FWM Analysis of PAM4 LR/ER PMDs

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Four-wave mixing (FWM) in O-band for LAN-WDM grids

- This analysis uses the same theory previously presented in IEEE 802.3ca contribution Johnson_3ca_1_0716.pdf for 25G-EPON wavelength plans.
- LAN-WDM grid PMDs in O-band longer than 2 km have all of the ingredients for FWM to be a significant potential impairment:
  - Requires co-polarization, which is typical for integrated LAN-WDM transmitters
  - Is highly efficient when channels are on either side of the zero dispersion frequency (ZDF)
  - Is highly probable when channels are equally spaced in frequency
  - Grows rapidly with the higher launch powers needed for ≥10 km reach
- Two important aspects of FWM in O-band will be discussed:
  - Magnitude of FWM impairment under conditions of worst-case alignment and power
  - Probability of occurrence of a significant FWM impairment (“outage probability”)
- In Part 1 of this contribution [1], using established analytical formulas, we look at the potential for FWM impairments in LAN-WDM LR4/ER4 type PMDs in O-band. Part 2 will look at the effects of launch polarization and PMD [2].
- Although 50G and 100G/lane PAM4 systems were analyzed in this contribution, the results are broadly applicable to 200G/lane PAM4 as well.

[1] A version of the material in Part 1 was originally presented to the 100G Lambda MSA in Oct. 2021.

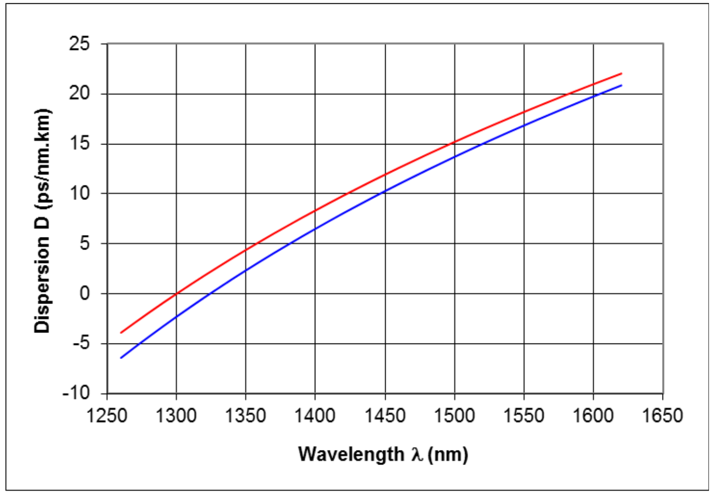
[2] A version of the material in Part 2 was originally presented to the 100G Lambda MSA in Feb. 2022.

Maximum magnitude of FWM

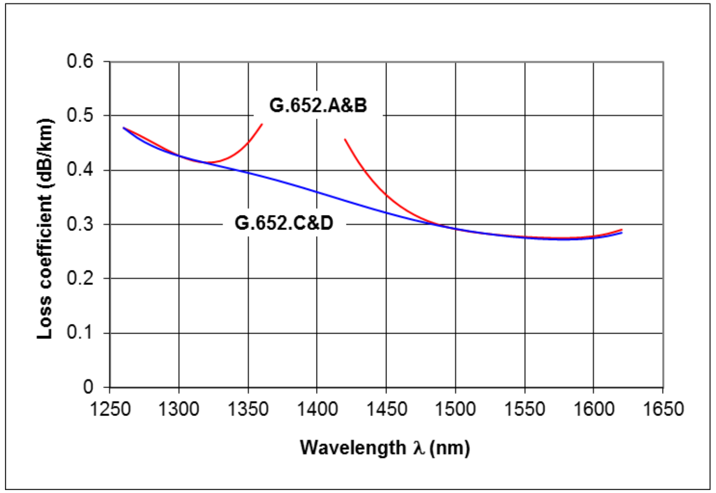
- FWM can only occur under three very specific alignment conditions:
  - Alignment of the laser frequencies such that $f_s = f_{ijk} = f_i + f_j - f_k$ (energy conservation)
    - *s* refers to the "target" signal and the subscripts *i, j* and *k* refer to the three pump frequencies.
    - The simplest form of this is for the lasers to be on a grid with equal frequency spacing.
  - Alignment of the frequencies with the ZDF of the fiber (phase matching) such that the optical propagation constants are related as $\beta_{ijk} = \beta_i + \beta_j - \beta_k = \beta_s$.
    - CWDM PMDs aren't subject to FWM because non-linear dispersion prevents phase matching
  - Alignment of the polarizations of the lasers to each other (co-polarization).
    - Both FWM generation and coherent beating of the FWM tone with the signal require co-polarization.
    - This condition is typical when using WDM TOSAs with integrated multiplexers.
- The maximum magnitude of FWM power is proportional to power and fiber length
  - The generated FWM power, $P_{FWM} \sim P^3$, so a 1dB increase in launch power increases the generated FWM power by 3dB.
  - The FWM power scales as L_{eff}^2, where L_{eff} is the effective (loss limited) fiber length, so a 1km span will have ~20dB less FWM power than a 10km span.
  - These two facts help explain why FWM penalties are not observed in short-reach WDM applications.

