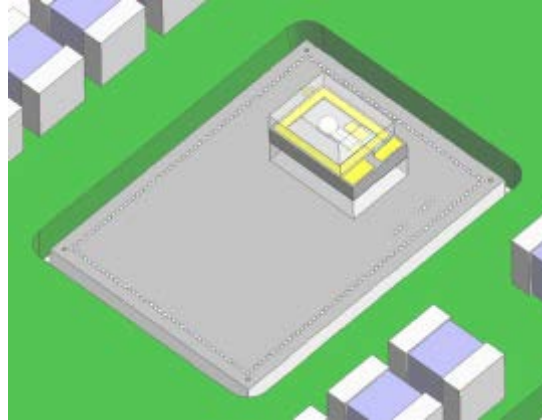
Module Comparison - BOM

| Component(s) | PSM4 | PAM | LR4 |
|-------------------|---------|---------|----------|
| CMOS Total | 1.22 | 1 | 1.63 |
| Light Source(s) | 1 (x1) | 1 (x1) | 4 (x1) |
| TEC(s) | 0 | 0 | 4 (x0.5) |
| Optical Coupler | 8 Fiber | 2 Fiber | 2 Fiber |
| Optical Connector | 8 Fiber | 2 Fiber | 2 Fiber |
| PCB | 1 | 1 | 1 |
| Housing | 1 | 1 | 1 |

Optical Assembly Steps

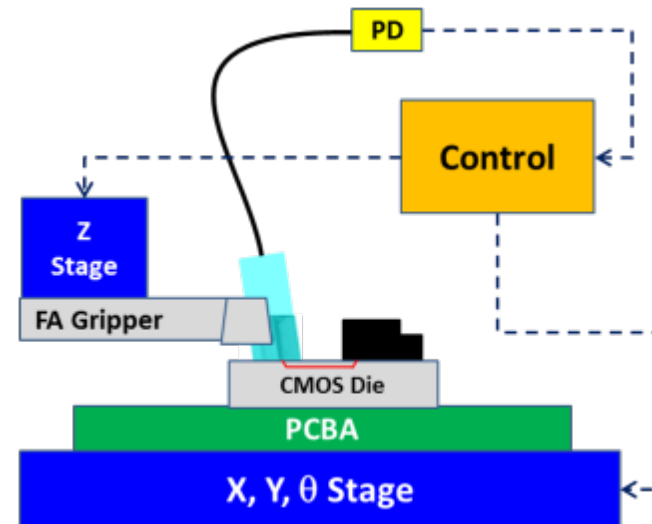
Alignment of Light Source to IC:

- Active alignment in seconds (X, Y, θ)
- Fixation by transparent adhesive



Alignment of Coupler to IC:

