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Bandwidth Requirements for PAM

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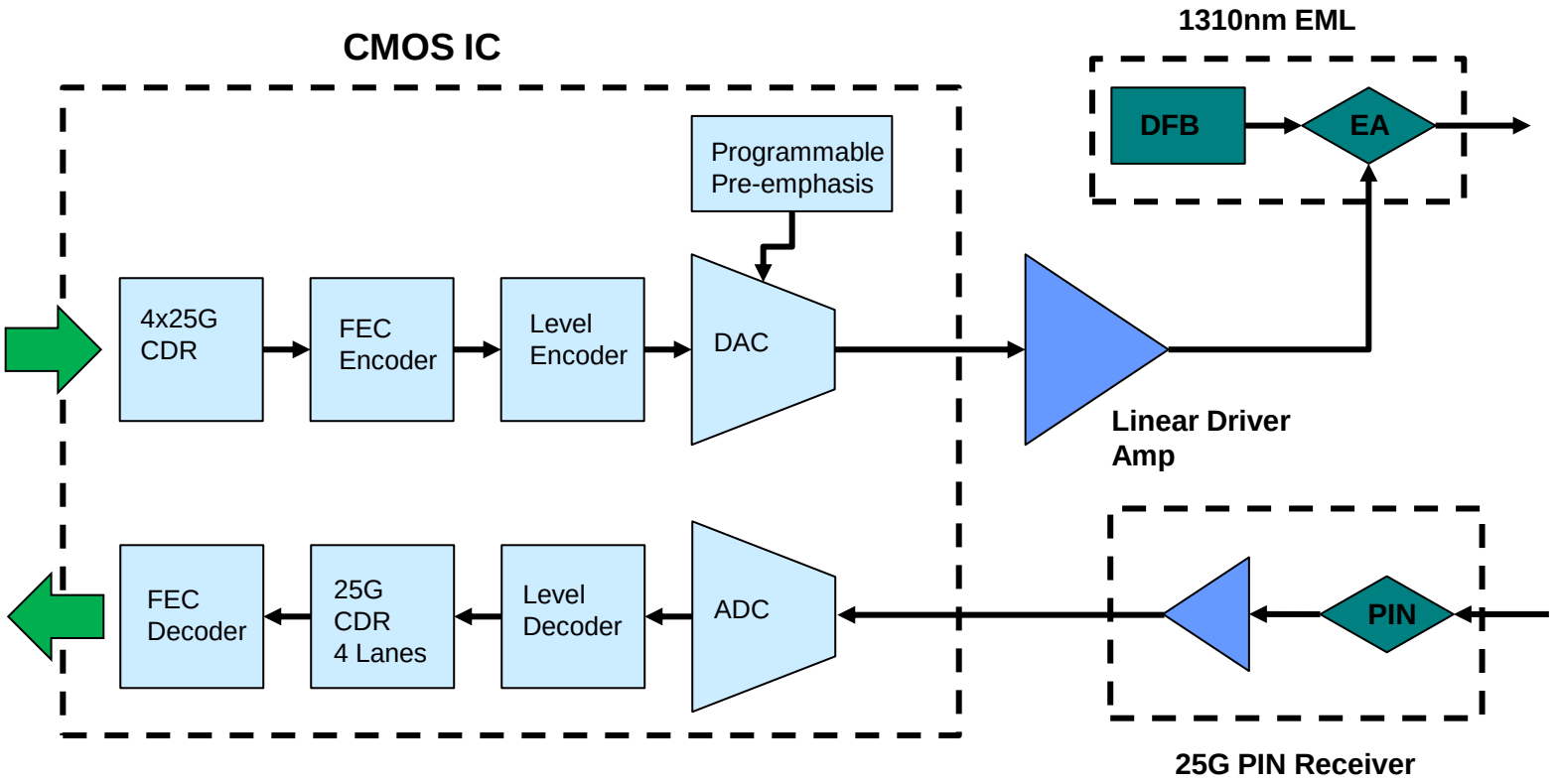
Proposed PAM Transceiver Architecture

- Example of digital generation architecture for multilevel modulation
  - Simple single 1310nm EML laser source
  - CMOS IC with quad CDR, FEC encoder, level encoder, and DAC
    - Level encoder and higher resolution DAC enables
      - Digital linearization of modulator transfer function
      - Multilevel coding with non-equal level spacing for optimum SNR performance
      - Digital pre-emphasis and frequency compensation



Challenges and Opportunities

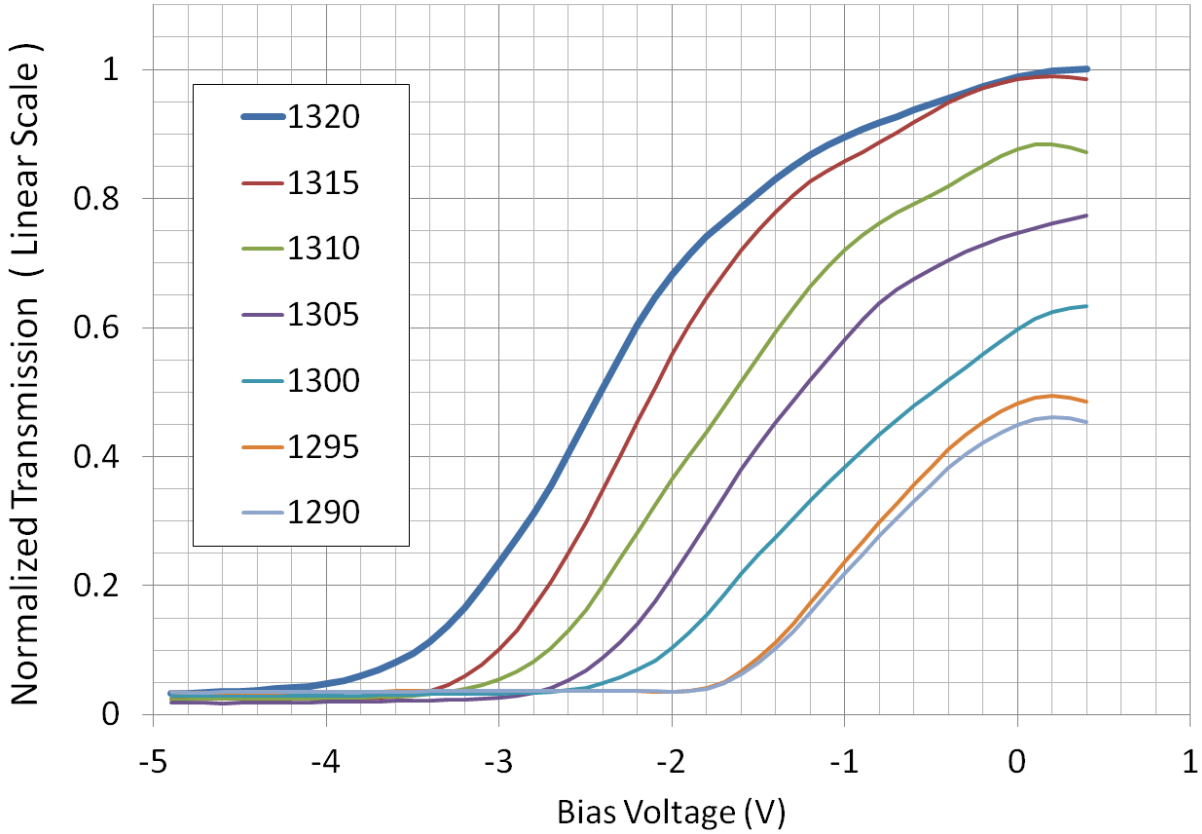
- Challenges
  - Nonlinear transfer function of EA
  - Reduced SNR of multi-level coding scheme
  - Increased Bandwidth requirements for high quality PAM encoding