Fiber properties

- Fiber parameters
  - Zero dispersion wavelength range = 1300 to 1324nm.
  - Dispersion slope at 1310nm = 0.093 ps/nm^2 km. Dispersion assumed to be linear in wavelength.
  - Max attenuation at 1310nm = 0.42 dB/km, but use more typical loss ~0.3 dB/km.
- Non-linear parameters
  - Non-linear index, n_2 = 2.6x10^{-20} m^2/W
  - Effective area, A_e = 55 um^2
  - Non-linear coeff, $\gamma = \frac{2\pi n_2}{\lambda A_e}$ ~ 2.3x10^{-6} (m mW)$^{-1}$



- Cabling and span length
  - Long fiber spans in a metro environment are normally installed as several shorter cable segments spliced together. ~5km is a typical maximum cable segment length for pulling through underground ducts or aerial installation.
  - Each segment can have a different ZDF, which limits generation of FWM to the first segment. A 40km span may have an effective length for FWM generation of only 5km.
  - This aspect of FWM penalty estimation would benefit greatly from additional input from network operators, cable installers and fiber vendors.



LAN-WDM LR/ER PMDs

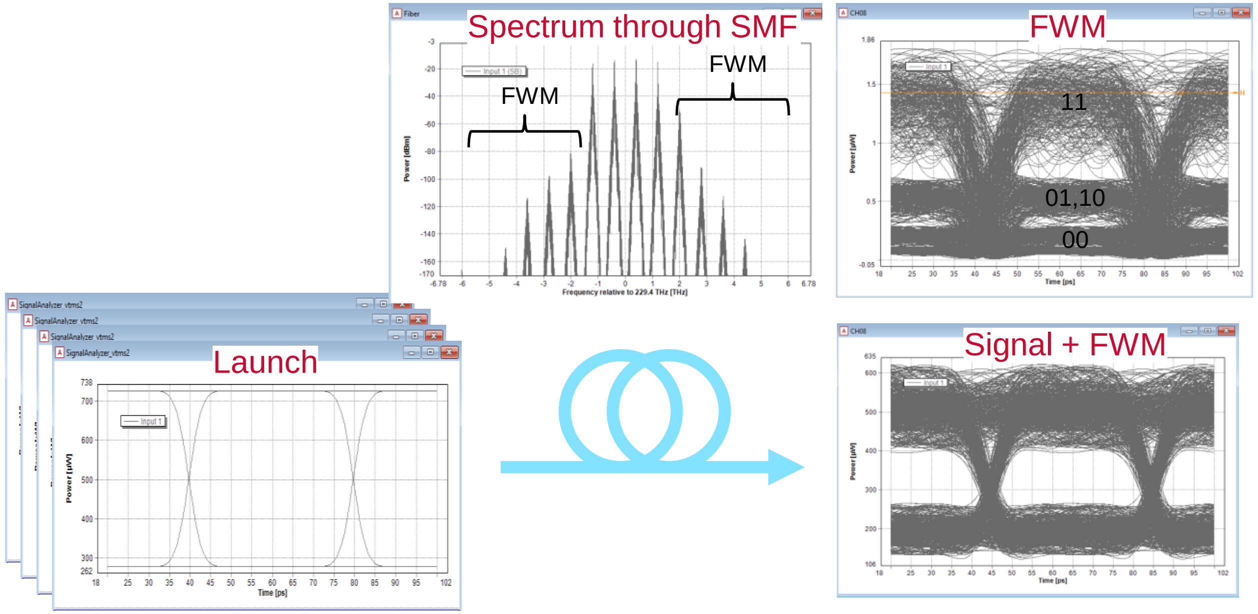
High maximum launch OMA allowed for PAM4 significantly increases the magnitude of FWM-induced penalties

