TDECQ Compliance Testing of High-Speed PAM4 Transmitters in Synopsys OptoCompiler and OptSim

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Introduction

In data center optics, 4-level Pulse Amplitude Modulation (PAM4) signaling is gradually overtaking Non-Return to Zero (NRZ) signaling. [1-3] Although both signaling schemes use intensity modulation and direct detection, PAM4 encodes two bits into four intensity levels, reducing bandwidth requirements for a given data rate by half. PAM4 is also a choice of modulation format in several IEEE Ethernet [4] and OIF-CEI [5] standards for data rates of 200G and higher.

Transmitter dispersion penalty (TDP) [6] has traditionally been an important measure of performance and compliance for transmitters. For NRZ, TDP is determined by directly measuring the bit error rate (BER) under test conditions, which can be time consuming. For PAM4, however, transmitter dispersion eye closure penalty quaternary (TDECQ) has become a commonly accepted measure of PAM4 transmitter quality. TDECQ symbol error rate is measured indirectly and is relatively fast compared to TDP [7]. The TDECQ test procedure is described in Ref [8].

In this paper, we describe TDECQ compliance testing of high-speed PAM4 transmitters in Synopsys OptoCompiler [10] and OptSim [11]. We have included a case study with an O-band interconnect using a multimode fiber with parabolic refractive index profile and a directly driven, high-speed vertical-cavity surface-emitting laser (VCSEL) based transmitter.

TDECQ

For a multilane setup, each lane is tested individually with other lanes active. The specified test pattern is transmitted in the optical lane under test, and the oscilloscope is set up to capture the eye diagram. The TDECQ derivation involves transmitter eye measurements as shown in Figure 1 and is described in detail in references [8-9].

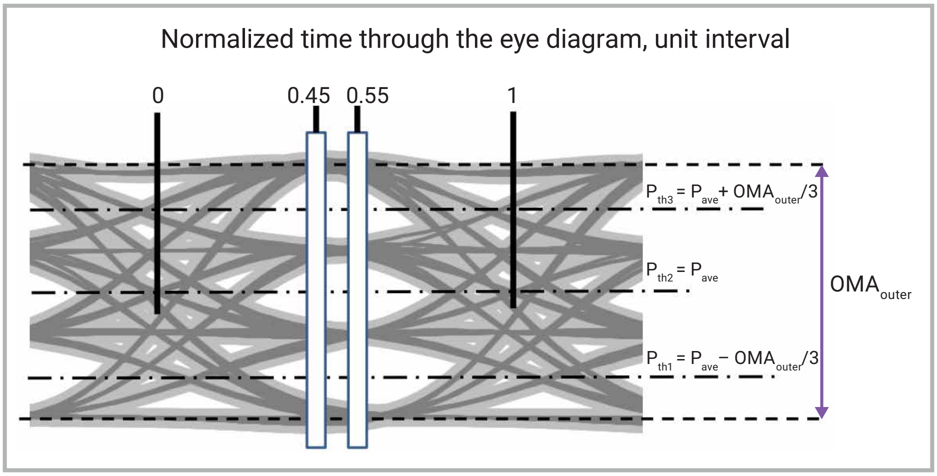


Figure 1: Illustration of transmitter eye measurements for calculating TDECQ [9]

For the specified value of symbol error rate (SER), the TDECQ algorithm seeks to determine the maximum amount of noise that can be added to the input signal while still meeting the target symbol error rate, and then compare this to the amount of noise that can be added if the signal were ideal. The TDECQ formula is:

$$\mathrm{TDECQ} = 10 \cdot \log_{10}\left(\frac{\sigma_{ideal}}{\sqrt{\sigma_g^2 + \sigma_s^2}}\right)$$

where σ_{ideal} is the amount of noise that can be added to an ideal signal, σ_g is the amount of noise that can be added to the actual TDECQ input signal, and σ_s is the amount of noise in the input signal. Furthermore, σ_{ideal} can be calculated as [7-8]:

$$\sigma_{ideal} = \frac{OMA_{outer}}{6 \cdot Q_t}$$

where OMA_{outer} is the outer optical modulation amplitude as specified in [8], and Q_t is related to the target symbol error rate as described in [7] and is equal to approximately 3.414 for the default target SER of 0.00048.