- Opportunities
  - Digital linearization of drive signal with DAC
  - Integrated low overhead FEC
  - Transmitter digital pre-emphasis and receiver digital equalization

- This presentation will focus on the transmitter design issues
  - Linearization of EA modulators transfer function
  - EA bandwdith requirements for effective PAM generation
  - Digital pre-emphasis for eye optimization

Measured EAM Voltage to Intensity Transfer Functions

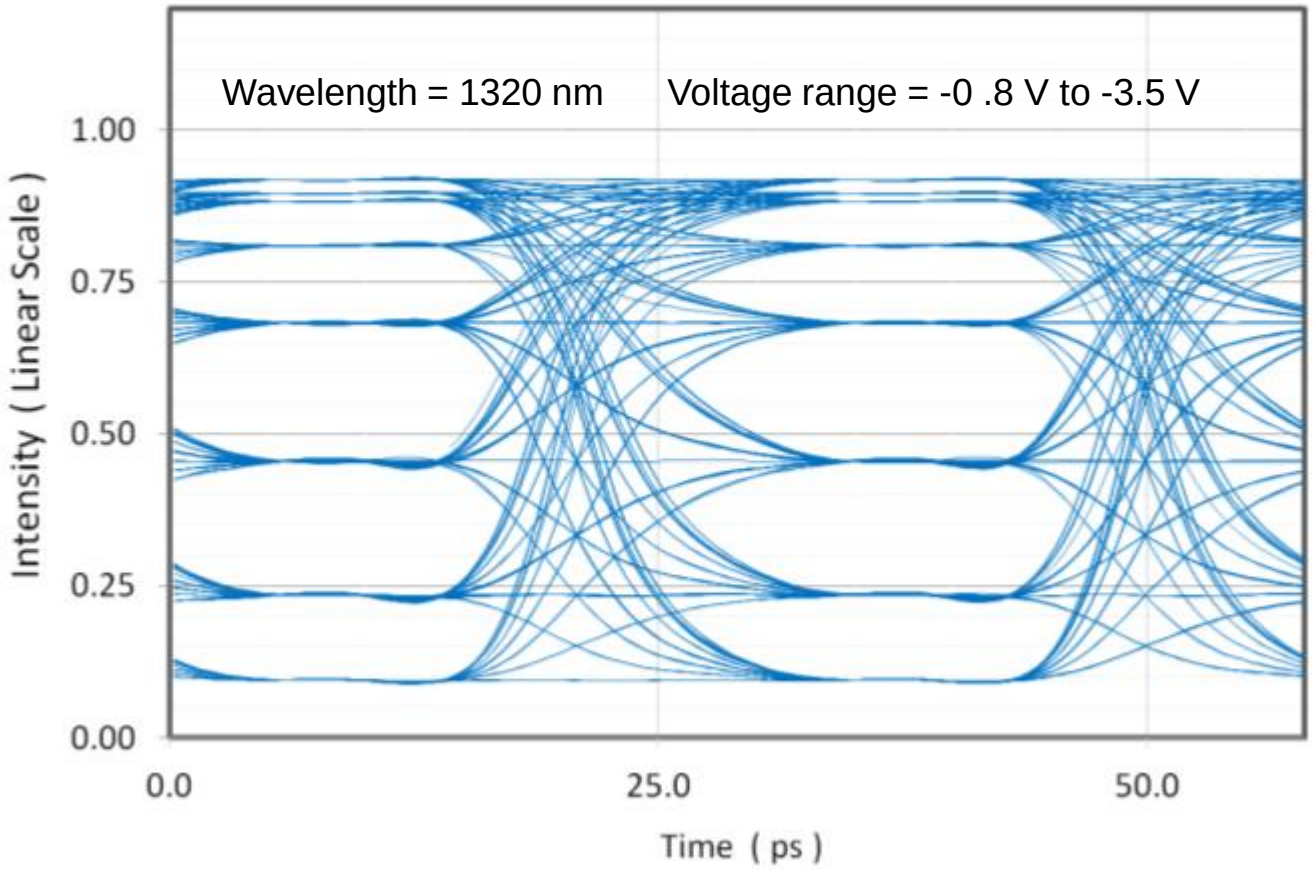
Normalized Transmission of a 125 μm long Electro-Absorption Modulator



- Typical EA modulator has a voltage to intensity transfer function that is not linear
- Even for a Mach Zehnder modulator the output intensity depends sinusoidally on the phase modulation and so will also need to be linearized using a DAC

PAM 8 Optical Eye at 37.375 Gbaud [112.125 Gbit/s]

