KM3NeT:

Proposed Real-time Optoelectronic Readout System

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CIP heritage

Over 30 years of world leading R&D under ownership of BT and Corning; 500 years of combined photonics experience

2007 Sales to 120 customers in 28 countries

2004 **Commercial launch of CIP Ltd**

Renamed Centre for Integrated Photonics

2003 EEDA East of England Development Agency takes on ownership of Centre after Corning withdrawal

2000 Corning purchase Centre and establish Corning Research Centre

1990s Products commercialised through BT&D (Agilent) and Kymata (Gemfire)

1980s Significant investment in components and hardware development at BTRL Martlesham Heath

1970s BT sets up Fibre Optics Group at Martlesham Heath

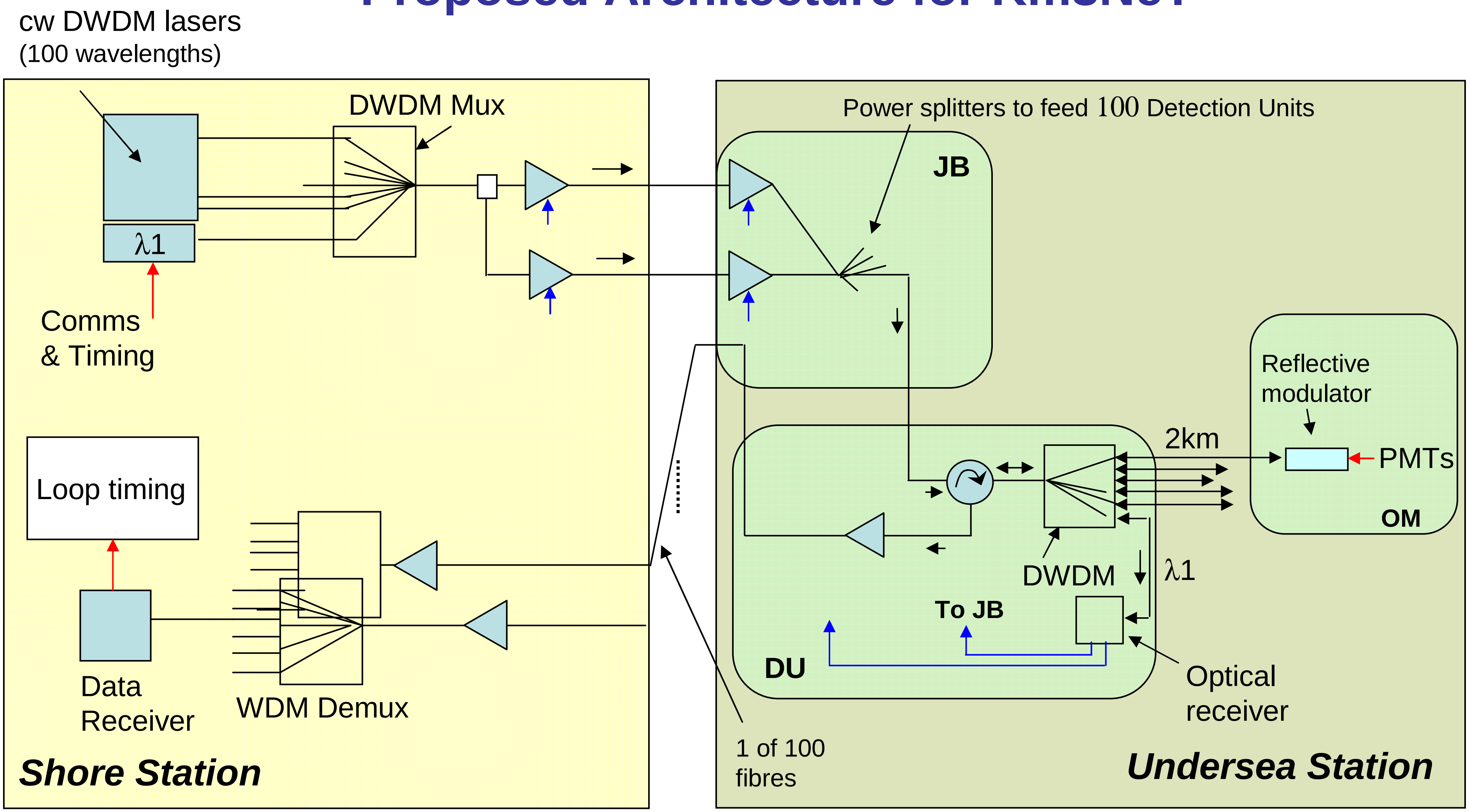
Major player in development of photonic devices and networks, MOVPE growth, Flame Hydrolysis Deposition (FHD),

CIP Technologies

Overview

- Optical transmission system architecture
  - Based on current Telecom technology
- Timing calibration
  - Transmission time skew
  - Time delay measurement
- Power budget
  - Optical Signal to Noise Ratio
  - Rayleigh backscatter and SBS noise
- Electronic encoder / multiplexer
  - Synchronisation and delay calibration
- First cut electrical power consumption