The TDECQ measurement block in OptSim provides the facility to measure and report values for not just TDECQ, but also optimized decision shift, reference-equalizer noise enhancement C_{eq} as described in [8], OMA_{outer}, σ_g, σ_{ideal}, σ_s, and Q_t. The results may be displayed in a detailed table containing full statistical information, or in plots showing the dependence of the properties on scanned parameters.

Case Study: Impact of Modal Dispersion in High-Speed PAM4 Data Links

Because of its lower system cost and less stringent tolerance requirements, multimode fiber (MMF) is often preferred for short-distance interconnects over singlemode fiber. However, an MMF supports multiple spatial modes, each traveling with different group velocity resulting in modal dispersion. The modal dispersion manifests itself as inter-symbol interference (ISI) at the direct-detection receiver and adversely affects the bandwidth x distance product, a figure of merit for MMF-based systems.

Simulation Schematic

In this case study, we consider an O-band interconnect using a multimode fiber with a parabolic refractive index profile and a directly driven, high-speed vertical-cavity surface-emitting laser (VCSEL) transmitter. The OptoCompiler schematic is shown in Figure 2.

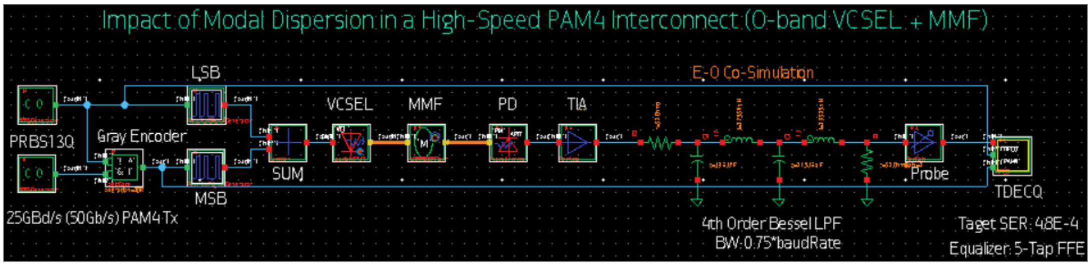


Figure 2: Schematic of a high-speed PAM4 transmitter and MMF-based interconnect in OptoCompiler

Since OptSim has its own graphical user interface (GUI), the schematic can also be created directly in OptSim.

A Gray-encoded, 25GBd PAM4 signal generated from a pseudo-random binary sequence of degree 13 quaternary (PRBS13Q) [12] directly drives an O-band VCSEL. The modulated signal propagates through an MMF whose length is varied during simulation. A photodetector converts received optical signal into a current waveform that includes detection noise. The waveform then passes to a transimpedance amplifier that convers a current signal into voltage (with gain and additional receiver noise). Since Synopsys OptoCompiler and PrimeWave are ideally suited for native domain E-O cosimulation, we implemented a 4th-order Bessel filter in electrical domain using analogLib components. The filter extracts the signal and limits the amount of noise in the filtered signal entering the TDECQ block that has target SER set to 4.8E-4, and the number of feed-forward equalizer (FFE) taps set to 5.

VCSEL Transmitter Waveforms

The center wavelength of the VCSEL is 1310nm and emits light in the Laguerre-Gaussian (0,0) mode with a beam radius of 1μm in X-and Y-polarizations. The average power launched into the fiber is -1.2dBm. Figure 3 summarizes the transmitter characteristics.