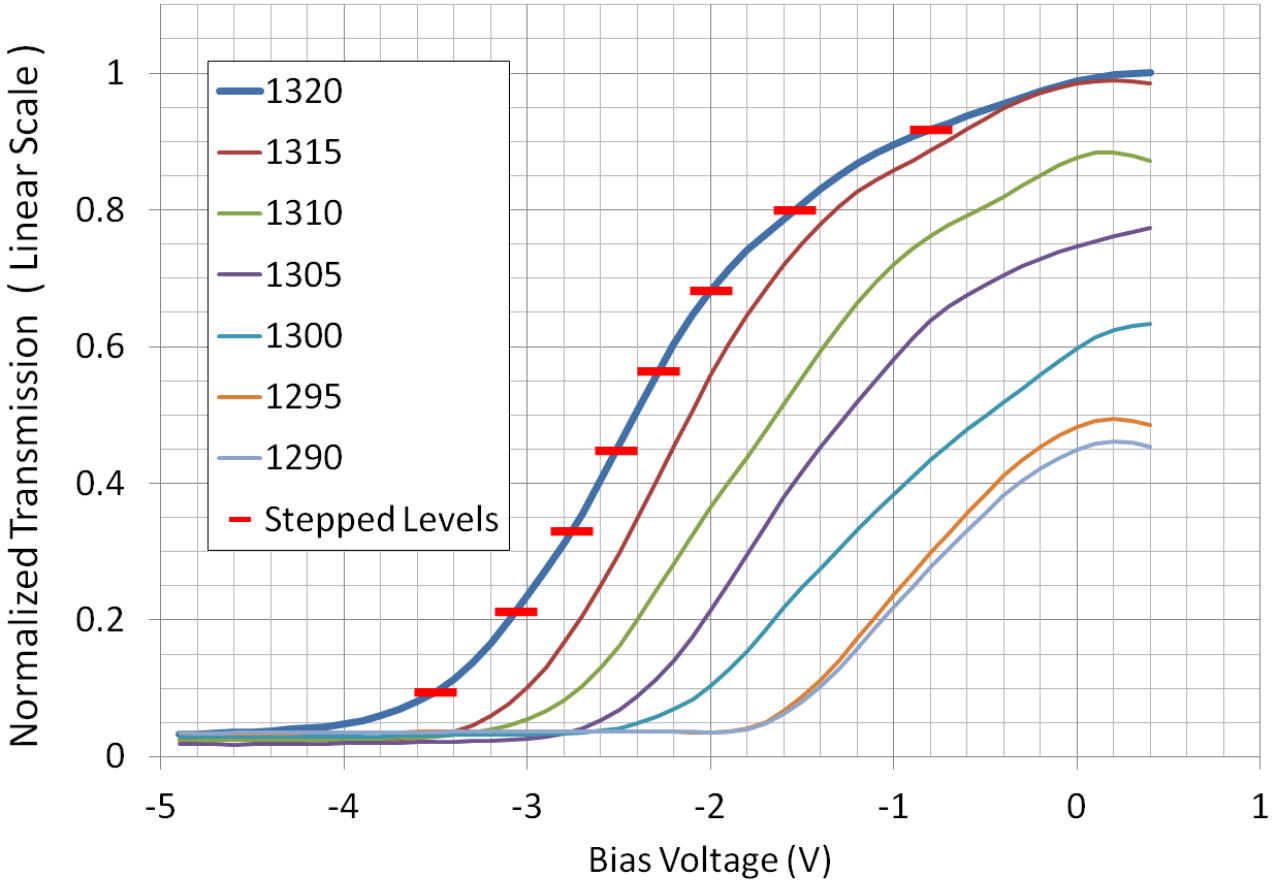
Predicted PAM 8 Eye Diagram for an Electro-Absorption Modulator



- Example PAM 8 eye diagram with nonlinear EA response using linear drive levels

PAM 8 : Linearization of EAM – Measured Results

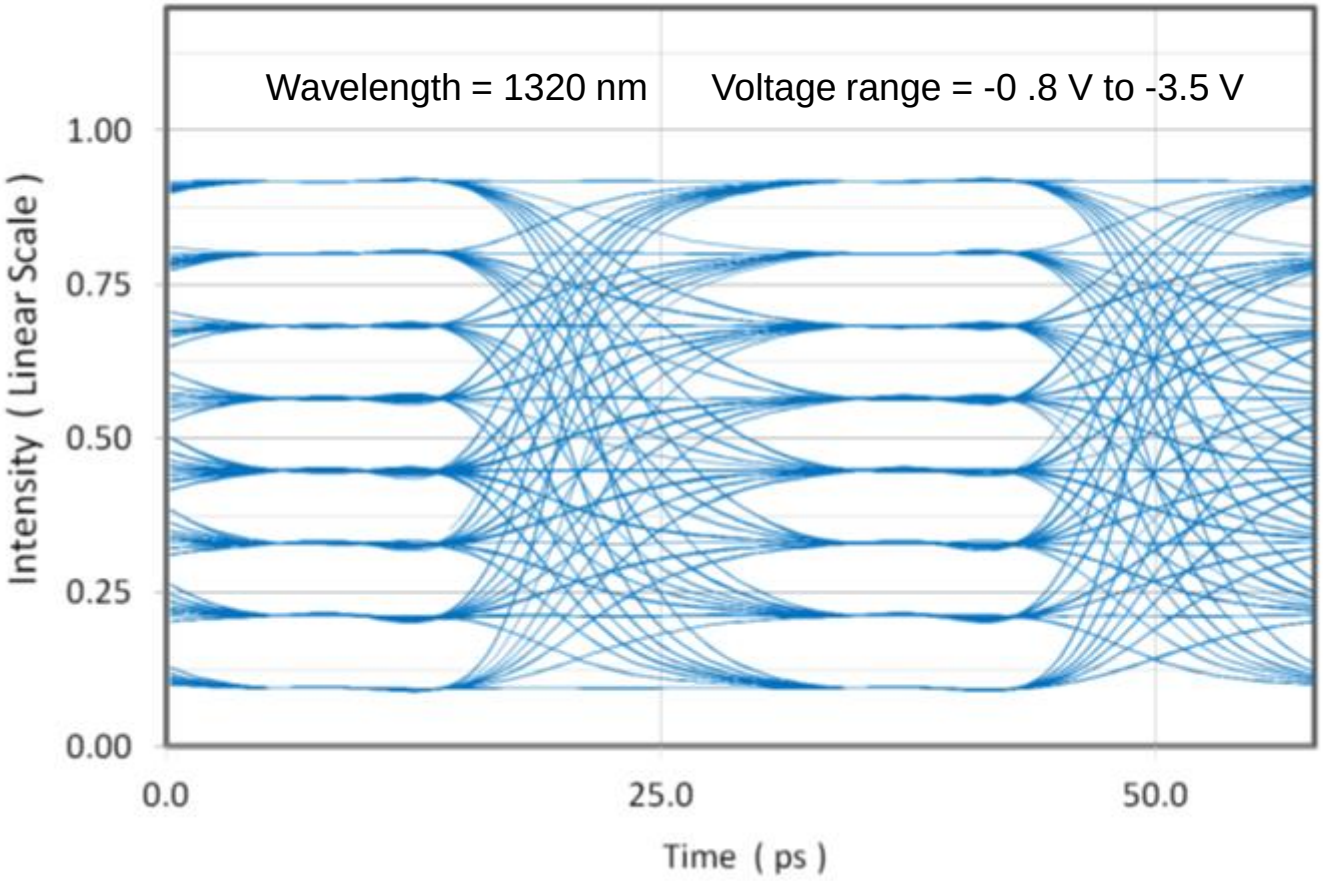
Normalized Transmission of a 125 µm long Electro-Absorption Modulator



- DAC on the transmit side enables the voltage drive levels to be tuned to compensate for the EAM transfer function and yield equally spaced output levels

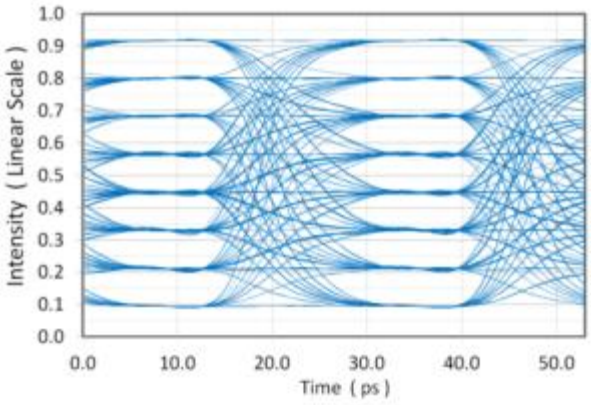
PAM 8 Optical Eye at 37.375 Gbaud [112.125 Gbit/s]