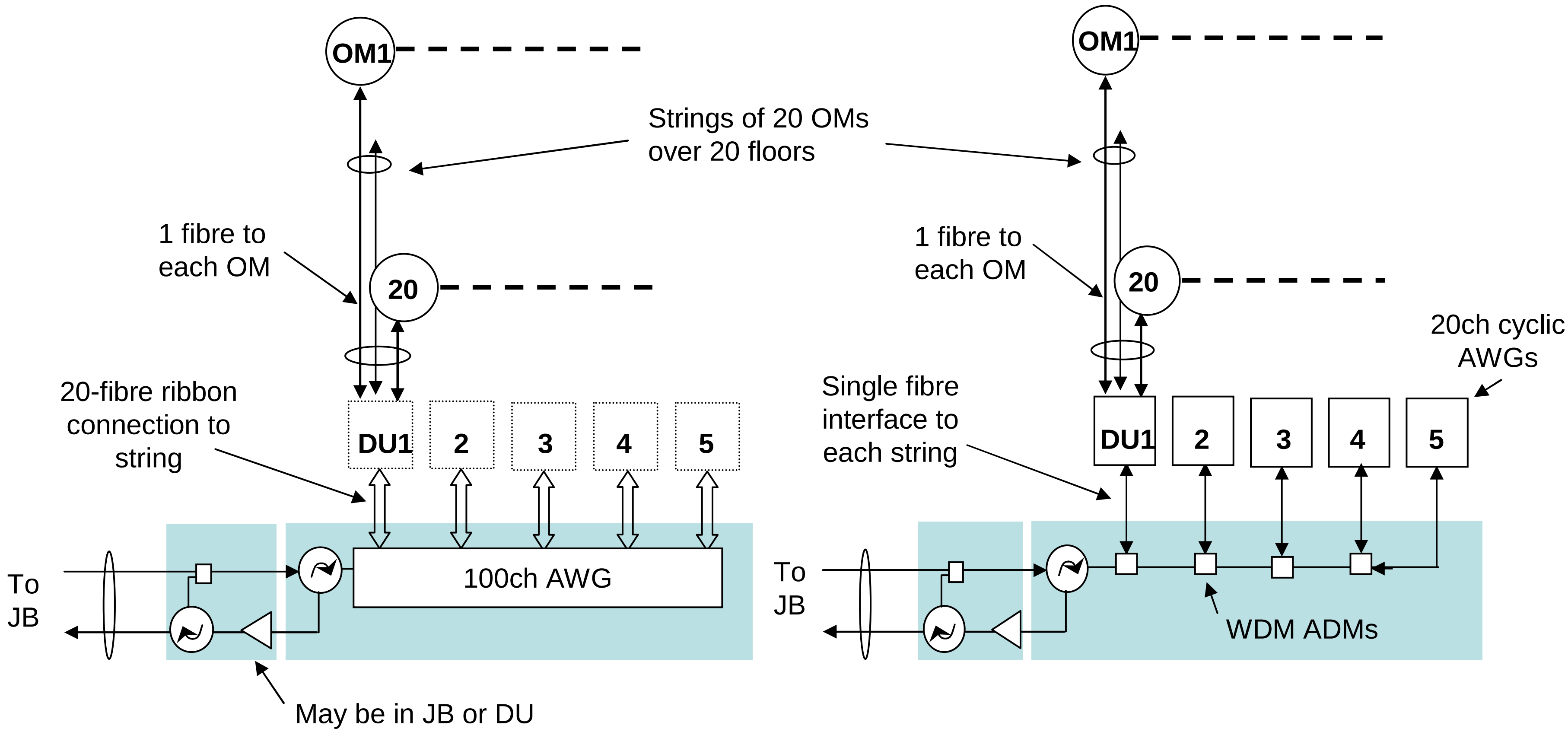
Proposed Architecture for Km3NeT



↑ (red) = fast electronic signals

↑ (blue) = slow electronic signals

5-string Detection Unit options



(a) Single AWG ribbon connectors

(b) Multiple AWGs + ADM single-fibre connectors

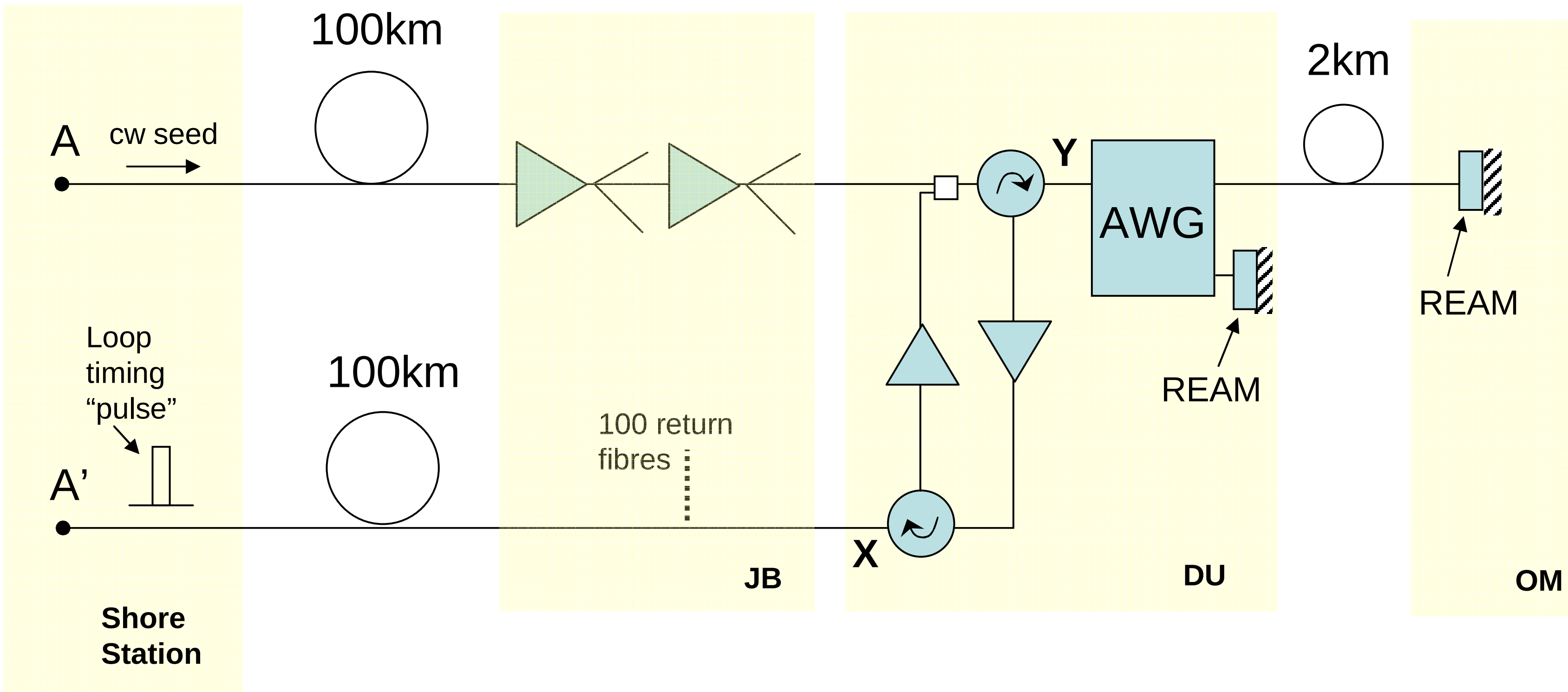
Transmission Timing Skew

- Wavelength dependent timing skew due to group delay over 100km (LEAF®)
  - ~90ns for 25GHz comb (1530nm – 1550nm)
  - ~140ns for 40GHz comb (1530nm – 1562nm)
  - This is deterministic, at fixed temperature
- Temperature dependence
  - estimates based on published data…
  - Bulk: 96ps/^{o}C per km → 9.6ns/^{o}C (100km) (LEAF®)
  - Skew: λ_0 ~ 0.03nm/^{o}C → 8.6ps/^{o}C (100km) (standard fibre 40GHz comb)