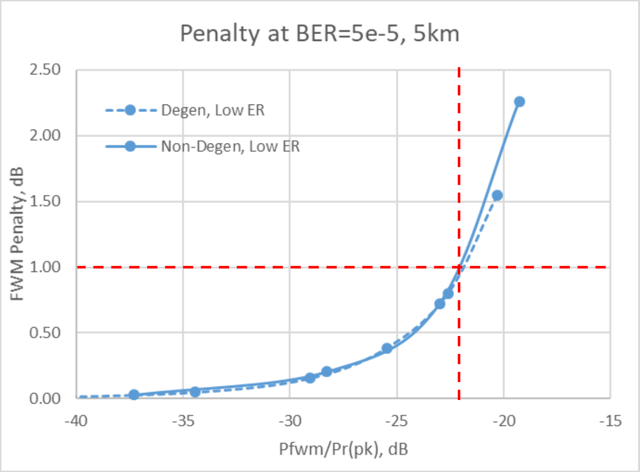
TX Specifications	100GBASE-LR4	100GBASE-ER4	200GBASE-LR4	200GBASE-ER4	400GBASE-LR8	400GBASE-ER8	400G-ER4-30 Straw Man	
Signaling rate, each lane (range)	25.78125 ± 100 ppm	25.78125 ± 100 ppm	26.5625 ± 100 ppm	26.5625 ± 100 ppm	26.5625 ± 100 ppm	26.5625 ± 100 ppm	53.125 ± 100 ppm	
Modulation format	NRZ	NRZ	PAM4	PAM4	PAM4	PAM4	PAM4	Unit
Lane wavelength (range)	1294.53 to 1296.59 1299.02 to 1301.09 1303.54 to 1305.63 1308.09 to 1310.19	1294.53 to 1296.59 1299.02 to 1301.09 1303.54 to 1305.63 1308.09 to 1310.19	1294.53 to 1296.59 1299.02 to 1301.09 1303.54 to 1305.63 1308.09 to 1310.19	1294.53 to 1296.59 1299.02 to 1301.09 1303.54 to 1305.63 1308.09 to 1310.19	1272.55 to 1274.54 1276.89 to 1278.89 1281.25 to 1283.27 1285.65 to 1287.68 1294.53 to 1296.59 1299.02 to 1301.09 1303.54 to 1305.63 1308.09 to 1310.19	1272.55 to 1274.54 1276.89 to 1278.89 1281.25 to 1283.27 1285.65 to 1287.68 1294.53 to 1296.59 1299.02 to 1301.09 1303.54 to 1305.63 1308.09 to 1310.19	1304.06 to 1305.1 1306.33 to 1307.38 1308.61 to 1309.66 1310.9 to 1311.96	nm
Nominal Grid Spacing	800	800	800	800	800	800	400	GHz
Outer Optical Modulation Amplitude (OMAouter), each lane (max)	4.5	4.5	5.1	7.4	5.7	6.4	6.4	dBm
Outer Optical Modulation Amplitude (OMAouter), each lane (min)	-1.3	0.1	-0.4	3.4	0.2	2.4	3	dBm
Difference in launch power between any two lanes (OMAouter) (max)	5	3.6	4	4	4	4	3.6	dBm
Launch power in OMAouter minus TDECQ, each lane (min) for ER ≥ ER0	-2.3	NA	-1.8	2	-1.2	1	1.6	dBm
Transmitter and dispersion eye closure for PAM4 (TDECQ), each lane (max)	2.2	2.5	3.2	3.2	3.1	3.4	3.9	dB
Extinction ratio, each lane (min)	4	8	3.5	6	3.5	6	5	dB

