# PAM-4 Four Wavelength 400Gb/s solution on Duplex SMF

IEEE P802.3bs 400Gb/sTask Force Meeting

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Presented by

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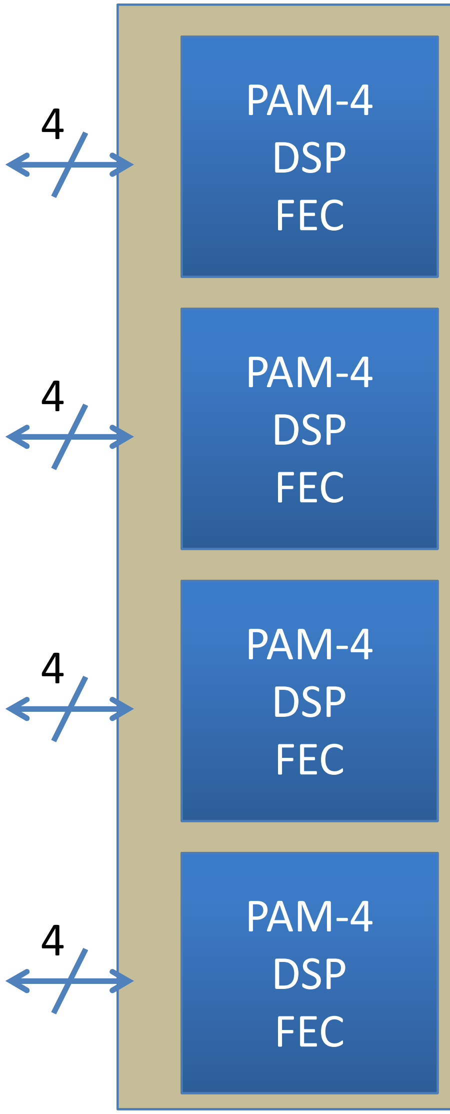
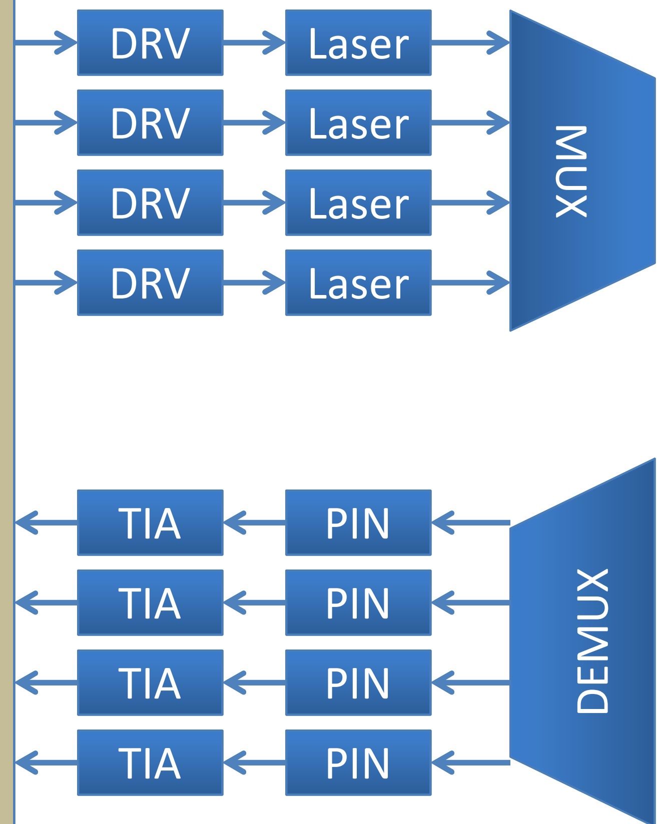
# Why Four Wavelengths for 400GE?

- It is what the market / industry desires
- Four wavelengths is the natural first step for 400GE transmission if one looks at the history of 100GE and 10GE
- To lower overall power and costs of 100GBASE-LR4 module the market is moving towards a single wavelength solution.  We should leverage this development to keep cost down and enable 400G development.
- The technology needed is here today to increase BW capacity per wavelength.
  - Mature and Low Power ADC and DACs are available
  - 802.3bj adopted High Gain FEC with low latency
  - Make use of the available SNR of the 500, 2km, and 10km links
- The projected market window dictates that we plan this technology today.
- 4x100G is a solution which would not be quickly superseded.