- Active alignment in seconds (X, Y, θ)
- Fixation by transparent adhesive



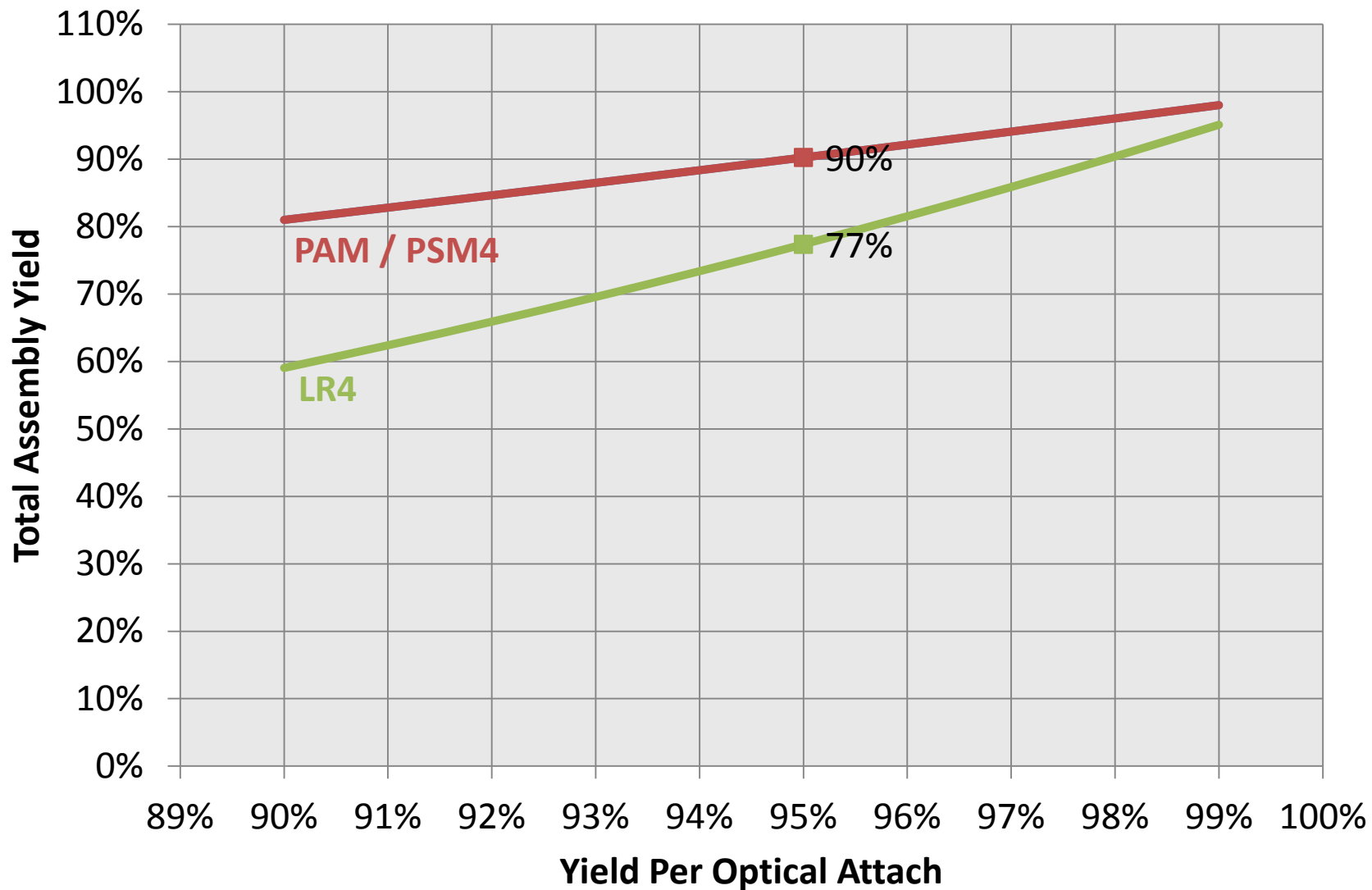
Module Assembly Steps

| Assembly Steps | PSM4 | PAM | LR4 |
|---------------------|------|-----|-----|
| CMOS Bonding | 1 | 1 | 1 |
| PCB Attach | 1 | 1 | 1 |
| Light Source Attach | 1 | 1 | 4 |
| Coupler Attach | 1 | 1 | 1 |