Predicted PAM 8 Eye Diagram for an Electro-Absorption Modulator

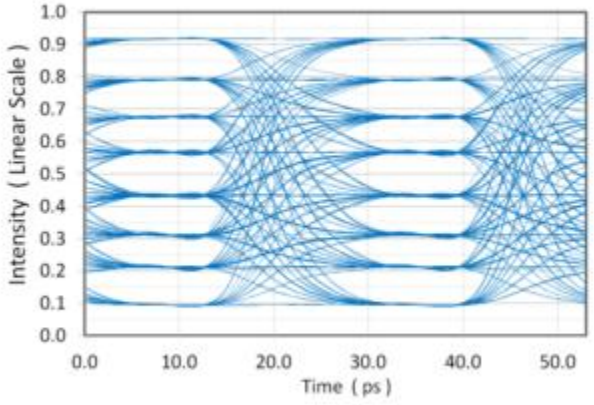


- Simulated eye diagram using an 8 bit DAC with a measured DC transfer function from our 25G EML

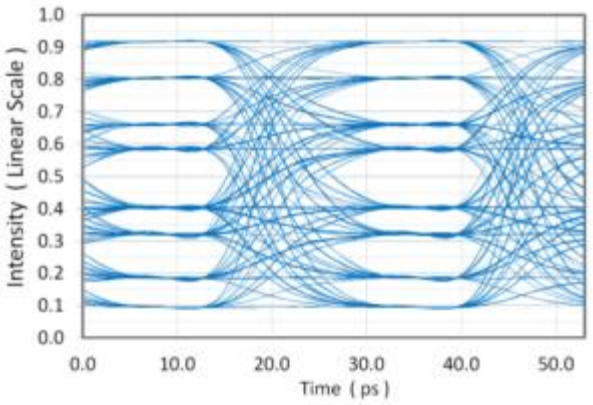
PAM N Optical Eyes : DAC Resolution - Theory