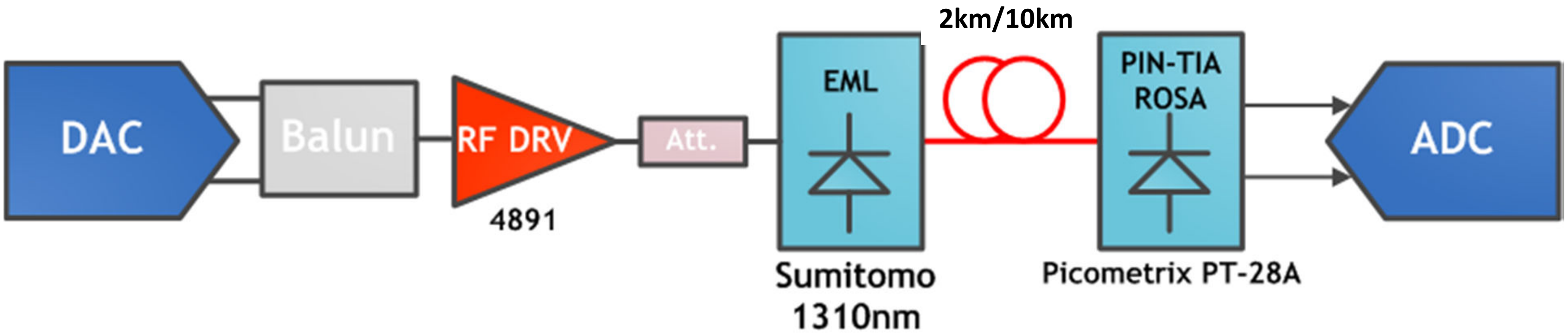
# Proposed Block Diagram




- PHY/Gearbox can be realized as single, dual or quad chip implementation, allowing for backwards compatibility with higher volume 100G applications
- Integrated FEC block enables improved performance for longer reached
- Integrated DSP allows for use of lower cost production released optics
- Client side interface can evolve to 8X50G or even 4X100G



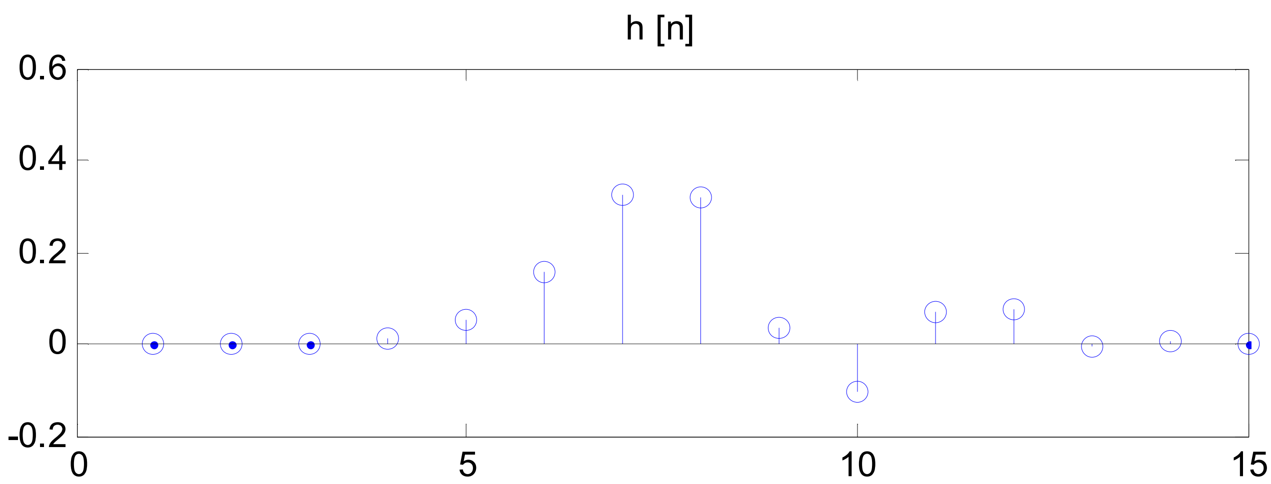
# EML Offline Experiment Measurements
# 60GB PAM-4