  - Shows that relative timing information will stay constant, even for large temperature variations

Clocking and Timing calibration

- Shore based optical ‘pulse echo’ system to measure absolute and/or relative propagation delays from each OM
- Clock and data recovery of each OM to continuously monitor OM “heart-beat”
  - needed for data recovery de-multiplexing anyway
- Shore based master clock / framing signal generator to track round-trip delay to each detection unit during system operation
  - also used for embedded control signals

Timing Diagram

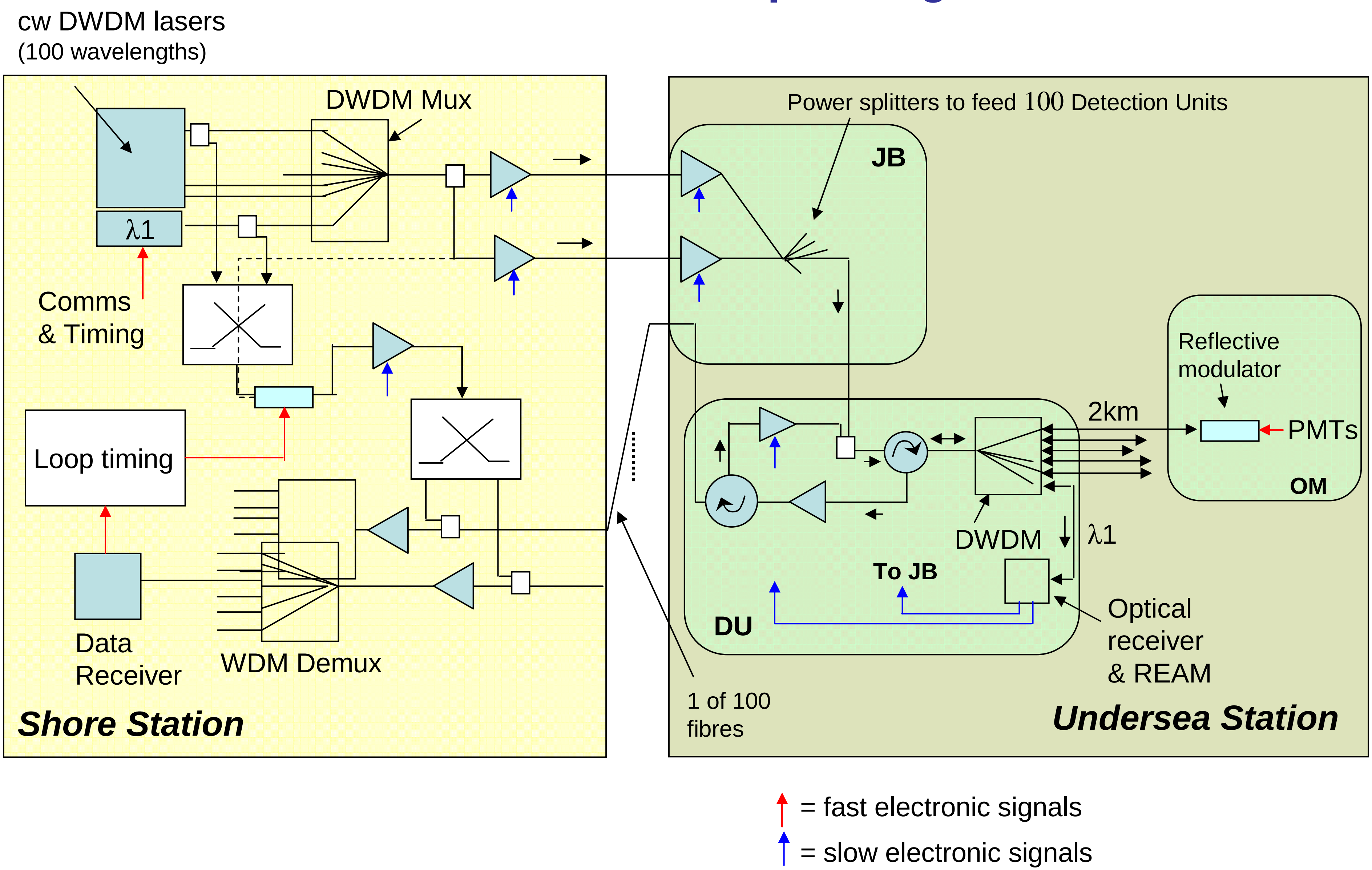


$T_{X\text{-}Y} = T_{Y\text{-}X}$ **For illustration (or measured during construction)**