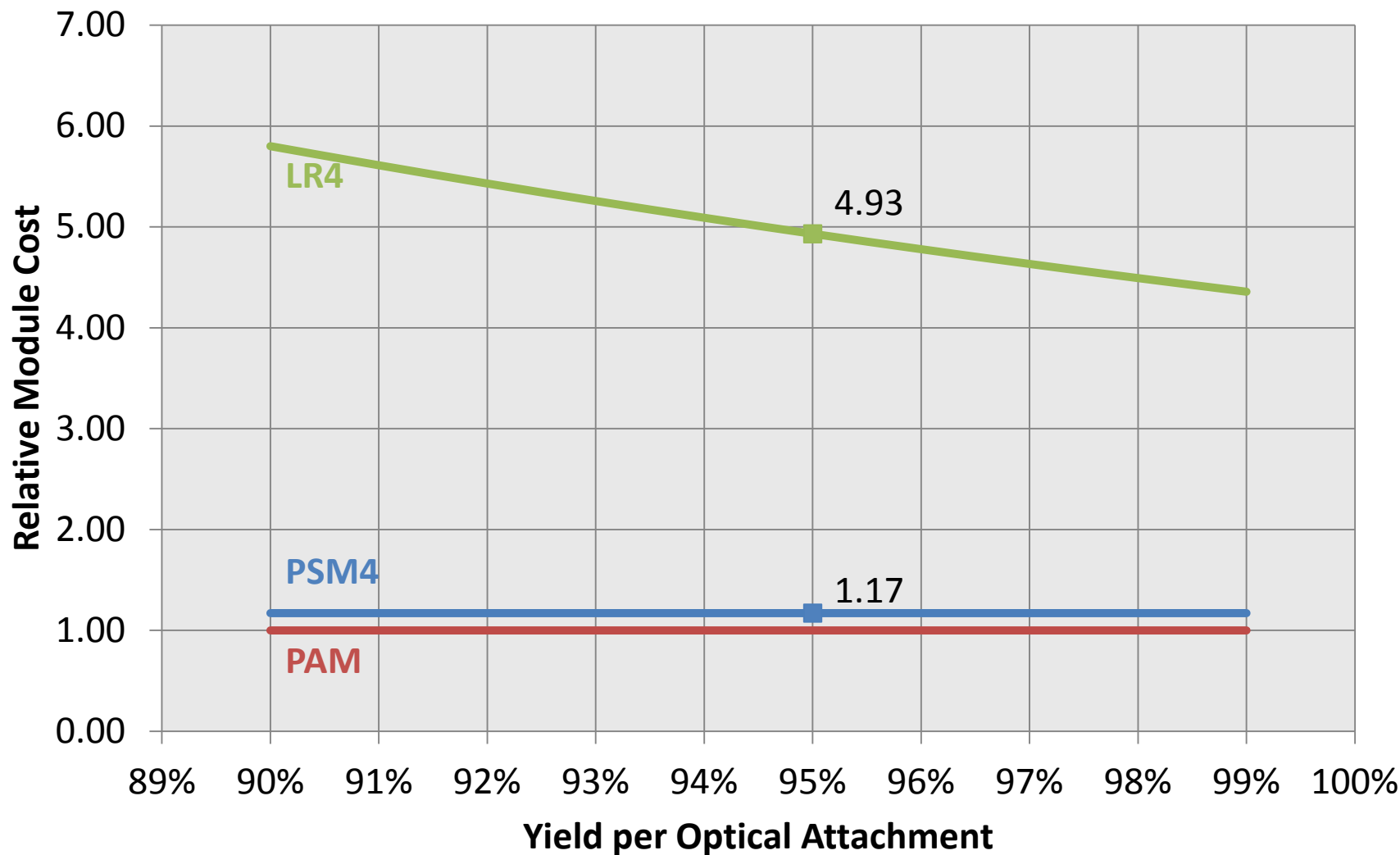
- Packaging Chipsets into modules incurs a cost adder
 - Due to passive BOM and transformation costs
- Cost adder can vary due to BOM complexity and assembly steps
 - Duplex vs. arrayed passive optics
 - Number of optical attaches : Processing time / Throughput
 - Housing and test complexity

| Cost Adder (Un-Yielded) | PSM4 | PAM | LR4 |
|--------------------------------|------|-----|------|
| Chipset Multiplier | 1.6 | 1.4 | 1.6 |
| Net Relative Cost (Normalized) | 1.17 | 1 | 4.23 |