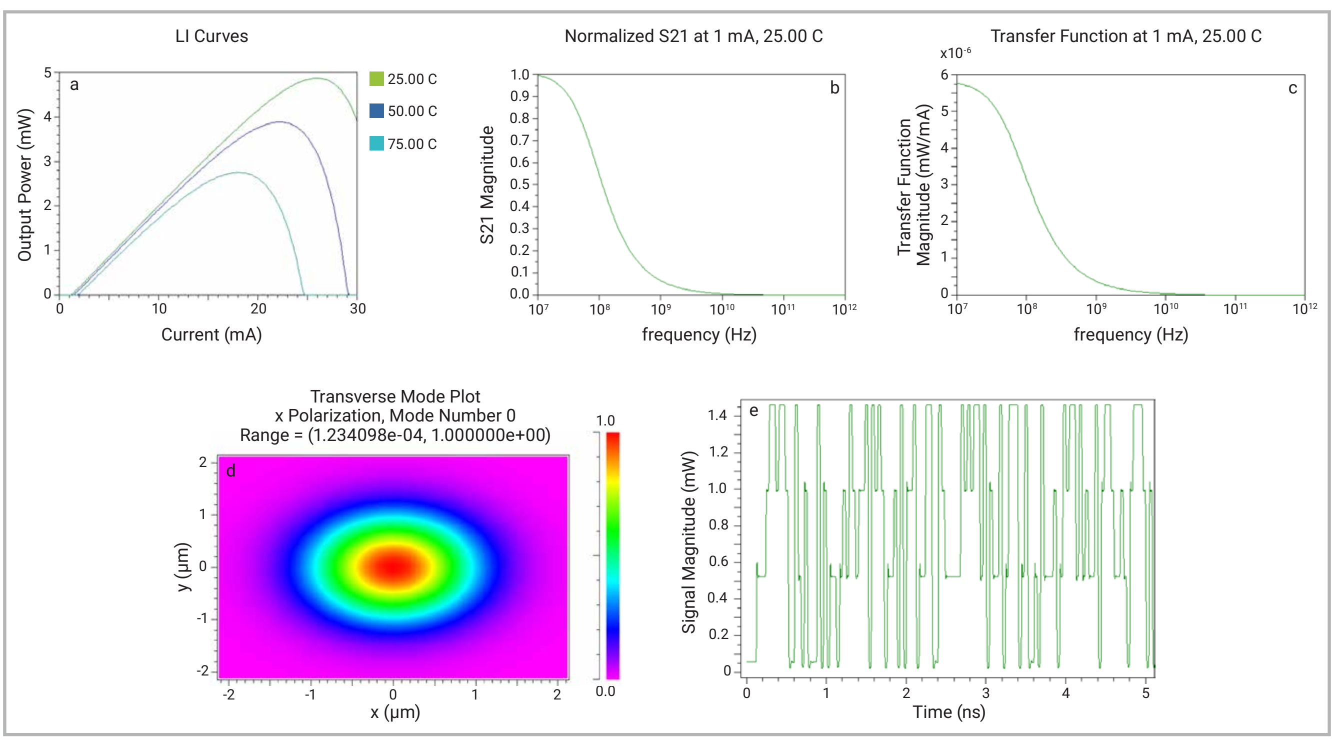


Figure 3: Properties of VCSEL (a) power vs. current (L-I) curve (b) small-signal transfer function at 25ºC (c) small-signal frequency response at 25ºC (d) transverse mode profile and (e) PAM4 modulated waveform

Multimode Fiber

The MMF has parabolic refractive index profile. At 1310 nm, there are 66 fiber modes. Figure 4 summarizes the MMF properties.