$T_{A'\text{-}OM\text{-}A'}$ **Pulse echo A' to all OMs and DUs**

$T_{OM\text{-}A'} = (T_{A'\text{-}OM\text{-}A'})/2$

Shore based loop timing

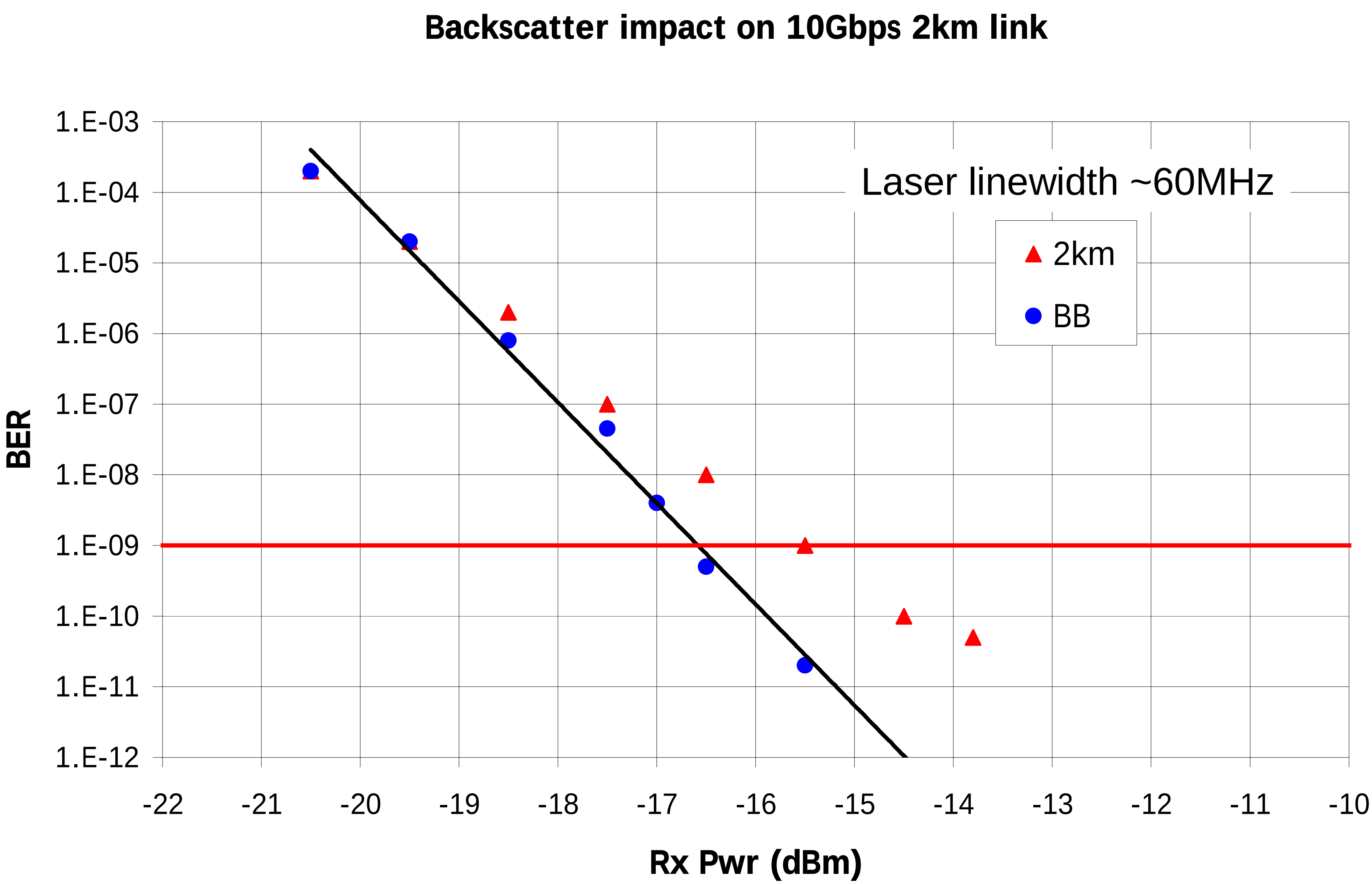


Optical Transmission power budget

	Power, dBm	Gain, (dB)	NF (dB)	Signal power, dBm	ASE power, dBm/0.1nm	OSNR, dB
DFB laser				**3**	-40	43
tap		**-3.5**		-0.5	-43.5	43
MUX		**-4**		-4.5	-47.5	43
tap		**-3.5**		-8	-51	43
Tx booster	**23**	**11**	**6**	**3**	-37.4	40.4
100km feeder fibre		**-20.0**		-17.0	-57.4	40.4
Split pre-amp	**16**	**13**	**6**	-4.0	-37.7	33.7
First split		**-13**		-17.0	-50.7	33.7
Split booster	**27**	**24**	**6**	7	-24.2	31.2
Second split		**-10**		**-3**	-34.2	31.2
tap		**-2**		-5	-36.2	31.2
Circulator		**-1**		-6	-37.2	31.2
MUX		**-4**		-10	-41.2	31.2
REAM		**-10**		-20	-51.2	31.2
MUX		**-4**		-24	-55.2	31.2
Circulator		**-1**		-25	-56.2	31.2
Transmit EDFA	**20**	**25**	**6**	0	-25.5	25.5
Return fibre		**-20**		-20	-45.5	25.5
tap		**-3.5**		-23.5	-49.0	25.5
Rx pre-amp EDFA	**16.5**	**20**	**6**	-3.5	-27.1	23.6
MUX		**-4**		-7.5	-31.1	23.6

For 10G system, minimum OSNR for 10^{-12} BER is 16dB, typical experimental value ~20dB. Our estimated value of 23.6dB at the shore-based Rx seems a good starting point

Rayleigh Backscatter penalty measurements



Rayleigh backscatter conclusions

- Coherent Rayleigh backscatter power penalties are manageable and can be kept to <2dB

  Precautions…

  – Maximise the signal to backscatter power ratio by minimising the signal return loss over the single fibre section

  – Use a large source line-width, 60MHz gave rise to a penalty of ~1dB at a BER of 10^{-9}

  – An error floor may exist at ~ 10^{-10} BER (equates to a background count rate of < 0.1 per PMT)