- TOSA: Sumitomo Electric STN41UX, **1310 nm**, specified BW =25 GHz, er = 5.5dB
- ROSA: Picometrix PIN-TIA ROSA P/N: PT-28A, measured BW = 25GHz, gain = 300V/W SE (Thermal noise: 44pA/Sqrt(Hz))
- Balun: Marki BAL-036
- RF driver: Triquint TGA4891
- Fiber: SSMF

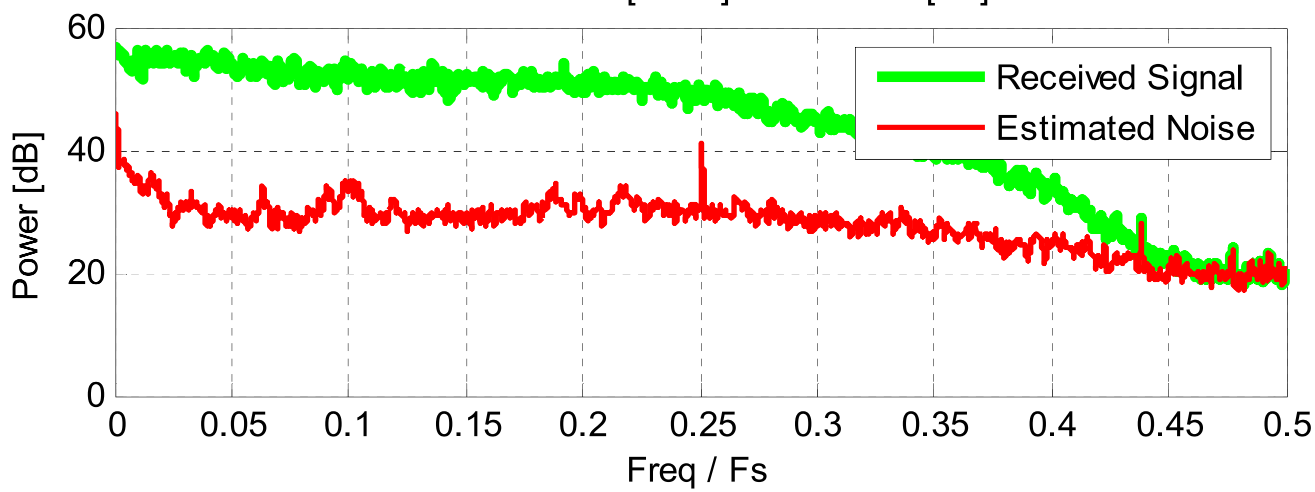
Measured BER
2km = 2.5x10-4
10km = 7.5x10-4