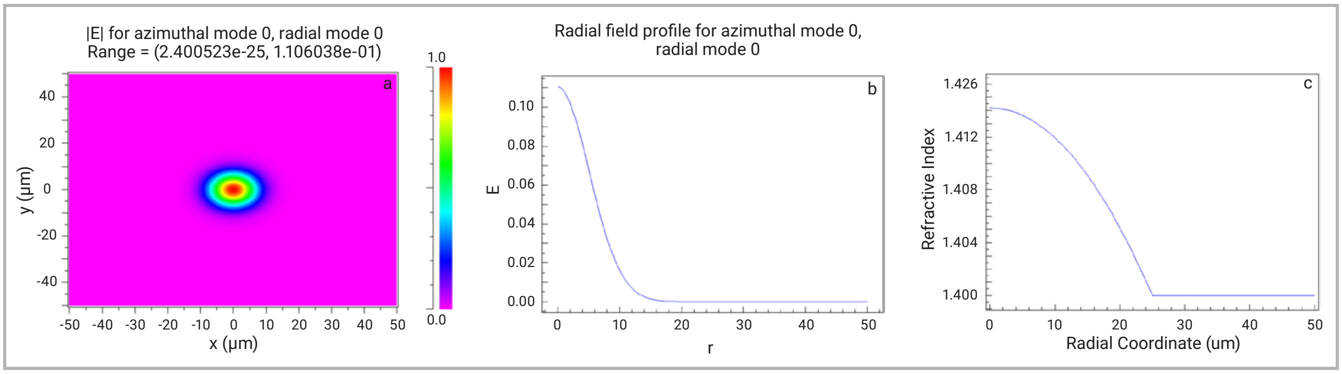


Figure 4: Properties of MMF at 1310nm (a) fiber mode plot (b) radial field plot (c) refractive index profile

A parameter scan is set to vary the fiber length from 0 m to 300 m in steps of 20 m. It is possible to obtain detailed transmission properties for every mode after the simulation. For example, the model produces tabulated data for coupling coefficients for all modes and degenerate mode groups (DMG). It also produces plots of modal delays and delay vs. DMG for each value of the parameter scan, thereby giving a detailed insight into the guided modes of the MMF.

Simulation Setup

The Synopsys OptoCompiler PrimeWave environment is used to set up testbench simulations. Since the schematic involves photonics and electronics, Synopsys OptSim and HSPICE were used as photonic and electronic circuit simulators to co-simulate the setup. The baud rate is set to 25GBd, with each symbol sampled in 32 uniform intervals; 8,192 symbols were transmitted.

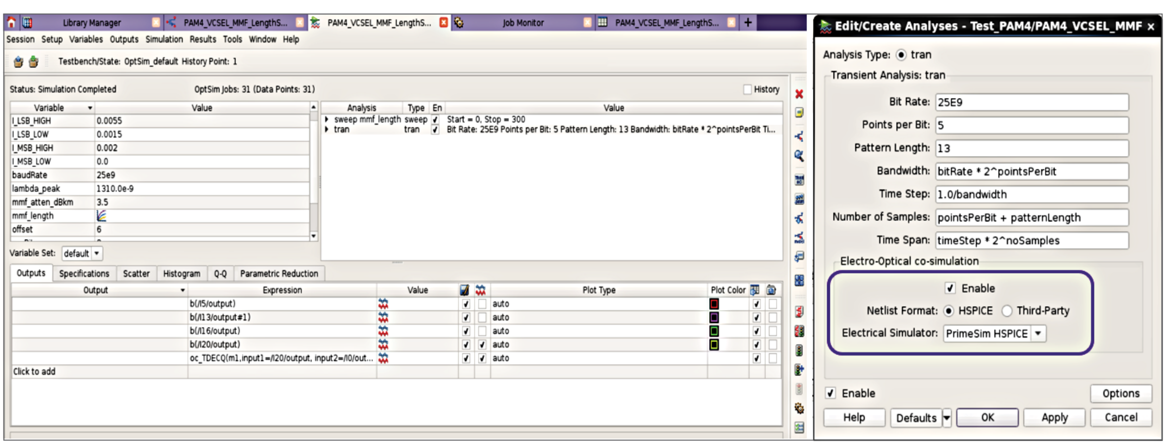


Figure 5: Testbench setup in the Synopsys OptoCompiler PrimeWave design environment

A parameter scan was performed for MMF length to vary from 0m to 300m in steps of 10m. TDECQ and associated plots were obtained after the scan (Figures 6, 8).