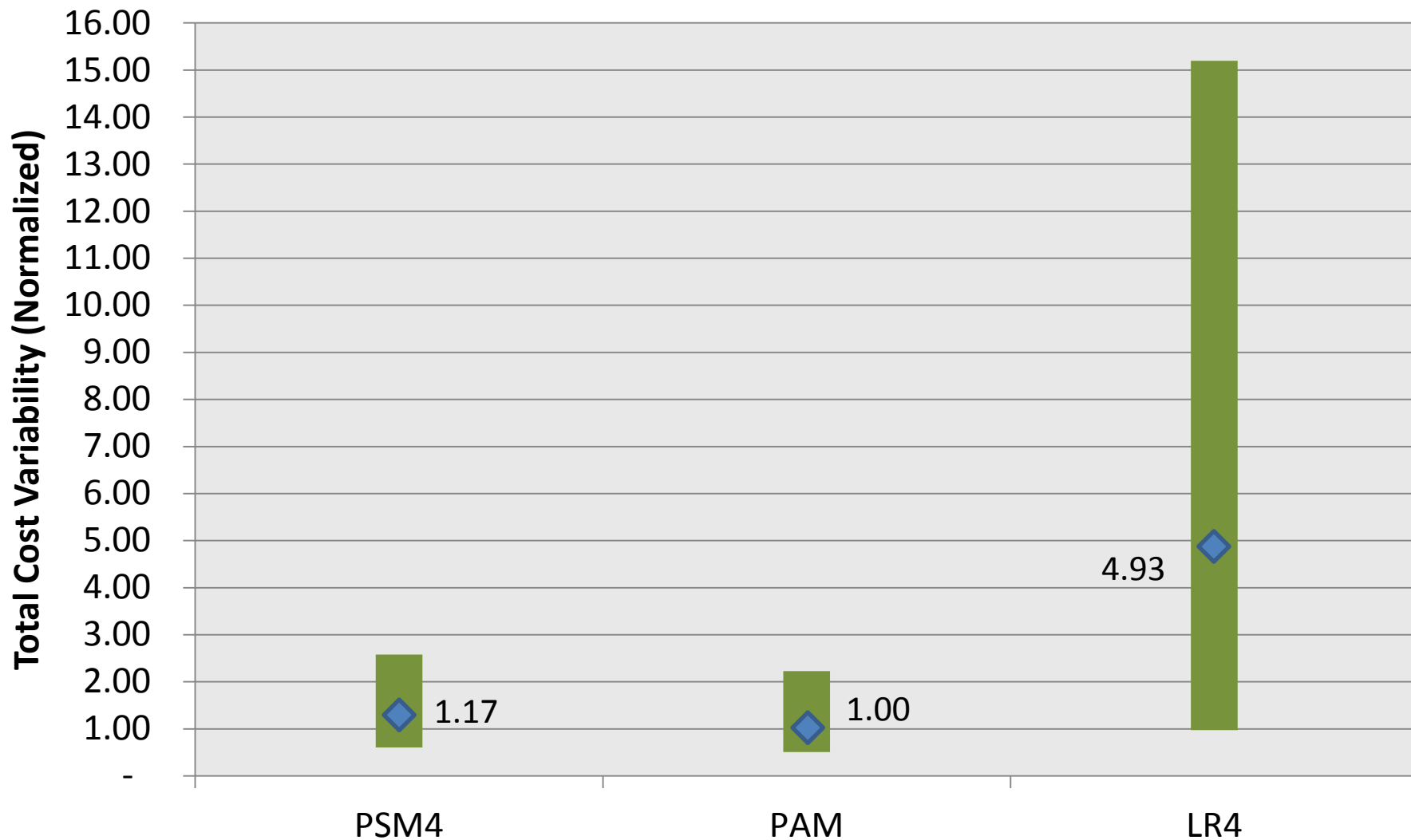
Module Assembly Comparison - Yield



Module Assembly – Yielded COGS



Yielded COGS Comparison - Variability



Module Cost Analysis - Example

| Transceiver Building Blocks | CFP LR4 (circa 2012) | | CFP2 LR4 | | CFP2 PAM | |
|-----------------------------|-----------------------------------|------|-----------------------------------|------|-----------------------------------|-------------|
| | Description | Cost | Description | Cost | Description | Cost |
| Tx (TOSA) | 4x discrete EML | 1 | 4xDML, integrated w/MUX in TOSA | 0.32 | Multiple Implementations | 0.18 - 0.02 |
| Rx (ROSA) | Integrated ROSA | 1 | Integrated ROSA | 1 | PIN/TIA | 0.35 |
| Opt Mux | Thin film | 1 | Integrated in TOSA | N/A | None Required | N/A |
| Opt Dmux | Thin film, Integrated in ROSA. | N/A | Integrated in ROSA | N/A | None Required | N/A |
| Serdes | 10x10→4x25 Gb gearbox (CMOS) | 1 | 4x25 Gb CDR (CMOS) | | PAM Serdes | |