Source: IEEE Std 802.3™ – 2018

Estimating FWM penalty

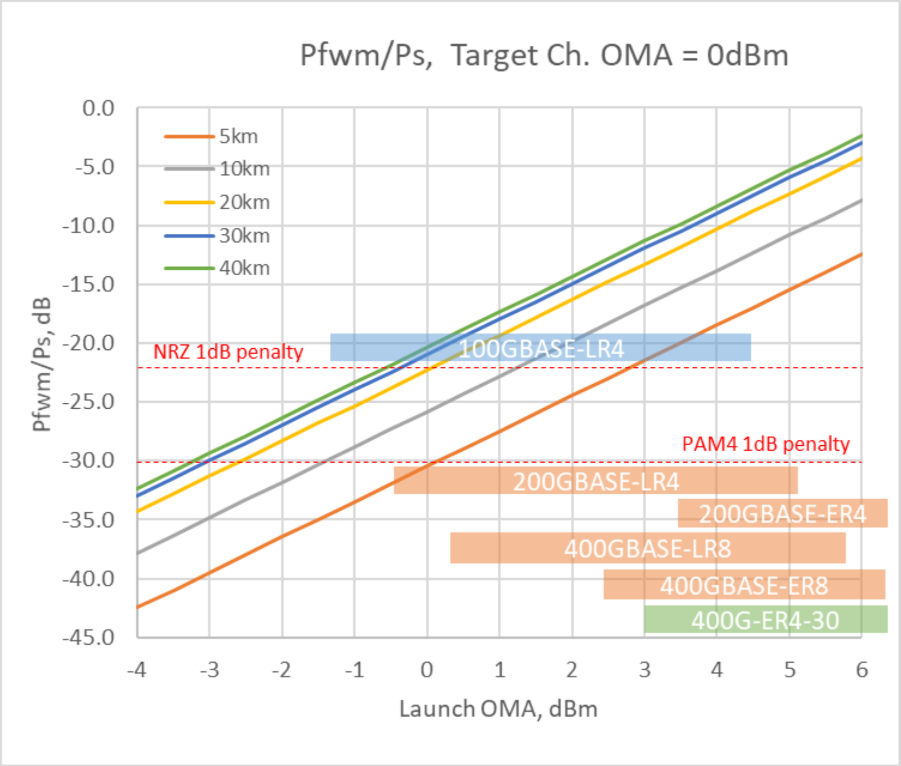
- Eye closure from coherent interference correlates to FWM peak power. The CW calculations give the peak FWM power but no statistics.
- Correlation of CW FWM power to BER can be established by transmission simulations or experiment.
- Literature [1] estimates P_{FWM}/P_S ~ -20 dB gives 1 dB BER penalty for high-extinction NRZ signals
  - 25Gb/s NRZ transmission simulations (at right) give P_{FWM}/P_S ~ **-22 dB** at 1 dB BER penalty with 4.2 dB ER
  - Good agreement on peak FWM power observed between transmission simulation and CW calculations
- P_{FWM}/P_S for PAM4 will be at least 5 dB worse due to 1/3rd smaller OMA_{inner}, plus additional penalty for mixing between upper eye levels.
  - Similar 25GBd PAM4 simulations (not shown) give ~ **-30dB** at 1 dB BER penalty with 7 dB ER