# Results 60GB at 10km fiber (1310nm)




**CIR** (Channel Impulse Response)
-Challenging "8 taps" -BW Limit
- Includes non-Linearities

**Measured SNR = 20.1dB**
**BER= 7.5E-4**

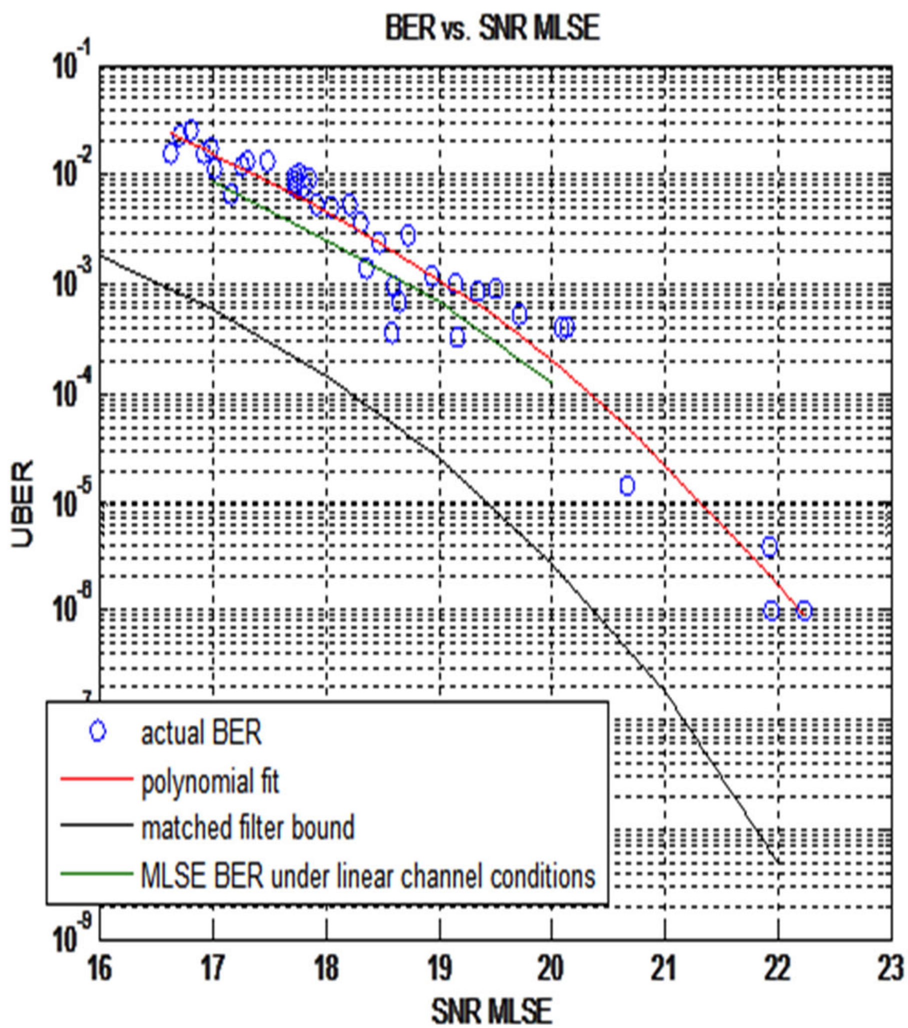



**PSD** (Power Spectral Density)
- At .35 Strong Rolloff
- At 20GHz channel down
  - 10dB
- Noise Estimated using Analytical Channel Model