SBS effects

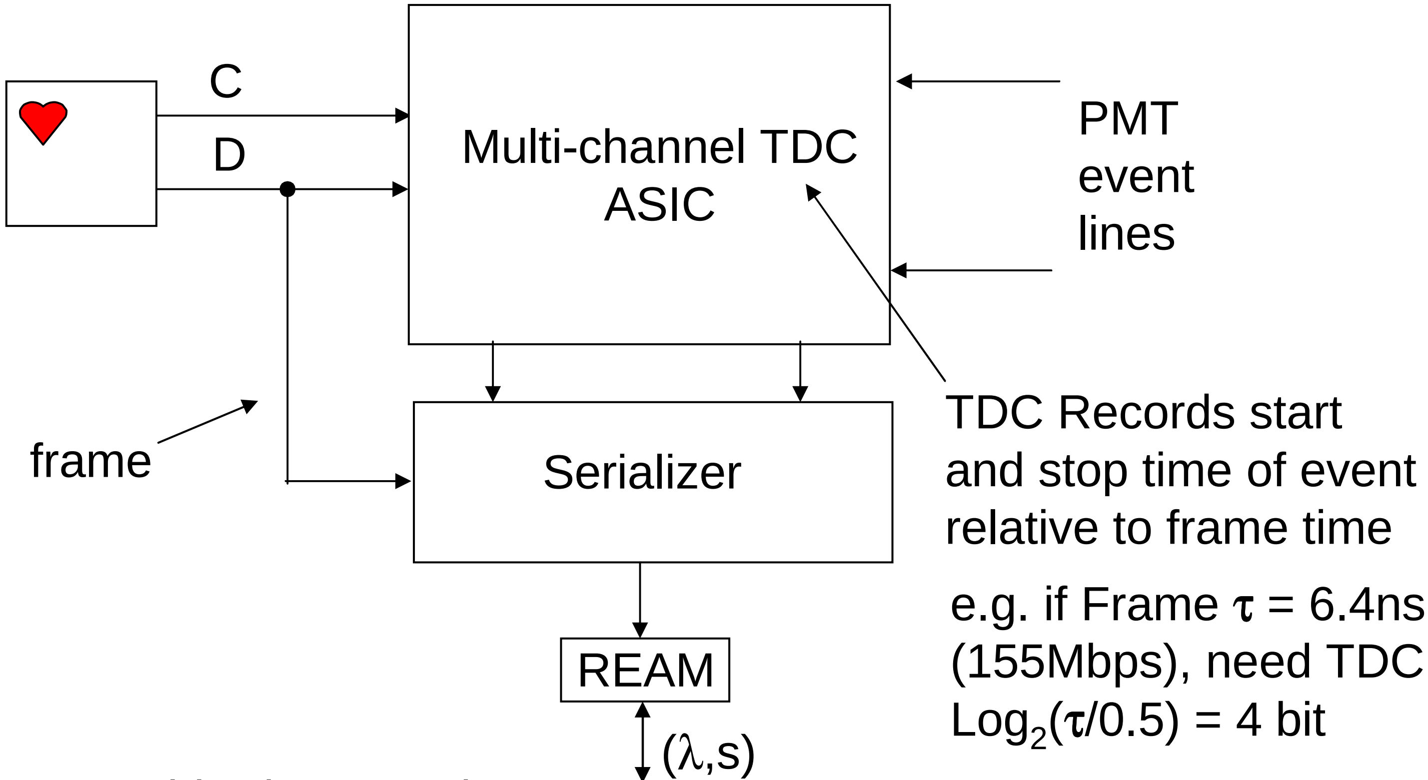
- Stimulated Brillouin Scattering (SBS) is a potential nonlinear impairment in SM fibres
- For long fibres, threshold is ~few mW at 1550nm, for laser linewidth <15MHz. Larger linewidths result in higher threshold
- Channel power in our system is always <2mW, and will have linewidth >15MHz for Rayleigh noise suppression.
- SBS will not be an issue

Electronic Multiplexing

Objective – to keep OM processing as simple as possible

- For 1ns event resolution, max number of PMTs for "real-time" sampling at 10Gbps = 9 (need 1 framing pulse)
- However taking account of signal properties
  - event duration ~2 to 15ns
  - event rate < 300kHz (bioluminescence burst)
- Can use simple pre-processing to increase number of PMTs to 32 or more
  - All we need to do is monitor the 'heart-beat' of the OM at the shore and time-stamp PMT events relative to this.

Serving more PMTs



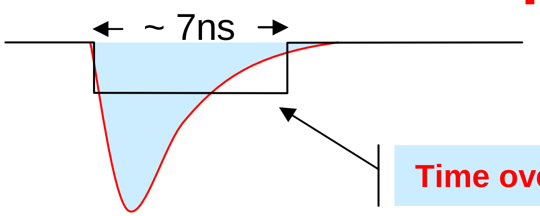
e.g. if Frame τ = 6.4ns (155Mbps), need TDC ~ $\mathrm{Log}_2(\tau/0.5)$ = 4 bit

PMT ID = 5 bits (32 PMTs)
TDC = 4 bits (0.5ns resolution)
= 9 bits per PMT + 1 frame bit per OM

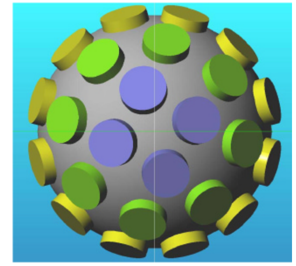
In this 32 PMT example, Max number of simultaneous OM events per frame = 7 for 10Gbps “real-time” measurement