| Laser driver IC | 4x25 Gb EML driver | 1 | 4x25 Gb DML driver | | | N/A (*) |
| Misc | PCBA, housing, connector, IC, etc | 1 | PCBA, housing, connector, IC, etc | | PCBA, housing, connector, IC, etc | |
| Assembly /Test | Assembly/test time and yield | 1 | Assembly/test time and yield | | Assembly/test time and yield | |
| Module Cost | | 1 | | 0.46 | | 0.23-0.13 |

Consistent with Current Findings

- Detailed cost analysis was performed on all aspects driving module cost
- Only Tx/Rx optics details shown above as tend to be dominate cost driver
- (*) Some implementations may include an external modulator driver

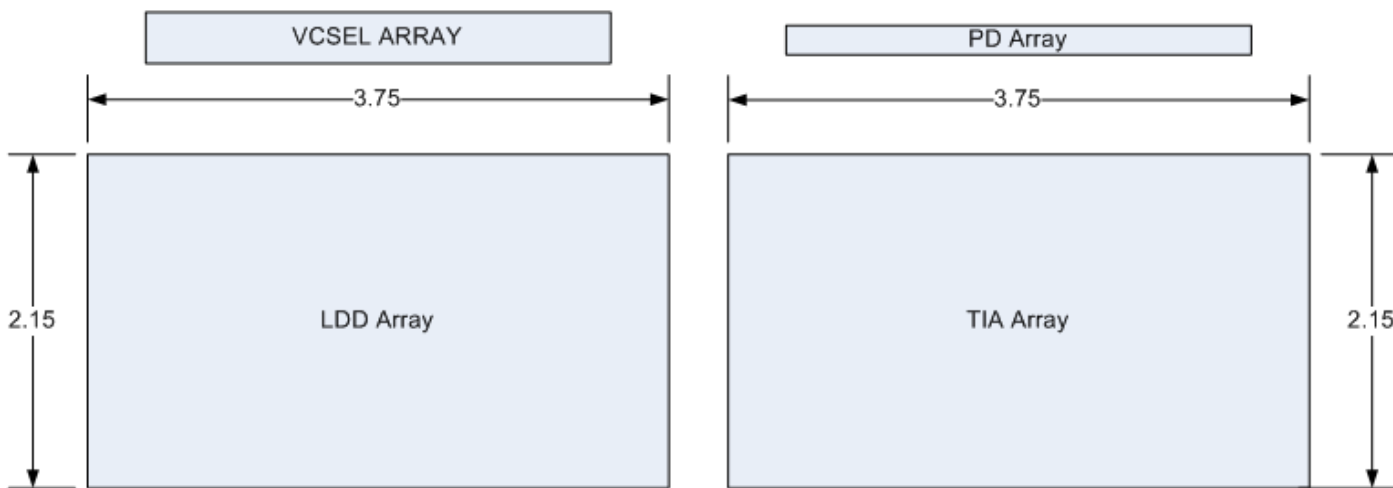
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Comparison to Industry

Contemporary Solutions

Comparison to Industry – SR10

| | | per Wafer |
|------------------|--------------------|-----------|
| Total CMOS Area | 21 mm ² | 3760 |
| Light Source (s) | 12x VCSEL Array | N/A |
| Photodiodes | 12x PD Array | N/A |