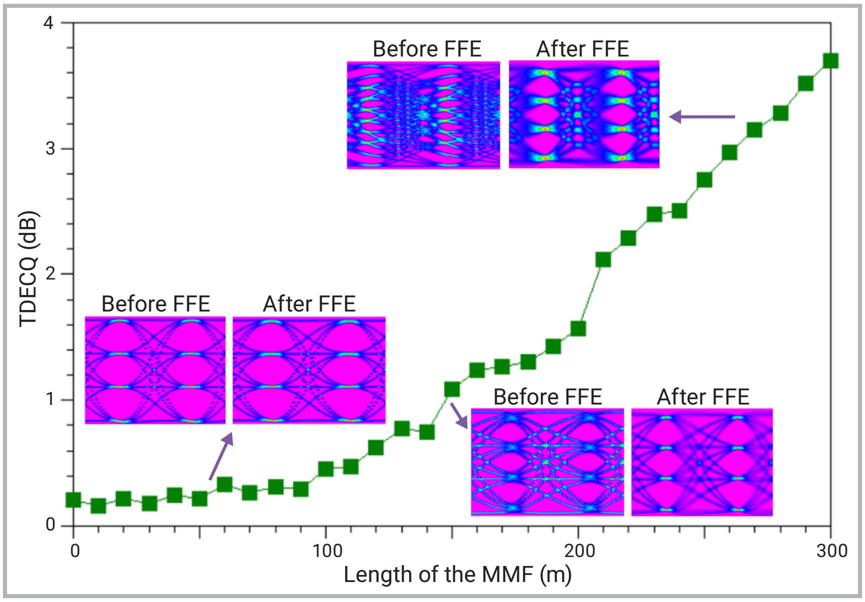


Figure 6: TDECQ as function of MMF length, with pre- and post-FFE eye diagrams

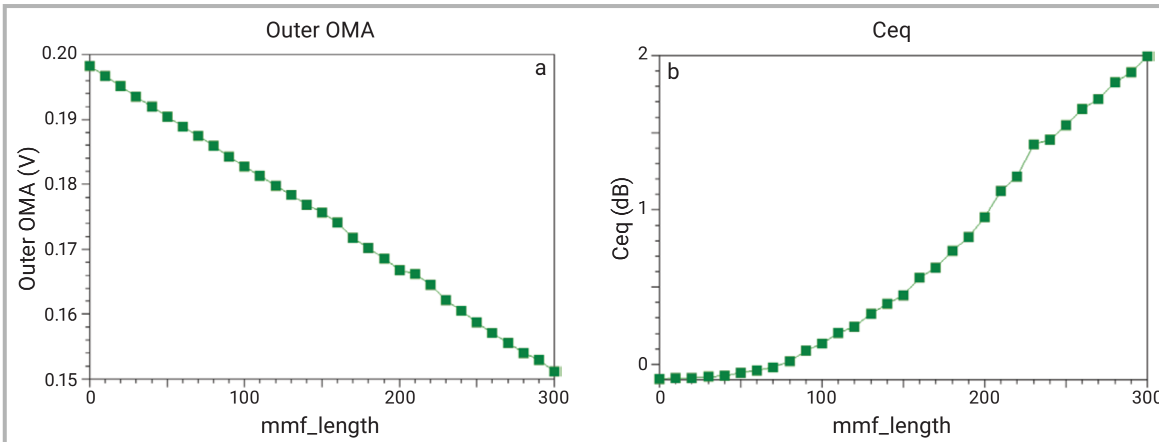
As can be seen in Figure 6, increasing fiber length results in stronger modal dispersion and bigger penalties on performance. The transmitter under test complies with the IEEE-recommended TDECQ of less than 3.2 (50GBASE-FR) for up to 270m transmission distance. The 5-tap FFE equalizer in the TDECQ model does a great job of equalizing transmission impairments as seen from the pre-and post-FFE eye diagrams.