Normalized to the Sampling Frequency .5 = 30GHz

# Theoretical Limit versus Proposed Solution

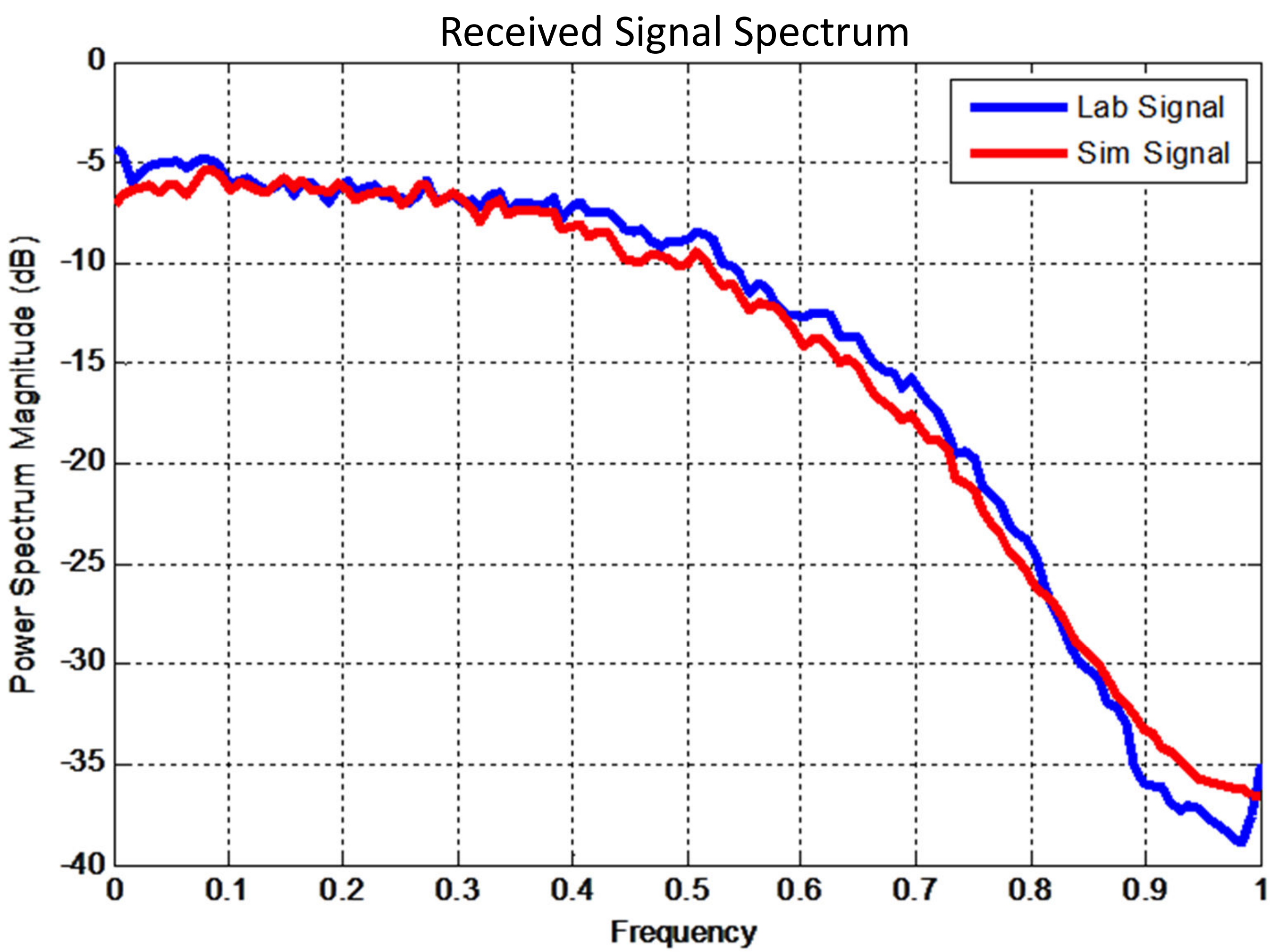
- The optical communication channel under direct detection is far more complicated than classical communication channel of linear convolution and AWGN
- **We present our test results using our RC-MLSE (Reduced Complexity- Maximum Likelihood Sequence Estimation) solution over multiple optical channels with various optical components**
- We compare our results with two theoretical bounds under classical communication channel:
  - **Matched filter bound** –minimal BER for the ISI free AWGN scenario- Black curve
  - **MLSE BER bound** –minimal BER under the limited BW channel plus AWGN scenario (using monte carlo simulations) –Green
- **Curve Fitting** – Polynomial Fit- Measured Data – Various modulators, Drivers, ROSAs
  - Our performance under optical channel is ~0.3dB from the bound for classical communication channel