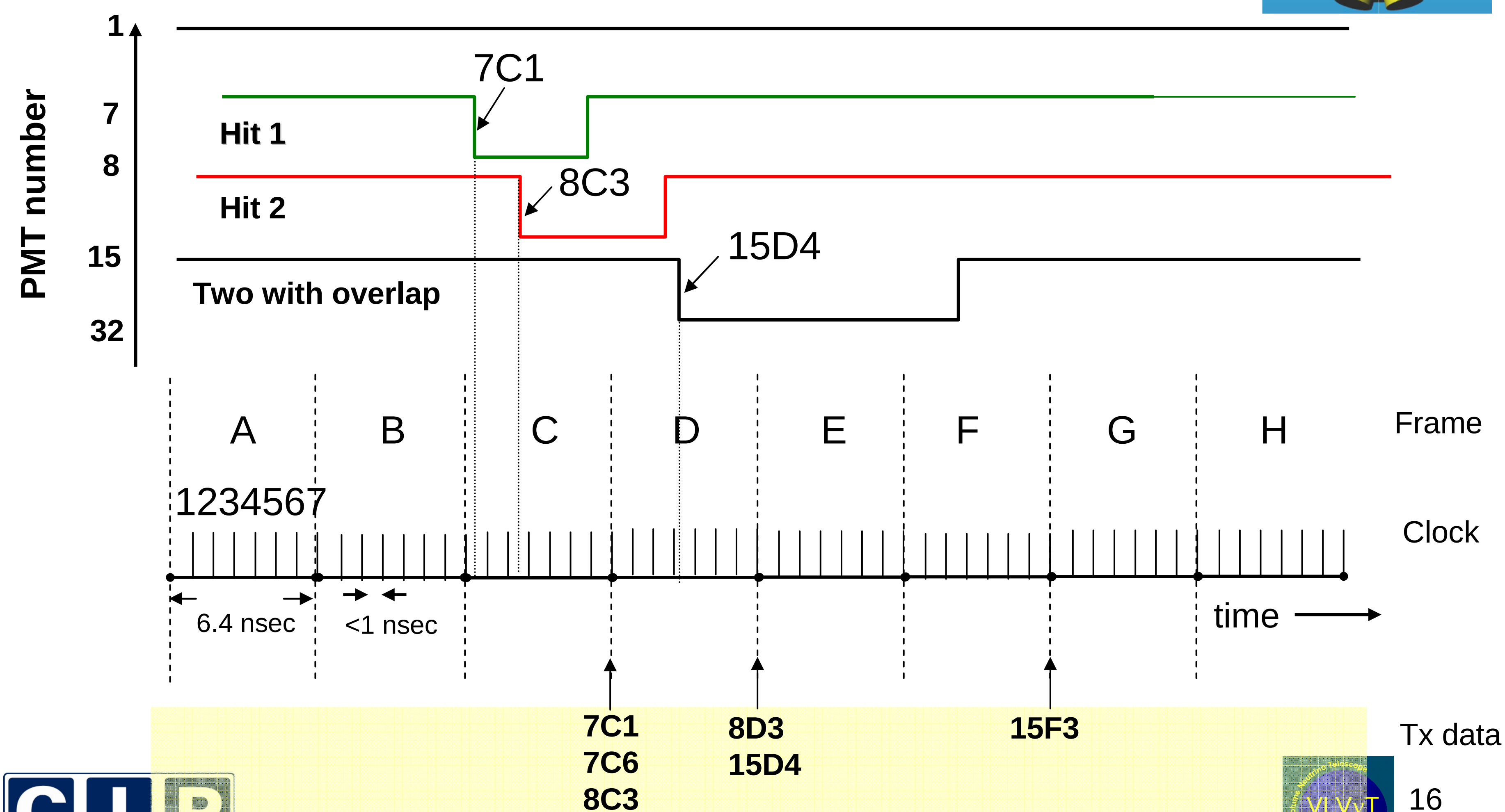
Probability of event in frame time < 0.002 (at worst case dark count of 300kpps)

PMT outputs of a typical event in a OM



Time over threshold single photon pulse resourced by a 3.5 " PMT





CIP Confidential

OM Power consumption

Dominated by OM electronics…

- Ultra-low-power REAM driven directly by digital electronics
  - using custom output stage
  - using integrated EAM driver chip (<0.5W)
- ~1.5W for custom TDC ASIC and serializer