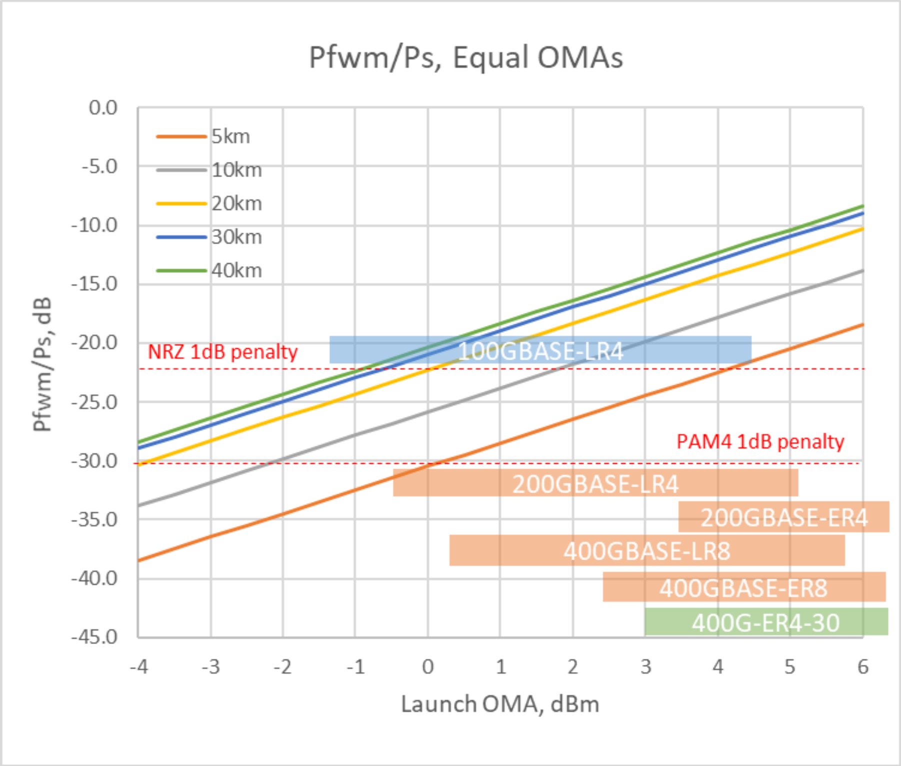


[1] F. Forghieri, R. W. Tkach and A. R. Chraplyvy, "Fiber Nonlinearities and Their Impact on Transmission Systems, Optical Fiber Telecommunications IIIA, I. P. Kaminow and T. L. Koch Eds., pp. 196-264, Academic Press, 1997.

Worst case magnitude of FWM



Bars show ranges of launch OMA for different PMDs



- The left plot shows the case of a weak target channel. The right plot is for all channels with equal launch power.
- 26GBd and 53GBd PAM4 LR/ER PMDs all have OMA ranges completely above the threshold for 1dB FWM penalty, even assuming 5km cable segments and equal launch power in all channels.
- The most widely deployed LAN-WDM PMD, 100GBASE-LR4, is partly below the FWM threshold at 10km, and totally below it assuming 5km cable segments and equal launch power.

