PSM4 vs. WDM : A Silicon Photonics Perspective

Brian Welch

Comparative Analysis

- Link Budget: What are the net link budget differences between PSM4, LR4, and CWDM.
  - Includes any component level differences than induce optical loss.
- Power: What power targets are achievable for each, and by extension what form factors.
  - Are they QSFP compatible?
  - Assumes fully integrated silicon photonics solution using 28nm (or better) CMOS node.
- Assembly and Cost: How does CWDM fit into the XCVR cost mix.
  - Can it be integrated into existing silicon photonics technologies?
- *Caveat: For Link budget and power sections temporarily assuming infinite optical bandwidth on grating couplers.*
- *Caveat: Where applicable, preference is to err on the side of generous to WDM solutions.*

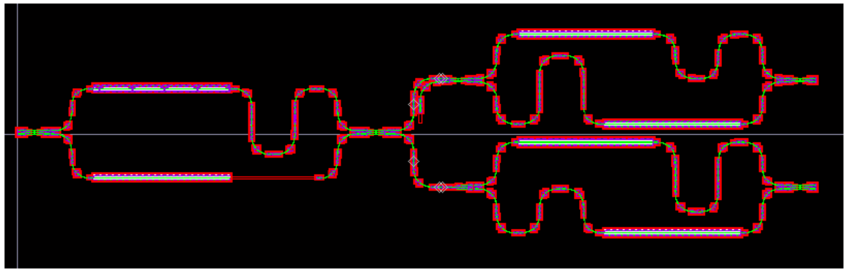
Link Budget

Comparison

WDM in Silicon Photonics

- Optical Multiplexor:
  - Two Configurations:
    - Optical combiner
    - Interleaver
  - Optical combiner is zero power, but high loss (> 6dB)
  - Interleaver is lower loss, but consumes power:
    - Approximately 3 dB insertion loss for 4 λ
    - Approximately 600mW for thermal tuning
      - » Tuning based on carrier injection possible, but with higher losses

- Optical De-Multiplexor:
  - Interleaver based design
  - Requires two interleaver de-multiplexors
    - One for each polarization
  - 3 dB insertion loss
  - Approximately 1200 mW power consumption



Link Budget Differences

Loss Budget†	PSM4	CWDM	LR4
Connector Losses	2.65 dB	3.66 dB	2 dB
Fiber Attenuation (500 m)	0.25 dB	0.25 dB	
Excess Fiber Attenuation (500m-2 km)	N/A	0.75 dB	4.3 dB
Excess Fiber Attenuation (2 km - 10 km)	N/A	N/A	
Total Loss Budget	2.90 dB	4.66 dB	6.3 dB

Components	PSM4	CWDM	LR4
WDM Mux	N/A	3 dB	3 dB
WDM Demux	N/A	3 dB	3 dB

FEC	PSM4	CWDM	LR4
No FEC	N/A	2.6 dB	2.6 dB

Note: CWDM projections above exclude excess grating coupler losses due to wide optical bandwidth required, which could be 10+ dB. Discussed more later in presentation.

† *Loss figures from: Kolesar_01_0213_smf.pdf*

Link Budget Differences

Totals	PSM4	CWDM	LR4
With FEC at 500m	2.90 dB	9.91 dB	N/A
With FEC at 2 km	N/A	10.66 dB	N/A
Without FEC at 2 km	N/A	13.26	N/A
Per baseline proposals (aggregate)	2.90 dB	13.26 dB	14.9 dB

- WDM solutions are **at least 7 dB worse** link budget than PSM4.
  - Net of fiber plant and module component losses.
- For 2 km non FEC operation a CWDM module will have to overcome **10.36 dB additional losses** compared to PSM4.
  - LR4 at 10 km is 12 dB higher total loss than PSM4

Note: CWDM projections above exclude excess grating coupler losses due to wide optical bandwidth required, which could be 10+ dB. Discussed more later in presentation.