# Simulation Parameters **(equivalent configuration as the lab setup)**

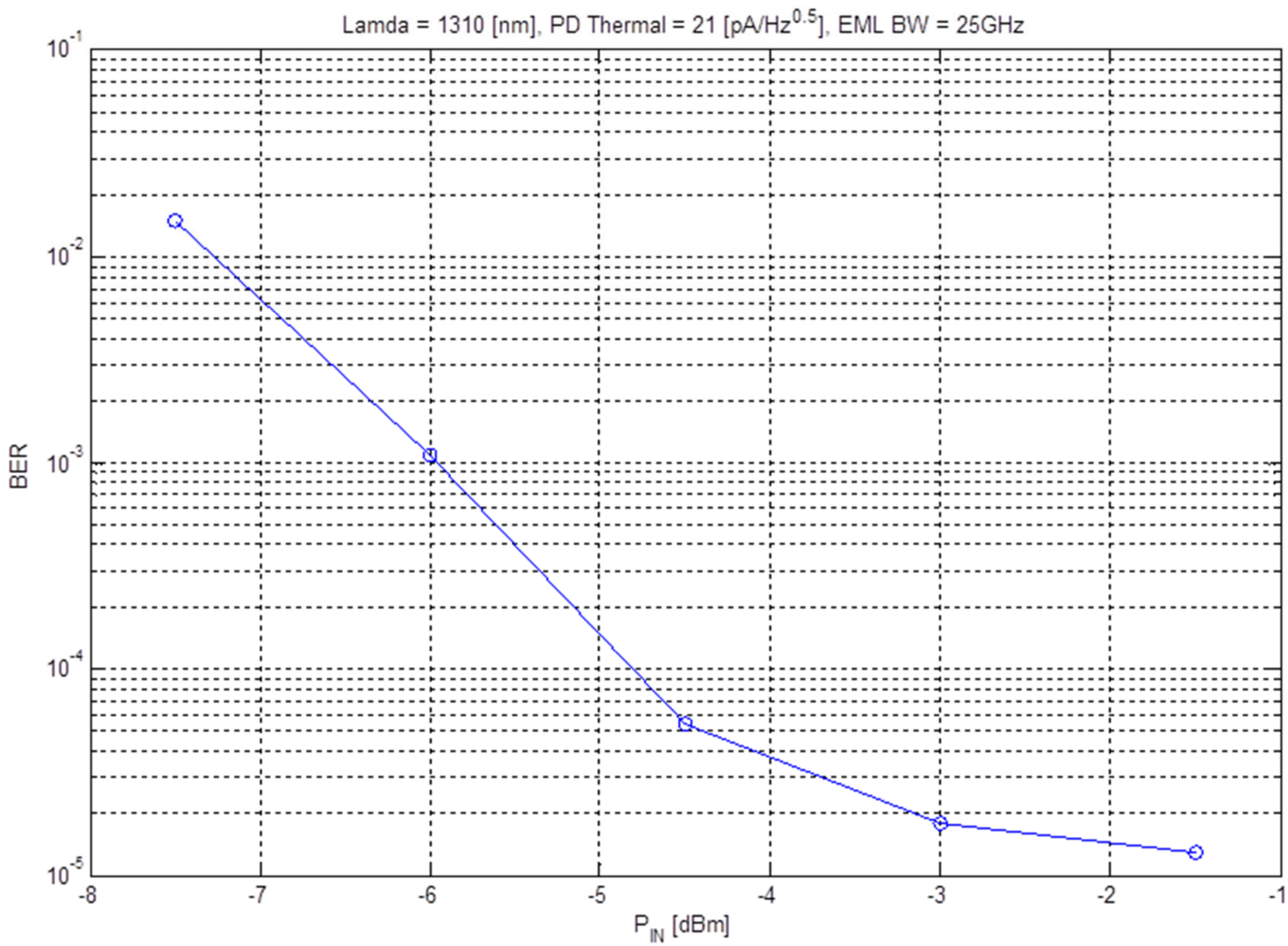
- Driver
  - BW = 25GHz
  - Type: Butter 4'th order
- EML
  - BW = 25GHz
  - Type: Bessel 4'th order
  - +3.0 dBm (2mW)
  - Er= 5.5dB
  - RIN = -144 dBc/Hz
  - THD 2.0%
- Fiber
  - Length = 2km and 10km
- Photo-Diode
  - Responsivity = 0.75 [A/W]
  - PD Thermal Density = 21 pA/sqrt(Hz)
  - LPF BW = 25GHz
  - LPF Type = Bessel 4'th order
  - TIA Gain = 550 Ohm
- DAC / ADC
  - DAC = BW = 16GHz
  - ADC = BW =18GHz
  - Type = Butter 3'rd order
  - SNR 27.7dB – Measured B2B
  - ENOB = 6bits