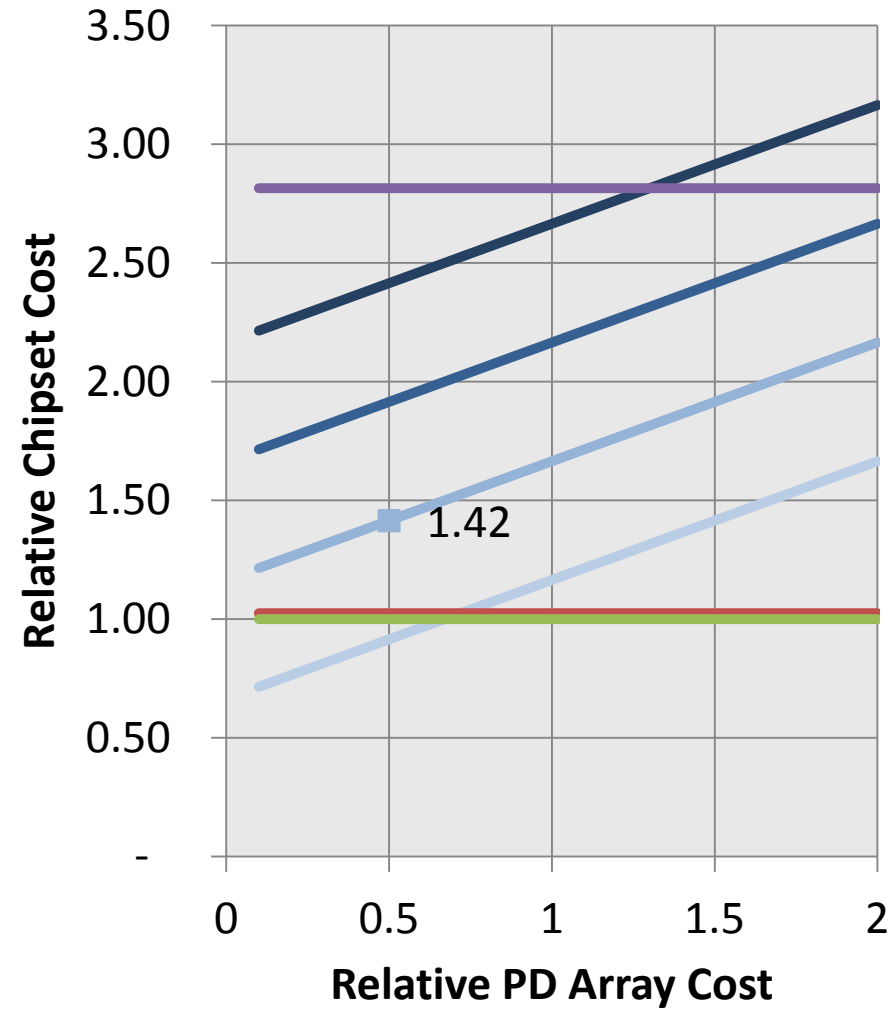
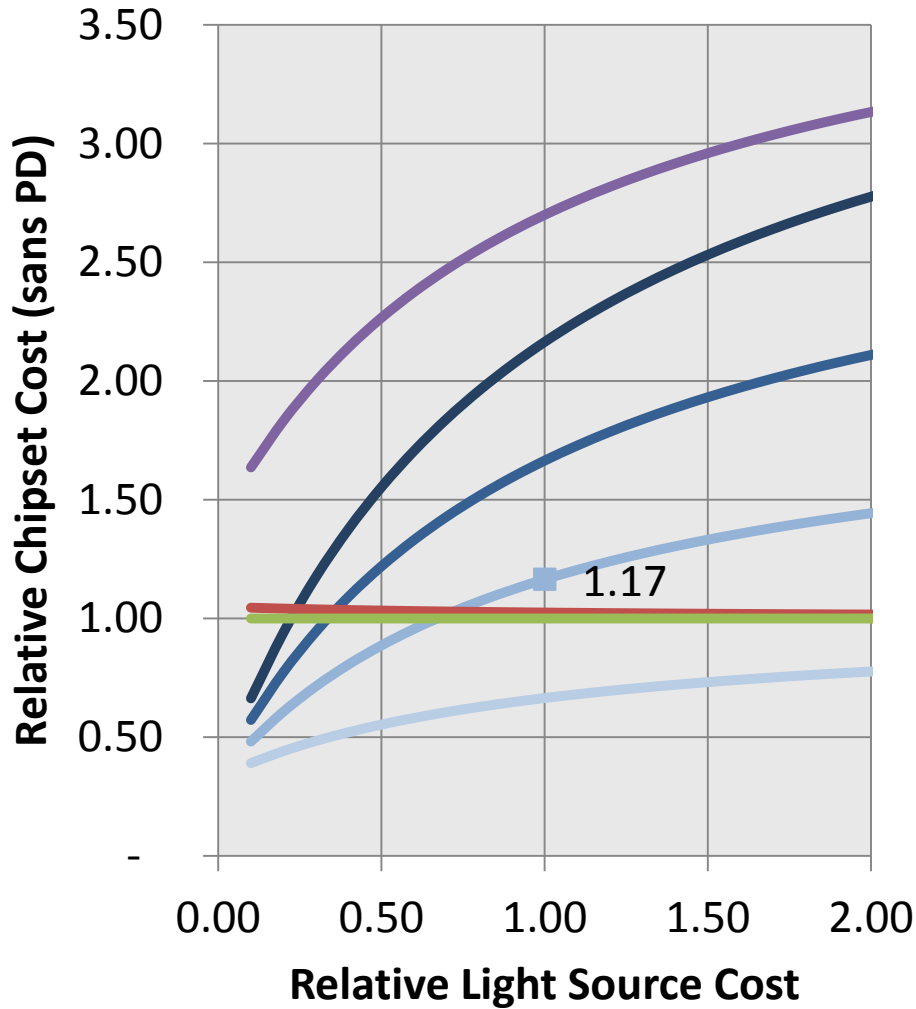