Power

QSFP Compatibility

Power Consumption – Dual Retimed Solutions

Transmitter (x4 per component) (mW)	PSM4	CWDM	LR4
Module Equalizer (CTLE)	120	120	120
Transmitter CDR	420	420	420
Transmitter/MZI	440	540	540
Optical Mux	0	600	600
Laser +TEC	200	800	2200
Receiver (x4 per component) (mW)	**PSM4**	**CWDM**	**LR4**
Optical DeMux	0	1200	1200
TIA	200	280	280
Receiver CDR	420	420	420
Output Driver	100	100	100
Total (mW)	**PSM4**	**CWDM**	**LR4**
Module Auxiliary	20	20	20
Module Total Power - Nominal	1920	4500	5900
Module Total Power – Worst Case	2496	5850	7670

Note: CWDM projections exclude excess grating coupler losses due to wide optical bandwidth required, which could be 10+ dB. Discussed more later in presentation.

Power Consumption – Single Retimed Solutions

Transmitter (x4 per component) (mW)	PSM4	CWDM	LR4
Module Equalizer (CTLE)	120	120	120
Transmitter CDR	420	420	420
Transmitter/MZI	440	540	540
Optical Mux	0	600	600
Laser + TEC	200	800	2200
Receiver (x4 per component) (mW)	**PSM4**	**CWDM**	**LR4**
Optical DeMux	0	1200	1200
TIA	200	280	280
Receiver CDR	0	0	0
Output Driver	100	100	100
Total (mW)	**PSM4**	**CWDM**	**LR4**
Module Auxiliary	20	20	20
Module Total Power - Nominal	1500	4080	5480
Module Total Power – Worst Case	1950	5304	7124

Note: CWDM projections exclude excess grating coupler losses due to wide optical bandwidth required, which could be 10+ dB. Discussed more later in presentation.

Power Consumption – Non Retimed Solutions

Transmitter (x4 per component) (mW)	PSM4	CWDM	LR4
Module Equalizer (CTLE)	120	120	120
Transmitter CDR	0	0	0
Transmitter/MZI	440	540	540
Optical Mux	0	600	600
Laser + TEC	200	800	2200
Receiver (x4 per component) (mW)	**PSM4**	**CWDM**	**LR4**
Optical DeMux	0	1200	1200
TIA	200	280	280
Receiver CDR	0	0	0
Output Driver	100	100	100
Total (mW)	**PSM4**	**CWDM**	**LR4**
Module Auxiliary	20	20	20
Module Total Power - Nominal	1080	3660	5060
Module Total Power – Worst Case	1404	4758	6578

Note: CWDM projections exclude excess grating coupler losses due to wide optical bandwidth required, which could be 10+ dB. Discussed more later in presentation.

Power Consumption Summary

- WDM solutions cannot reasonably fit inside QSFP thermal envelope
  - 100GBase-LR4 module with Caui-4 over 7.6 W.
    - 100GBase-LR4 non-retimed module over 6.5 W.
  - 100G-CWDM module with Caui-4 over 5.8 W.
    - 100G-CWDM non-retimed module over 4.7 W.
- PSM4 can fit inside the QSFP thermal envelope
  - 100GBase-PSM4 module with Caui-4 less than 2.5 W (class III)
  - 100GBase-PSM4 with single retimer less than 2.0 W (class II)
  - 100G-Base-PSM4 non-retimed less than 1.5 W (class I)

- QSFP Power Classes:
  - Class I : 1.5 W max
  - Class II: 2 W max
  - Class III: 2.5 W max
  - Class IV: 3.5 W max

Note: CWDM projections exclude excess grating coupler losses due to wide optical bandwidth required, which could be 10+ dB. Discussed more later in presentation.