The simulation log file (Figure 7), in addition to the simulation status for each model in the schematic, produces optimized tap coefficients that can be helpful in designing the equalizer and in setting up an experimental measurement testbench.

```
Simulating component 'MMF' of type 'MultimodeFiber'
Simulating component 'PD' of type 'Photodetector'
Simulating component 'TIA' of type 'ElecAmp'
Simulating component 'RxEye1' of type 'EyeDiagram'
Simulating component 'LPF4' of type 'SpiceInterface'
Simulating component 'TDECQ' of type 'TDECQ'

Average lowest level calculated from run of 6 symbols.
Average highest level calculated from run of 5 symbols.

Optimized FFE taps:
{0.00386046, -0.000741368, 0.990143, 0.00749547, -0.000757253}

Simulating component 'RxSig' of type 'SignalAnalyzer'
Simulating component 'RxEye' of type 'EyeDiagram'
Starting New Iteration: Current Status: (In) =  (2/16)
Simulating component 'MMF' of type 'MultimodeFiber'
Simulating component 'PD' of type 'Photodetector'
Simulating component 'TIA' of type 'ElecAmp'
Simulating component 'RxEye1' of type 'EyeDiagram'
Simulating component 'LPF4' of type 'SpiceInterface'
Simulating component 'TDECQ' of type 'TDECQ'

Average lowest level calculated from run of 6 symbols.
Average highest level calculated from run of 5 symbols.

Optimized FFE taps:
{0.00370451, -0.00059838, 0.990684, 0.00670541, -0.000495157}

Simulating component 'RxSig' of type 'SignalAnalyzer'
Simulating component 'RxEye' of type 'EyeDiagram'
Starting New Iteration: Current Status: (In) =  (3/16)
Simulating component 'MMF' of type 'MultimodeFiber'
Simulating component 'PD' of type 'Photodetector'
Simulating component 'TIA' of type 'ElecAmp'
Simulating component 'RxEye1' of type 'EyeDiagram'
Simulating component 'LPF4' of type 'SpiceInterface'
```

Figure 7: Simulation log including FFE tap weights

As mentioned previously, the TDECQ block in Synopsys OptSim produces plots of a number of quantities of interest, in addition to the TDECQ, to help with a detailed assessment of the transmitter compliance and equalizer performance.