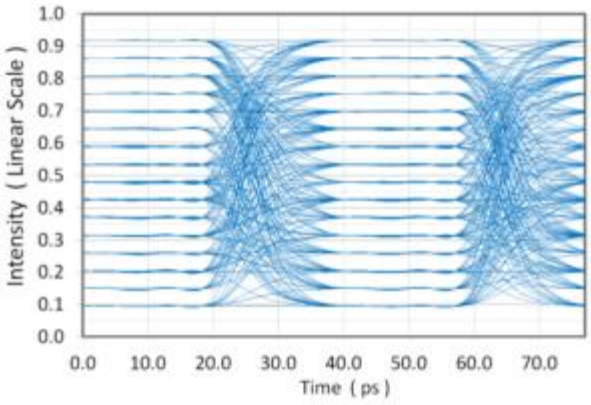
PAM 8 8 bit DAC



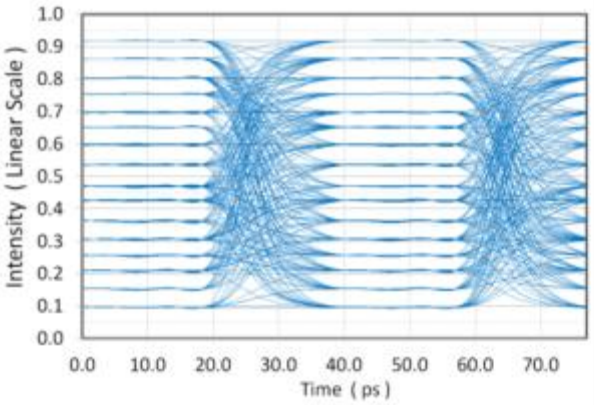
5 bit DAC



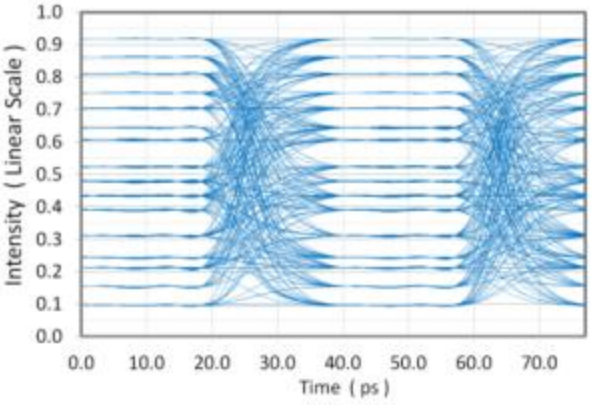
4 bit DAC



PAM 16 9 bit DAC

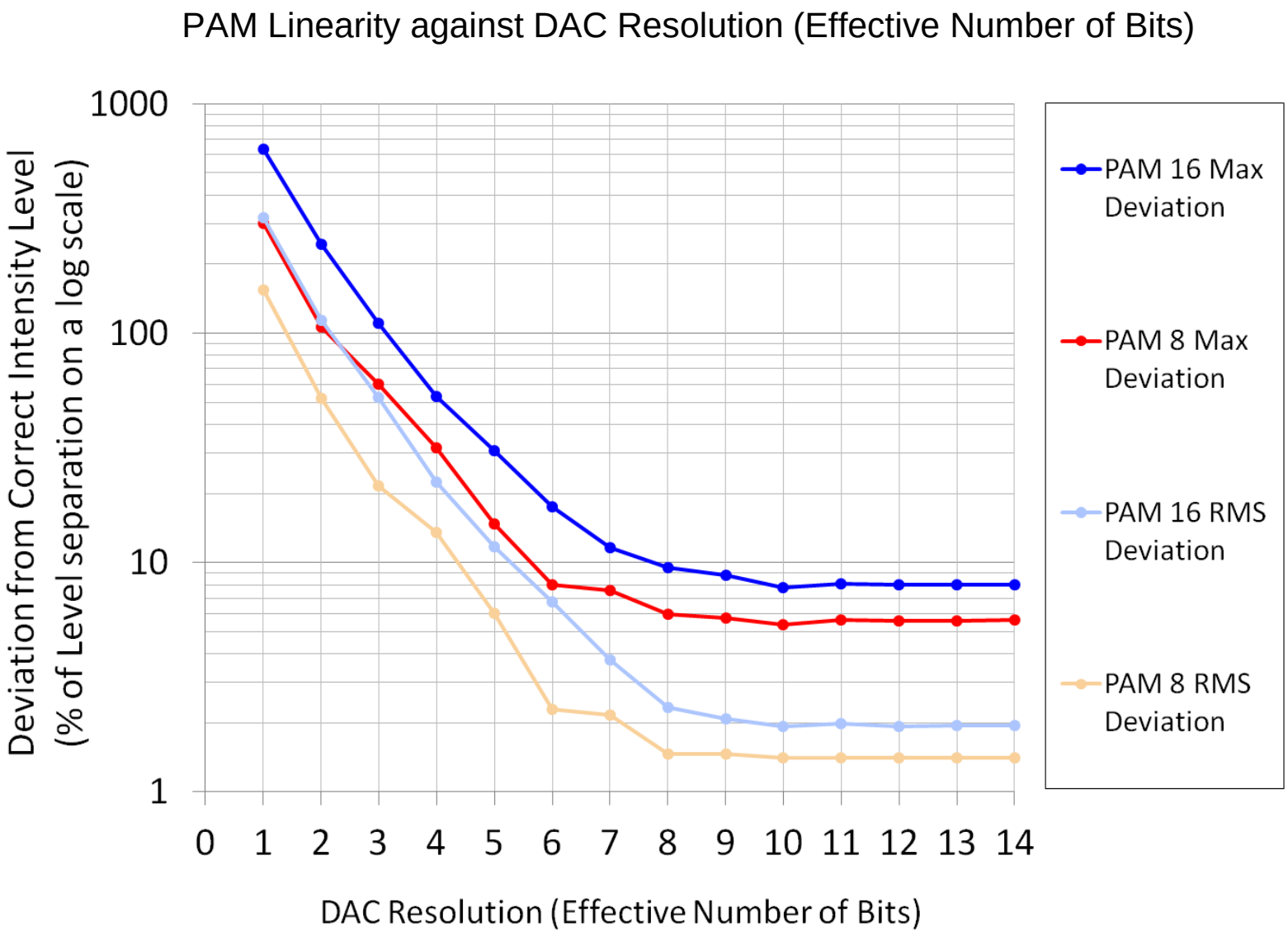


6 bit DAC



5 bit DAC

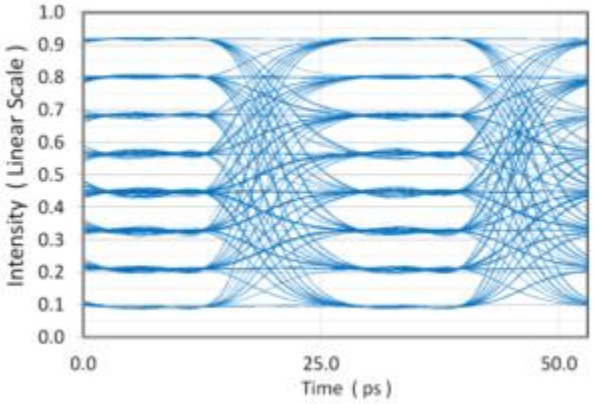
PAM N Optical Eyes : DAC Resolution - Theory



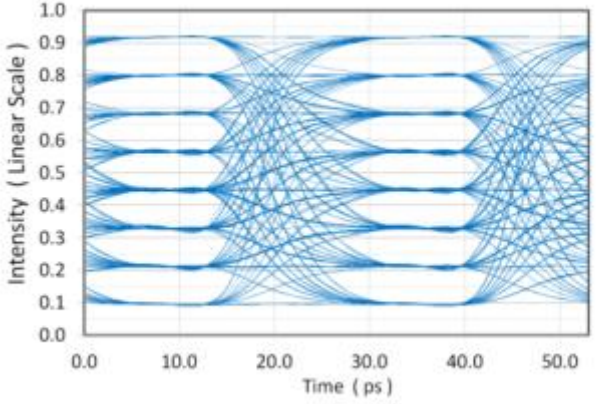
Summary of Linearization Slides

- A non-linear EAM can be driven with a DAC to generate the equally spaced intensity levels required for PAM N
- The SNR is reduced for multilevel PAM N coding because the eye height is reduced by the factor N-1 compared to on-off keying (OOK)
- To guarantee > 80% eye opening the resolution of the DAC must be at least 4 bits higher than the number of bits represented by the PAM N code
  - 7 bits for PAM 8 and 8 bits for PAM 16
- There is a trade-off between linearity and extinction ratio so that the practical extinction ratio will depend on the resolution of the DAC

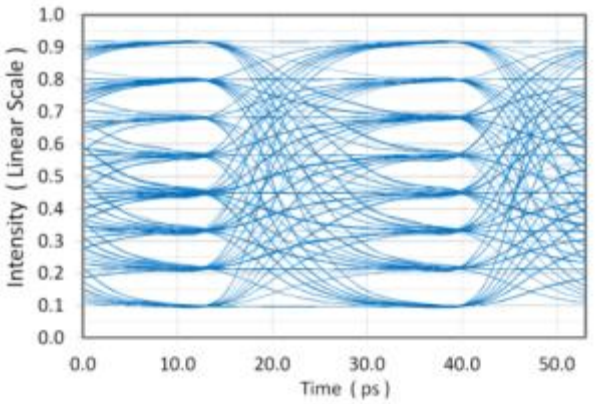
PAM 8 Optical Eyes : Frequency Response - Theory