# Comparison between Measurements and Simulation Results

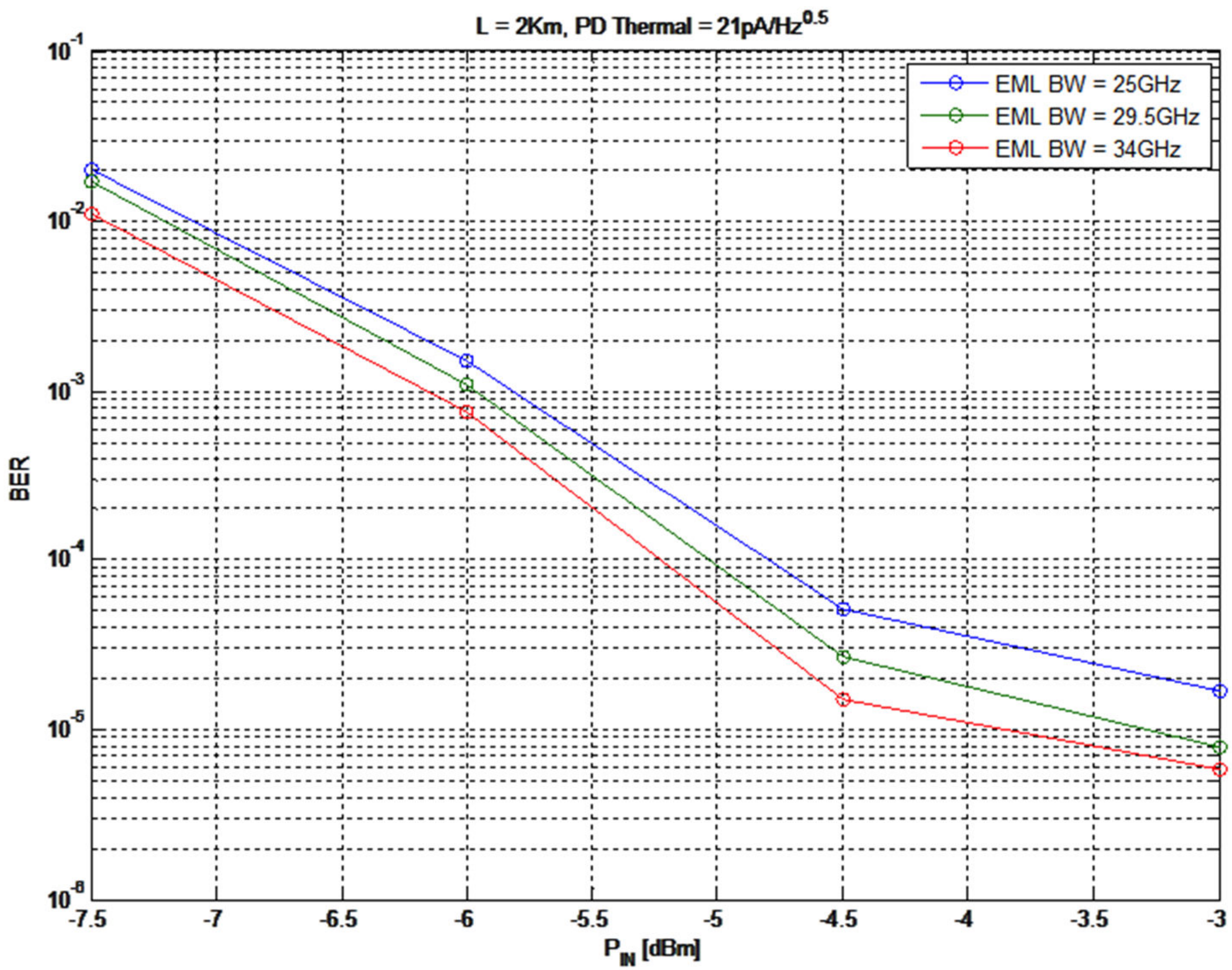



Normalized to Nyquist frequency, 1 = 30GHz

# EML Sensitivity Analysis to Input Power (simulation results)
## 60GB PAM-4, 2km link over 1310nm

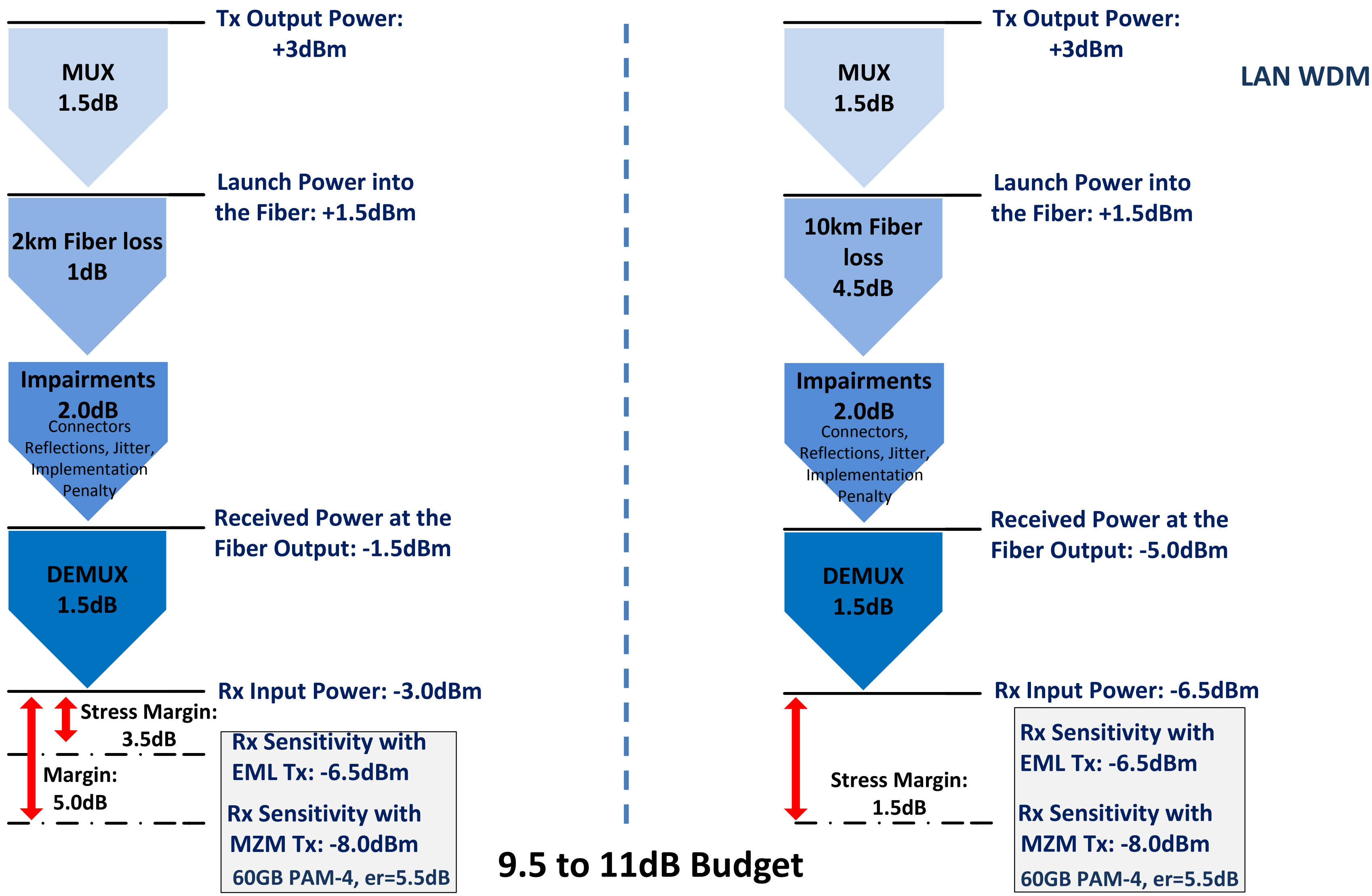


# Sensitivity Analysis to EML Bandwidth Simulation Results
# 60GB PAM-4, 2km link over 1310nm




**Conclusion**: TOSA bandwidth can be reduced down to 25GHz; Introduces 0.5dB Penalty at BER=1E-4

# 480G - 4x120Gbit/sec PAM-4 link budget for 2/10km 1310nm



# Requirements and Link Budget (2/10km) (* preliminary assumptions)

| | Parameter | Value |
|---|---|---|
| **General** | **Modulation format** | PAM4 |
| **Optics Tx+Rx** | **Bit rate** | 112Gb/sec |
| | **Line Baud rate** | 56GB |
| | **# ג** | 1 |
| | **Wavelength** | 1310 |
| | **TOSA** | EML, ER = 4-5dB, linear , RIN -144dB/Hz<br>Differential input signal 1-1.5VPP<br>BW =25G |
| | **ROSA** | PIN+Linear TIA, XMD<br>Include AGC, 500mVpp differential output<br>BW = 25G<br>21pA/(Hz)^1/2 |
| **Channel** | **Fiber type** | SSMF<br>Length: 500m-10km |
| | **Link Power budget:** | Tx output power= +3dBm<br>Mux insertion loss = 1.5dB<br>Fiber loss 2/10km = 1dB /4.5dB<br>Impairments (connectors, reflections, jitter, implementation penalty): 2.0dB<br>De-Mux insertion loss = 1.5dB<br>Rx sensitivity = -6.5dBm/ -8.0dBm (EML / MZM)<br>Link margin = 5.0dB /1.5dB |

# Summary

- A 4 lambda solution for 400G is certainly achievable and fits well with the history of optical transmission
- A 4 lambda solution is backwards compatible to the higher volume and more price sensitive 100G needs
- We encourage the group to work on 4x100G standard now as there is time to meet the expected market window