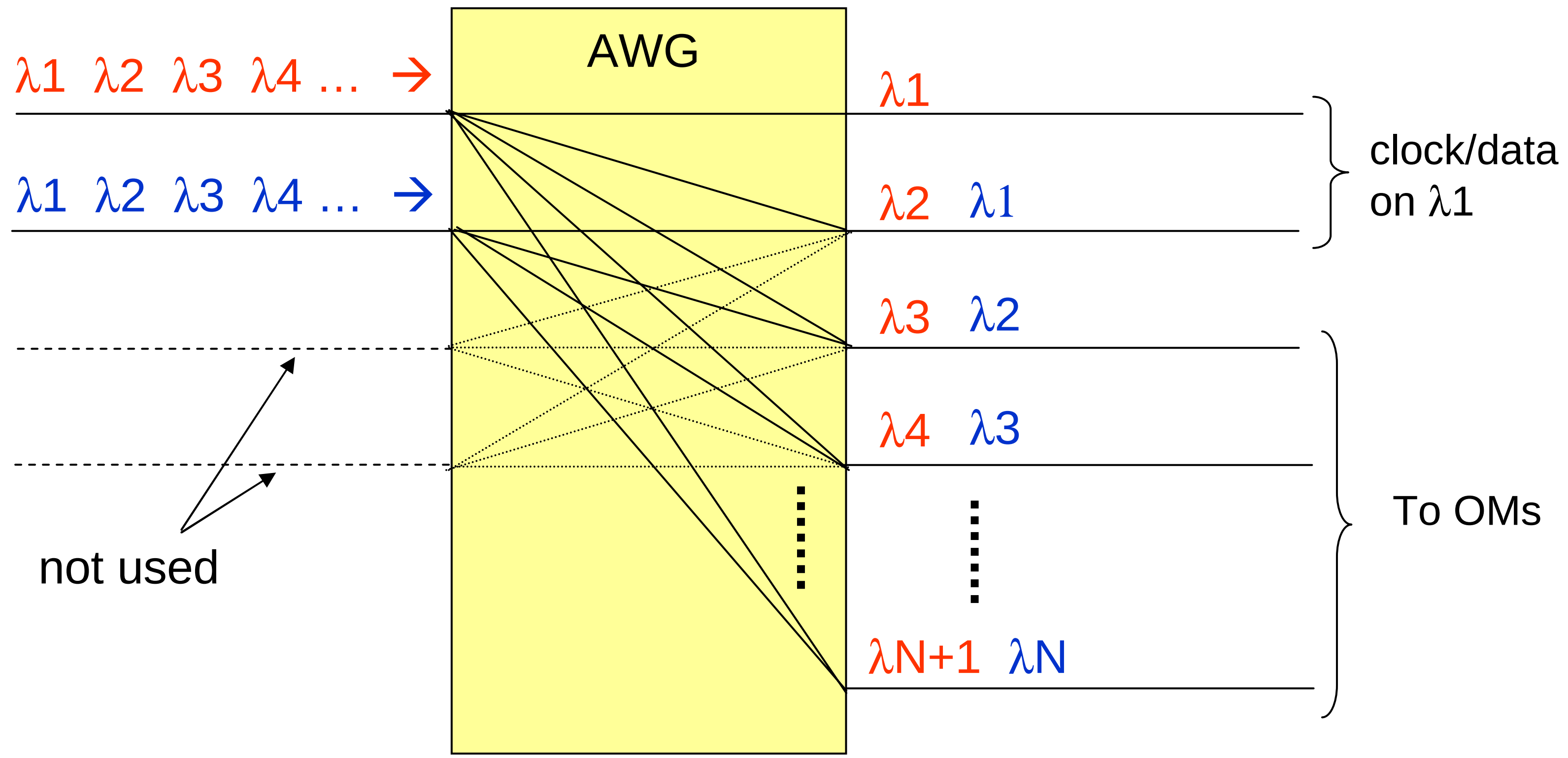
Conclusions

- Optical power budget calculations show that, with realistic component values, low system error rate can be achieved. Rayleigh backscatter in bi-directional part of system is manageable
- Timing calibration solutions identified. Relative timing is insensitive to, for example, temperature variations, while OM clock ‘heart-beat’ monitored on shore
- Simple electronic multiplexing scheme identified
- Opto-electronics power consumption of each OM should be ~ 1.5 to 2W
- Published systems work shows no issues in propagating 80 x 10G channels with 50GHz spacing over >500km of LEAF® fibre, with multiple amplification stages, so expect minimal penalty from 100km transmission