Assembly and Cost

The Achilles heel of CWDM

Silicon Photonics Coupling Techniques

Surface Coupling

- Pros:
  - Does not violate CMOS design rules (guard ring)
  - Does not require CMOS post-processing (precision dice/polish)
  - Enables full OE wafer scale testing
  - Enables easy fiber attach
    - Large area for bonding to CMOS
    - Bonding footprint not a function of IC thickness
    - Metal alignment fiducials for vision systems
  - Allows for higher density of couplers (2d Array)
  - Can separate out separate polarizations from a standard SMF.
  - Already in high volume production
    - Millions of grating couplers already shipped
- Cons:
  - Finite optical bandwidth (approx. 30 nm 3dB BW)
    - Parabolic roll-off, > 10 dB loss at 60nm BW

Edge Coupling

- Pros:
  - Theoretically Larger optical bandwidth
- Cons:
  - Violates CMOS design rules (guard ring)
  - Requires precision post processing to create coupler interface
  - Does not allow for full OE wafer scale testing
  - Fiber attach extremely difficult
    - Very little area available for a CMOS bond
    - Inability to employ metal alignment fiducials
    - Thin IC height likely require additional packaging layers/steps for integrated solution
      - Prohibiting chip on board cost reductions
  - Couplers restricted to a single row
  - Couplers can not separate out different polarities
    - Mandates polarization maintaining fiber or more complex receiver design.
  - Not yet in production

Options for CWDM with Silicon Photonics

- Surface Coupling with External Mux/Demux
  - Need to integrate external filter, and have another fiber boundary
- Edge Coupling with Internal Mux/Demux
  - Can theoretically integrate Mux/Demux function

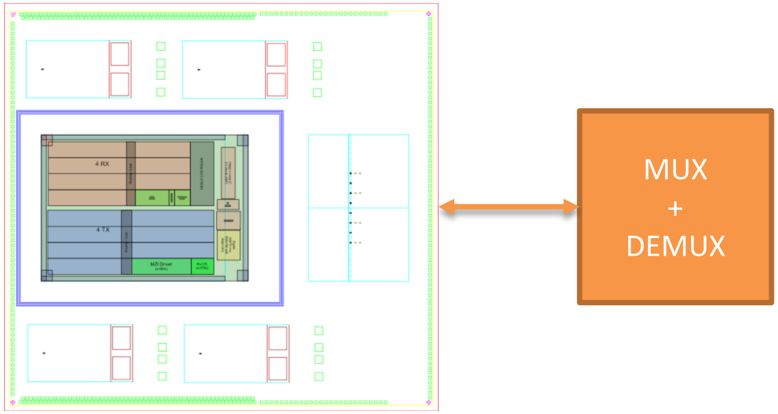
CWDM Chipset Costs

Surface Coupling

- Similar to LR4 chipset, but with added parallel fiber interface
  - Increase in area of approximately 10%
- Addition of external MUX/DEMUX
  - <u>Assuming net cost equivalent to silicon photonics IC cost</u>

Edge Coupling

- Insufficient technology maturity to reasonably project costs/yields



Cost Comparison

Chipset†	PSM4	LR4	CWDM – Surface Coupling
Chipset Only	1.03	2.70	3.54
Chipset with TEC	1.03	3.70	3.54
Cost Relative to PSM4	100%	359%	344%
Module (Un-Yielded)	**PSM4**	**LR4**	**CWDM – Surface Coupling**
Net Relative Cost	1.17	4.23	4.55
Cost Relative to PSM4	100%	361%	389%
Yield	**PSM4**	**LR4**	**CWDM – Surface Coupling**
Optical Attachments	2	5	7
Aggregate Yield (@ 95% per)	90%	77%	70%
Module (Yielded)	**PSM4**	**LR4**	**CWDM – Surface Coupling**
Net Relative Cost	1.3	5.49	6.5
Cost Relative to PSM4	100%	422%	500%

† *from welch_01b_0113_optx.pdf*

Summary

- PSM4 the lowest cost solution at under ¼ the cost of either WDM alternative
- CWDM actually has the highest cost floor of any possible solution (using silicon photonics)
  - Five times the cost of PSM4
  - 20% higher cost than LR4
- WDM solutions pose dramatic link budget hurdles compared to PSM4
  - CWDM Penalty: 7 – 10+ dB worst than PSM4
- PSM4 is the only solution that can fit into a QSFP form factor
  - Depending on host system specification, could even be as low as class I power consumption