c

mmf length	RUN#	TDECQ(dB)	decision shift	Ceq(dB)	OMA outer(V)	sigma g(V)	sigma ideal(V)	sigma s(V)	Qt
0.0000e+00	1	2.0466e-01	8.0000e-03	-9.7405e-02	1.9828e-01	9.1744e-03	9.6796e-03	1.0483e-03	3.4141e+00
1.0000e+01	1	1.6439e-01	8.0000e-03	-9.0699e-02	1.9669e-01	9.1859e-03	9.6017e-03	1.0445e-03	3.4141e+00
2.0000e+01	1	2.1437e-01	8.0000e-03	-9.2202e-02	1.9511e-01	9.0062e-03	9.5249e-03	1.0408e-03	3.4141e+00
3.0000e+01	1	1.8102e-01	8.0000e-03	-7.8972e-02	1.9355e-01	9.0032e-03	9.4484e-03	1.0369e-03	3.4141e+00
4.0000e+01	1	2.4445e-01	8.0000e-03	-7.4475e-02	1.9200e-01	8.7994e-03	9.3729e-03	1.0332e-03	3.4141e+00
5.0000e+01	1	2.1910e-01	8.0000e-03	-5.6915e-02	1.9046e-01	8.7801e-03	9.2977e-03	1.0294e-03	3.4141e+00
6.0000e+01	1	3.3330e-01	8.0000e-03	-3.8538e-02	1.8894e-01	8.4804e-03	9.2235e-03	1.0254e-03	3.4141e+00
7.0000e+01	1	2.6489e-01	8.0000e-03	-1.9319e-02	1.8743e-01	8.5475e-03	9.1497e-03	1.0216e-03	3.4141e+00
8.0000e+01	1	3.0995e-01	8.0000e-03	1.8777e-02	1.8593e-01	8.3901e-03	9.0768e-03	1.0175e-03	3.4141e+00
9.0000e+01	1	2.9693e-01	8.0000e-03	8.7063e-02	1.8425e-01	8.3387e-03	8.9946e-03	1.0137e-03	3.4141e+00
1.0000e+02	1	4.5506e-01	8.0000e-03	1.3231e-01	1.8275e-01	7.9704e-03	8.9217e-03	1.0097e-03	3.4141e+00
1.1000e+02	1	4.7356e-01	8.0000e-03	2.0434e-01	1.8129e-01	7.8718e-03	8.8500e-03	1.0057e-03	3.4141e+00
1.2000e+02	1	6.2263e-01	8.0000e-03	2.4017e-01	1.7982e-01	7.5396e-03	8.7784e-03	1.0021e-03	3.4141e+00
1.3000e+02	1	7.7539e-01	8.0000e-03	3.2689e-01	1.7835e-01	7.2142e-03	8.7065e-03	9.9813e-04	3.4141e+00
1.4000e+02	1	7.4509e-01	8.0000e-03	3.9232e-01	1.7688e-01	7.2051e-03	8.6347e-03	9.9445e-04	3.4141e+00
1.5000e+02	1	1.0844e+00	8.0000e-03	4.4587e-01	1.7563e-01	6.6057e-03	8.5740e-03	9.9082e-04	3.4141e+00
1.6000e+02	1	1.2395e+00	8.0000e-03	5.6035e-01	1.7411e-01	6.3123e-03	8.4994e-03	9.8703e-04	3.4141e+00
1.7000e+02	1	1.2663e+00	8.0000e-03	6.2321e-01	1.7170e-01	6.1842e-03	8.3818e-03	9.8347e-04	3.4141e+00
1.8000e+02	1	1.3043e+00	8.0000e-03	7.3162e-01	1.7016e-01	6.0733e-03	8.3069e-03	9.7987e-04	3.4141e+00
1.9000e+02	1	1.4317e+00	8.0000e-03	8.2168e-01	1.6854e-01	5.8361e-03	8.2279e-03	9.7641e-04	3.4141e+00
2.0000e+02	1	1.5682e+00	8.0000e-03	9.5221e-01	1.6676e-01	5.5894e-03	8.1407e-03	9.7278e-04	3.4141e+00
2.1000e+02	1	2.1158e+00	8.0000e-03	1.1216e+00	1.6621e-01	4.8897e-03	8.1140e-03	9.6937e-04	3.4141e+00
2.2000e+02	1	2.2846e+00	8.0000e-03	1.2152e+00	1.6455e-01	4.6476e-03	8.0329e-03	9.6606e-04	3.4141e+00
2.3000e+02	1	2.4805e+00	8.0000e-03	1.4247e+00	1.6214e-01	4.3664e-03	7.9155e-03	9.6245e-04	3.4141e+00
2.4000e+02	1	2.5029e+00	8.0000e-03	1.4524e+00	1.6057e-01	4.2993e-03	7.8386e-03	9.5937e-04	3.4141e+00
2.5000e+02	1	2.7515e+00	8.0000e-03	1.5490e+00	1.5877e-01	4.0008e-03	7.7510e-03	9.5622e-04	3.4141e+00
2.6000e+02	1	2.9684e+00	8.0000e-03	1.6512e+00	1.5704e-01	3.7512e-03	7.6664e-03	9.5298e-04	3.4141e+00
2.7000e+02	1	3.1509e+00	8.0000e-03	1.7190e+00	1.5556e-01	3.5512e-03	7.5941e-03	9.5004e-04	3.4141e+00
2.8000e+02	1	3.2843e+00	8.0000e-03	1.8238e+00	1.5397e-01	3.3989e-03	7.5163e-03	9.4692e-04	3.4141e+00
2.9000e+02	1	3.5179e+00	8.0000e-03	1.8884e+00	1.5291e-01	3.1837e-03	7.4649e-03	9.4396e-04	3.4141e+00
3.0000e+02	1	3.6997e+00	8.0000e-03	1.9959e+00	1.5119e-01	3.0048e-03	7.3809e-03	9.4105e-04	3.4141e+00

Figure 8: (a) Outer optical modulation amplitude and (b) reference equalizer noise enhancement as function of MMF length, with (c) tabulated details on signal and noise for every parametric scan

The plots in Figure 8 are consistent with the TDECQ plot of Figure 6 and confirm increasing penalties from higher modal dispersion as the length of the MMF is increased.

Summary

TDECQ is a commonly accepted measure of PAM4 transmitter quality. Synopsys OptoCompiler and OptSim provide extensive simulation and compliance testing capabilities for high-speed PAM4 transmitters. OptSim's rich library of circuit and system design components, together with the native signal domain E-O cosimulation capabilities of OptoCompiler, provide a powerful functional verification platform for wide-ranging photonic integrated circuit (PIC) and fiber-optic system applications.

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