SR10 'Chipset'

Comparison to Industry = SR10

| Relative Cost | PSM4 | PAM | LR4 | SR10 |
|-----------------------------------|------|------|------|-----------|
| Silicon Photonics IC [†] | 0.82 | 0.67 | 1.18 | 0 |
| CMOS IC | 0.40 | 0.33 | 0.45 | 0.33 |
| CMOS Total Area | 1.05 | 1 | 1.63 | 0.33 |
| Light Source(s) | 1 | 1 | 4 | 12x Array |
| Discrete PD | 0 | 0 | 0 | 12x Array |

Comparison to Industry – SR10

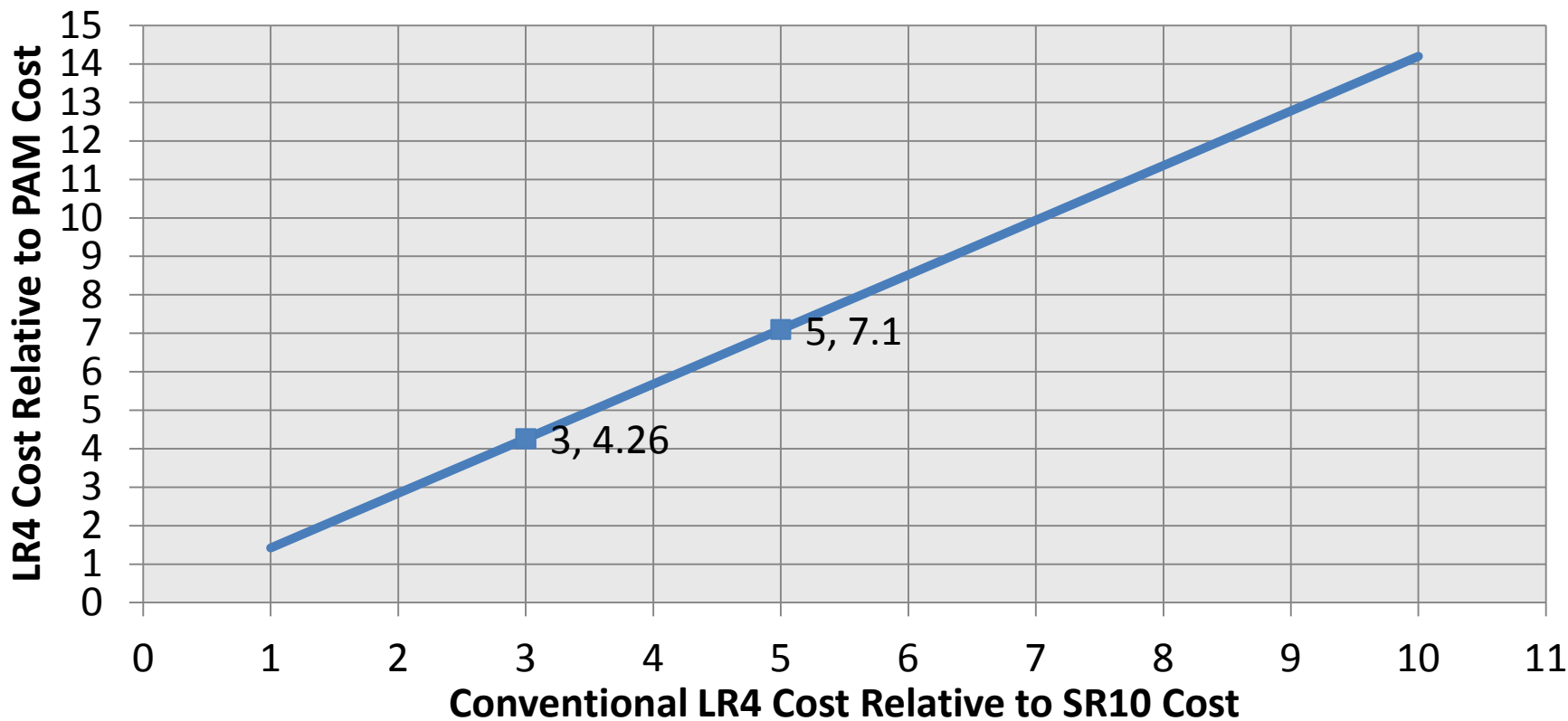


PAM PSM4 LR4 SR10 @ 1x VCSEL Array / Light Source Cost 2x 3x 4x

Module Assembly Comparison

| Component(s) | PSM4 | PAM | LR4 | SR10 |
|--------------------------------|---------|---------|----------|---------------|
| CMOS Total | 1.22 | 1 | 1.63 | 0.4 |
| Light Source(s) | 1 (x1) | 1 (x1) | 4 (x1) | 1 (12x Array) |
| Discrete PD(s) | 0 | 0 | 0 | 1 (12x Array) |
| TEC(s) | 0 | 0 | 4 (x0.5) | 0 |
| Optical Coupler | 8 Fiber | 2 Fiber | 2 Fiber | 24 Fiber |
| Optical Connector | 8 Fiber | 2 Fiber | 2 Fiber | 24 Fiber |
| PCB | 1 | 1 | 1 | 2 (CXP MSA) |
| Housing | 1 | 1 | 1 | 1 |