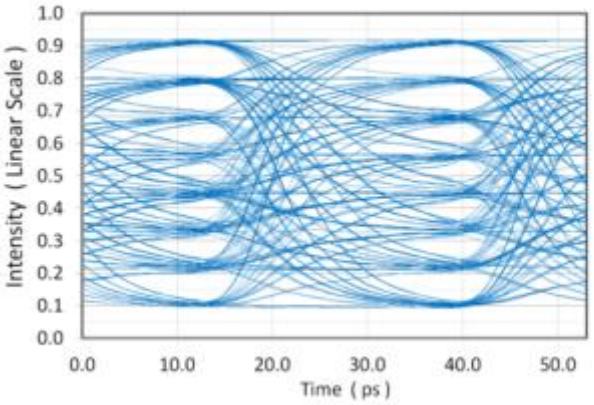
37 GHz 3dB



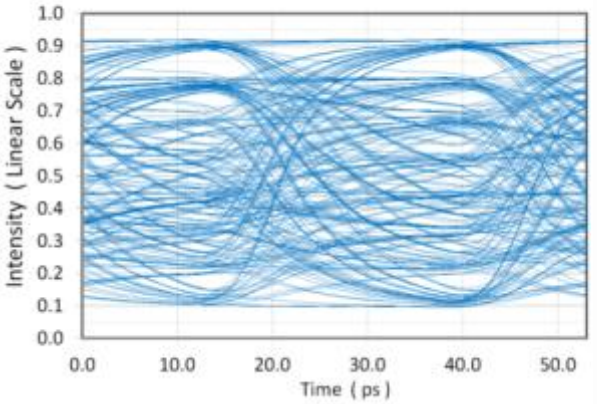
32 GHz 3dB



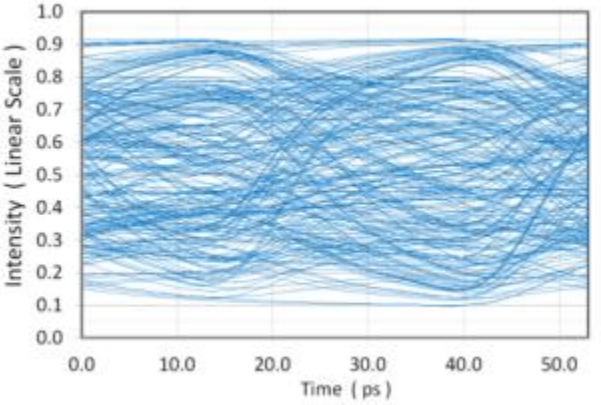
25 GHz 3dB



20 GHz 3dB

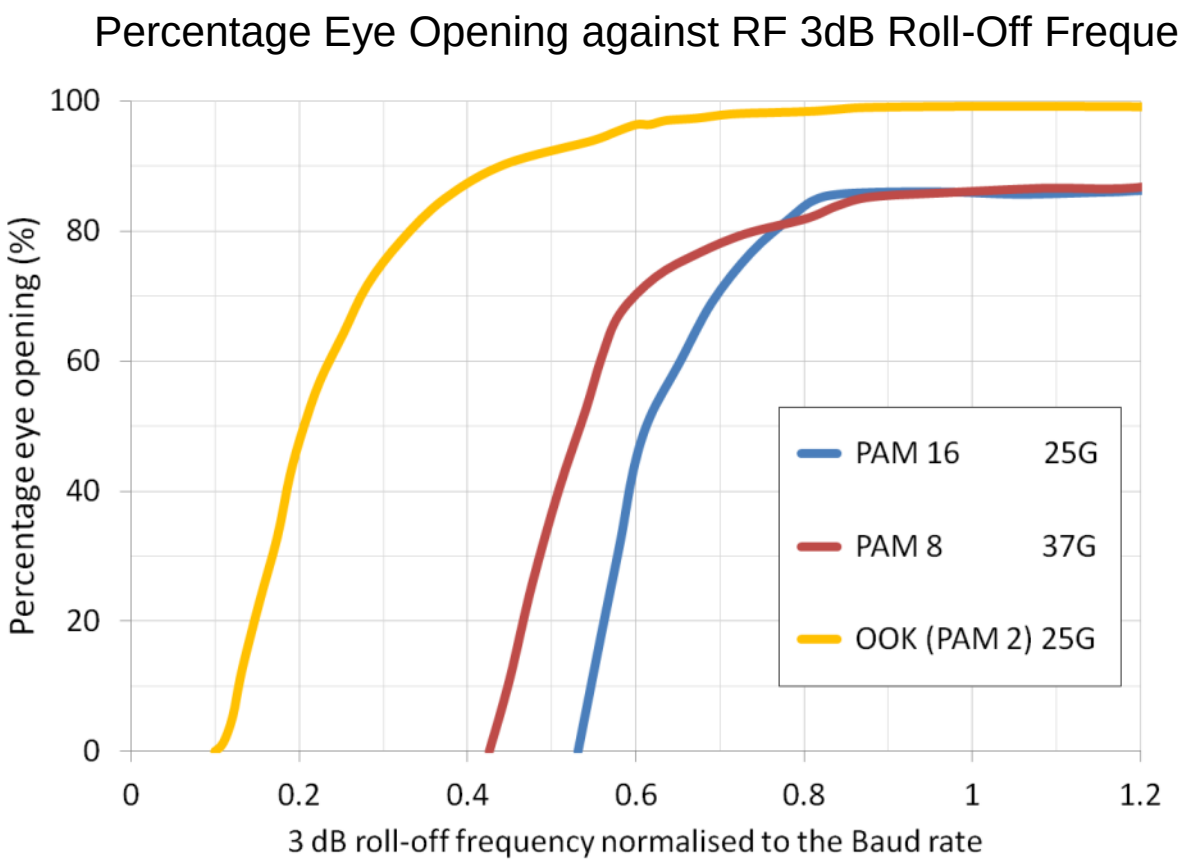


15 GHz 3dB



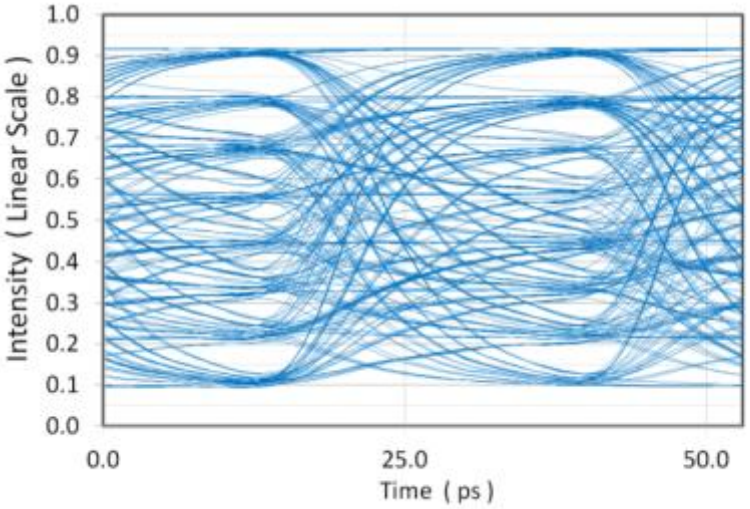
10 GHz 3dB

PAM N : Eye Opening Comparison Calculations

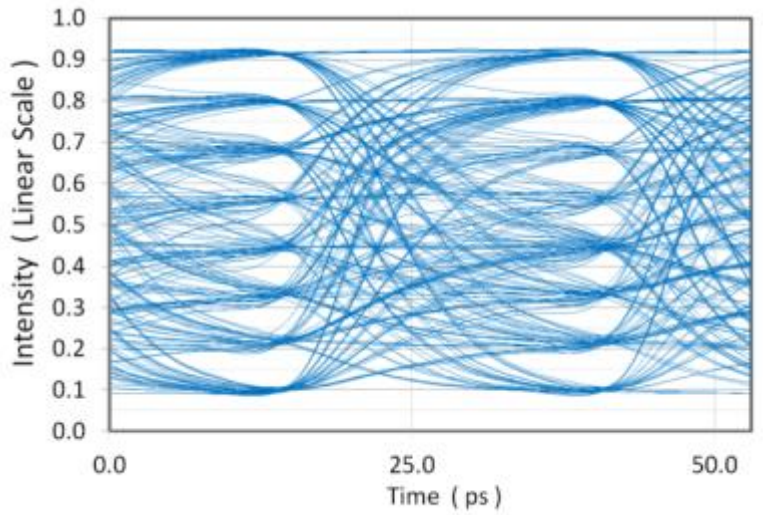


- Normalized BW requirements increase for higher order PAM encoding
- PAM 16 requires ~0.8 times the baud rate or 20GHz of bandwidth compared to ~0.6 times the baud rate for OOK data
- PAM 8 is in between and needs ~0.7 times the baud rate for or ~24GHz of bandwidth