Further slides, if necessary

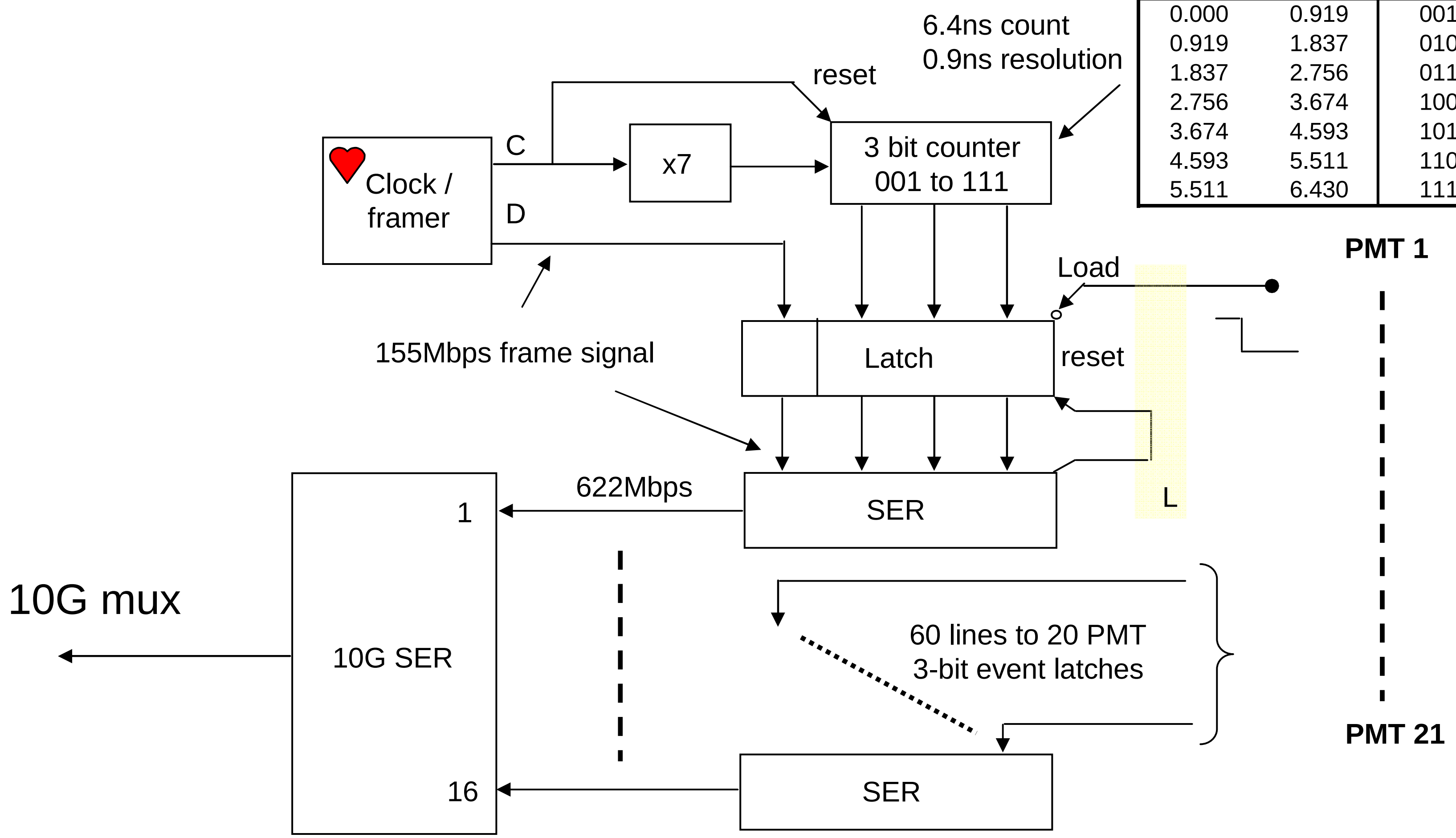
Arrayed Waveguide Grating

- An AWG can be used as a wavelength router…



Example 21 PMT real-time Multiplexer

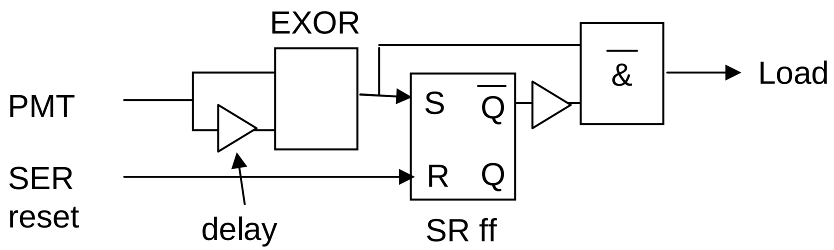
from	to (ns)	code
0.000	0.919	001
0.919	1.837	010
1.837	2.756	011
2.756	3.674	100
3.674	4.593	101
4.593	5.511	110
5.511	6.430	111

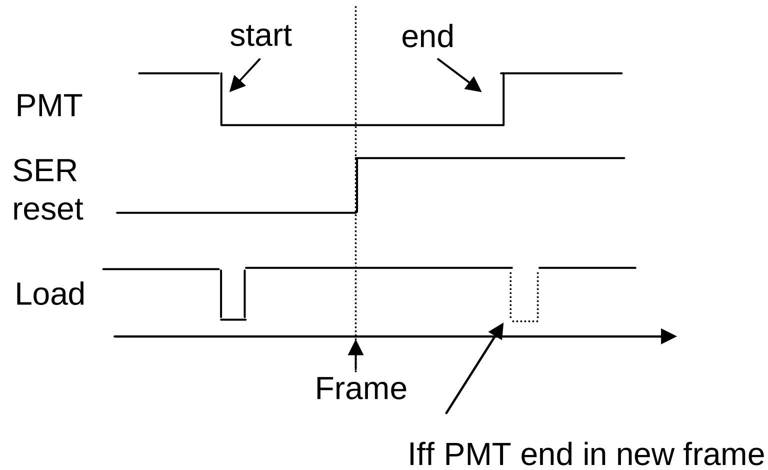


Digital electronics in one or two custom chips; e.g., Broadcom BCM8124 16:1 mux (450mW) and timing in custom ASIC (<1W).

Logic to capture event end time

Load PMT pulse end time if and
only if it occurs in a new frame





Echo OSNR (one λ at a time)

	Power, dB	Gain, (dB)	NF (dB)	Signal power, dBm	ASE power, dBm/0.1nm	OSNR, dB
DFB laser				**3**	**-40**	43
tap		**-3.5**		-0.5	-43.5	43
Switch		**-3**		-3.5	-46.5	43
Pulser		**-10**		-13.5	-56.5	43
Tx booster	**10**	**23.5**	**6**	10	-27.0	37.0
Switch		**-3**		7	-30.0	37.0
tap		**-3.5**		3.5	-33.5	37.0
100km feeder fibre		**-20.0**		-16.5	-53.5	37.0
Circulator		**-1.0**		-17.5	-54.5	37.0
Pulse-amp	**2**	**19.5**	**8**	2	-29.0	31.0
tap		**-5.5**		-3.5	-34.5	31.0
Circulator		**-1**		-4.5	-35.5	31.0
MUX		**-4.0**		-8.5	-39.5	31.0
Fibre		**-1.0**		-9.5	-40.5	31.0
REAM		**-10**		-19.5	-50.5	31.0
MUX		**-4**		-23.5	-54.5	31.0
Circulator		**-1**		-24.5	-55.5	31.0
Transmit EDFA	**3**	**28**	**6**	3	-22.8	25.8
Return fibre		**-20**		-17	-42.8	25.8
tap		**-3.5**		-20.5	-46.3	25.8
Rx pre-amp EDFA	**-10.5**	**10**	**6**	-10.5	-35.2	24.7
MUX		**-4**		-14.5	-39.2	24.7

Echo OSNR (all λ at same time)

	Power, dB	Gain, (dB)	NF (dB)	Signal power, dBm	ASE power, dBm/0.1nm	OSNR, dB
DFB laser				**3**	**-40**	43
tap		**-3.5**		-0.5	-43.5	43
Switch		**0**		-0.5	-43.5	43
Pulser		**-10**		-10.5	-53.5	43
Tx booster	**26**	**16.5**	**6**	6	-33.1	39.1
Switch		**-3**		3	-36.1	39.1
tap		**-3.5**		-0.5	-39.6	39.1
100km feeder fibre		**-20.0**		-20.5	-59.6	39.1
Circulator		**-1.0**		-21.5	-60.6	39.1
Pulse-amp	**20**	**21.5**	**6**	0	-29.8	29.8
tap		**-5.5**		-5.5	-35.3	29.8
Circulator		**-1**		-6.5	-36.3	29.8
MUX		**-4.0**		-10.5	-40.3	29.8
Fibre		**-1.0**		-11.5	-41.3	29.8
REAM		**-10**		-21.5	-51.3	29.8
MUX		**-4**		-25.5	-55.3	29.8
Circulator		**-1**		-26.5	-56.3	29.8
Transmit EDFA	**23**	**30**	**6**	3	-21.0	24.0
Return fibre		**-20**		-17	-41.0	24.0
tap		**-3.5**		-20.5	-44.5	24.0
Rx pre-amp EDFA	**14.5**	**15**	**6**	-5.5	-28.7	23.2
MUX		**-4**		-9.5	-32.7	23.2