| Cost Adder (Un-Yielded) | PSM4 | PAM | LR4 | SR10 |
| Chipset Multiplier | 1.6 | 1.4 | 1.6 | 1.6 |
| Net Relative Cost (Normalized) | 1.17 | 1 | 4.23 | 1.42 |
| Yielded Relative COGS | PSM4 | PAM | LR4 | SR10 |
| At 95% Attachment Yield | 1.17 | 1.0 | 4.93 | 1.42 |

Comparison to Conventional LR4



Strawpoll 3 (Chicago rules)

A: I would be interested in a PMD supporting a 500m reach at 75% the cost of 100GBASE-LR4

B: I would be interested in a PMD supporting a 500m reach at 50% the cost of 100GBASE-LR4

C: I would be interested in a PMD supporting a 500m reach at 25% the cost of 100GBASE-LR4

A:1 B:10 C:40

Summary

- PSM4 and PAM offer significantly lower BOM costs than LR4.
 - Approximately 1/5th the cost
- PSM4 and PAM are much less sensitive to assembly yields and supply chain variability than LR4 solutions.
 - Fewer BOM components and Assembly steps
- PSM4 and PAM are lower cost than contemporary solutions
 - PAM solutions are about 30% lower cost than SR10
 - Assuming contemporary LR4 is 5x SR10, PAM is approximately 85% lower cost