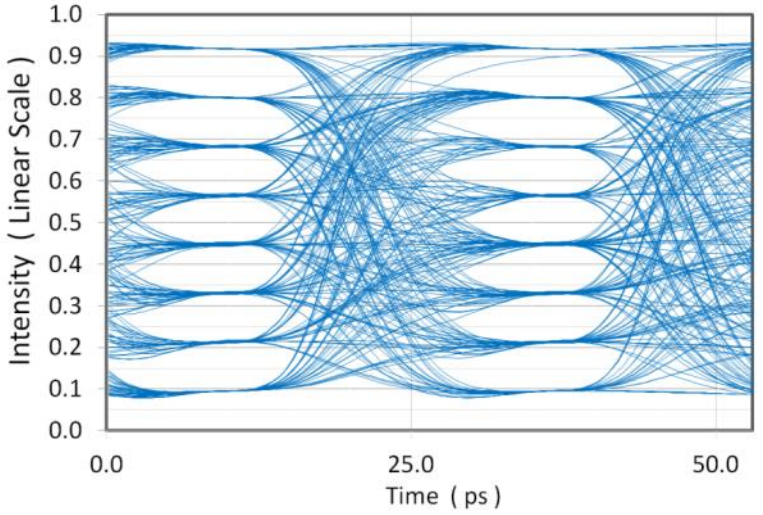
PAM 8 : Pre-Emphasis with 1x and 2x Oversampling



PAM 8 Original Eye (18 GHz 3 dB)

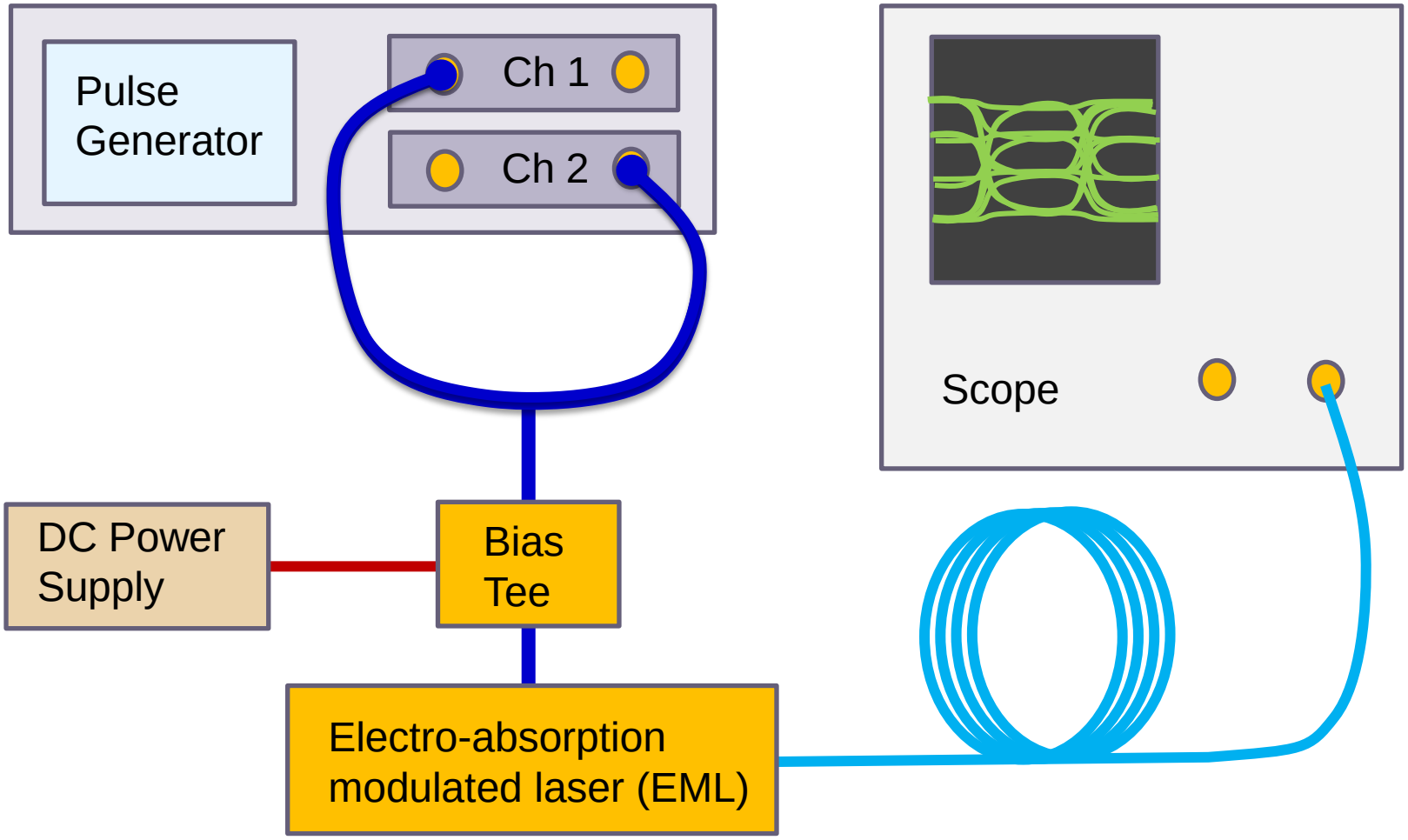


Pre-Emphasis with 1x Oversampling

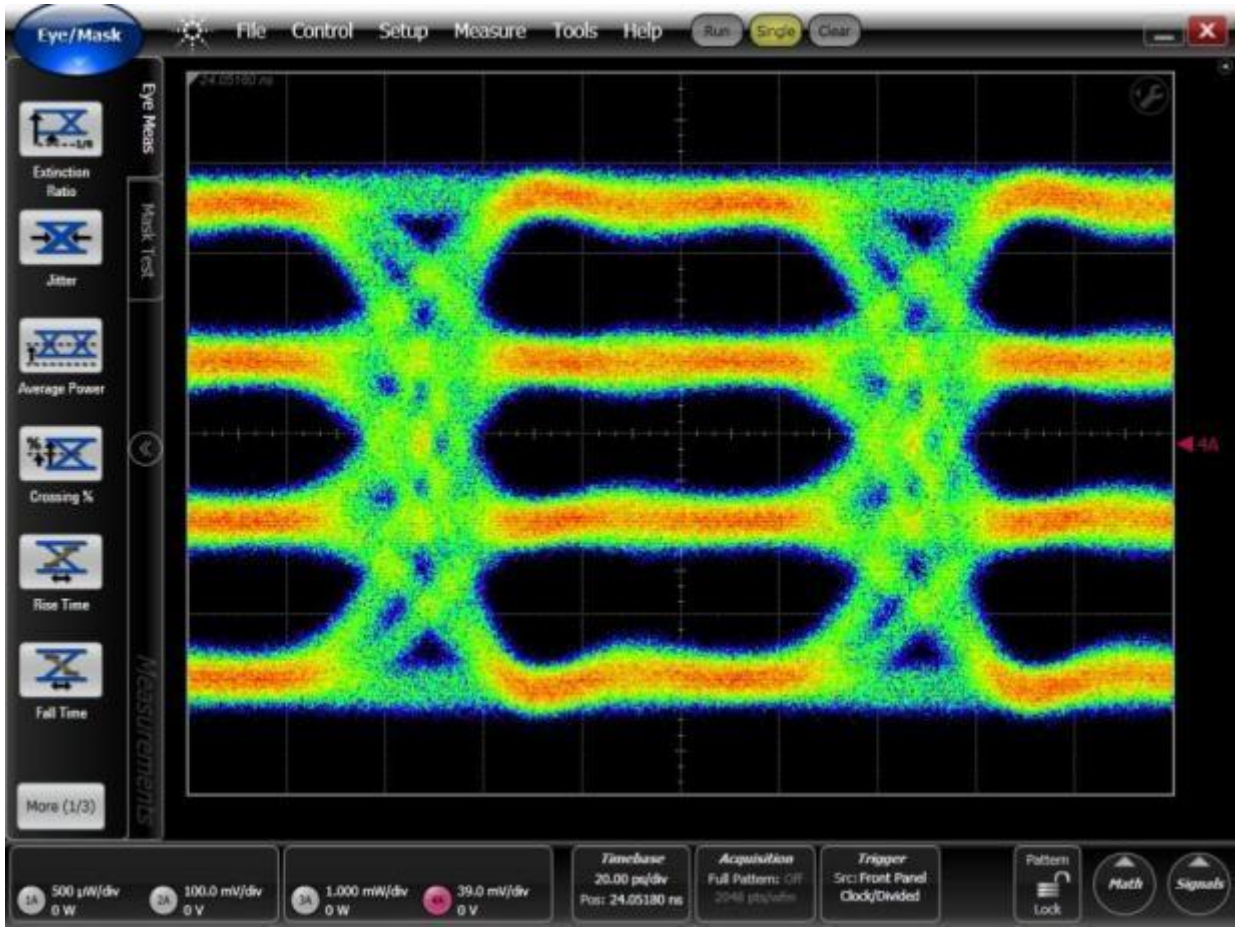


Pre-Emphasis with 2x Oversampling

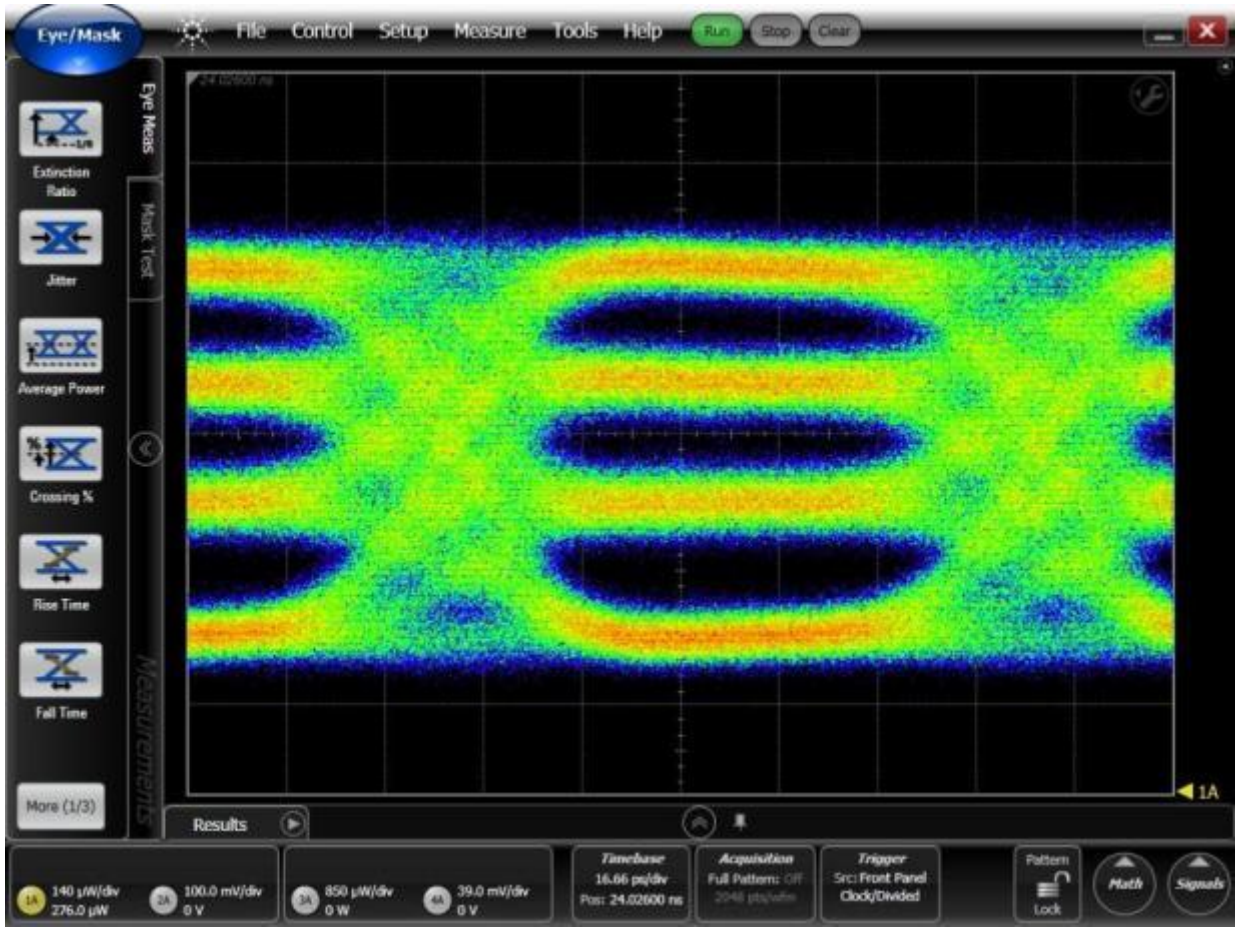
10G PAM 4 Test Setup



10G PAM 4 Electrical Eye



10G PAM 4 Optical Eye - EML



Summary

- For 100 Gbit/s operation PAM 16 has the best eye opening (86%) with the lowest 3 dB roll-off frequency (22 GHz)
  - This is probably because the EAM parameters were optimized for PAM 16
- 100 Gbit/s OOK (PAM 2) has a better eye opening (97%) but at the expense of a much higher 3 dB roll-off frequency (58 GHz)
- 25 Gbit/s OOK (PAM 2) has the best eye opening (>99%) with a 3 dB roll-off frequency of 26 GHz
- The eye opening reduces as the 3 dB frequency reduces - as expected
- The eye opening also reduces slightly as the 3 dB frequency increases
  - Mainly because of more pronounced ringing effects