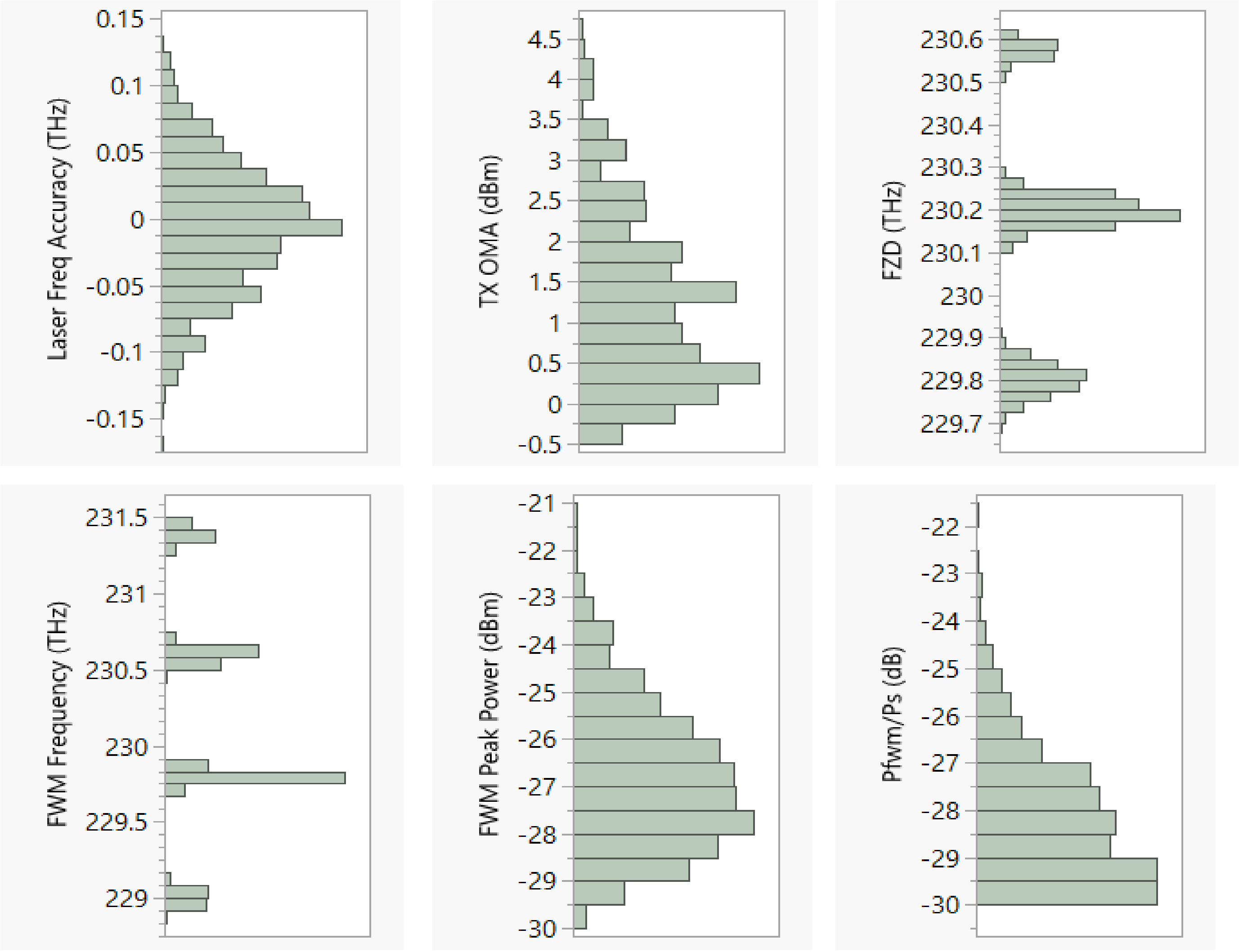
Outage Probability due to FWM

- Laser frequency tolerance
  - For the FWM tone to interfere coherently with the signal, the FWM frequency must be within the receiver bandwidth, *B*, of the signal: $| f_s - f_i - f_j + f_k | < B$.
  - If the laser frequency tolerance is ±*df*, then for *N*=4 the rms difference for between signal and FWM is 2*df*, and the probability of the FWM being within the RX bandwidth is ~ *B*/2*df*.
  - For 800 GHz grid, *df* ~ 100GHz, so the probability is ~ 13% for 26 GBd and 26% for 53 GBd for each FWM combination.
- Fiber cable segment length
  - Assuming a fiber length of 5km and linear dispersion, the phase matching bandwidth at which the relative FWM power drops by half is ~ ±45 GHz for 800 GHz channel spacing and 5km fiber.
  - Assuming the ZDF is uniformly distributed over 1300 to 1324nm, then the probability of near-phase matched FWM is ~ 2% per phase-matched ZDF. No public information about the actual PDF is available.
- Aligned launch polarization (more on this in Part 2)
  - Ethernet WDM transmitters of interest are typically integrated, so probability of alignment = 100%
  - For 4-channel TX, FWM can be significantly reduced by polarization interleaving
  - Polarization mode dispersion (PMD) in the fiber further reduces the outage probability on average
- Laser power
  - To minimize power dissipation, TX are usually tuned to minimum OMA plus margin. The PDF is implementation dependent, but may approximate a truncated Normal distribution.
  - The PAM4 LR4/ER4 PMDs all have OMA(min) greater than the FWM threshold, so probability = 100%.
- Estimated probability of a 800GHz spaced 100G/lane LR4/ER4 link experiencing > 1dB FWM penalty is on the order of 0.26 *0.02 = 0.5%, thus it’s unlikely to be observed in small scale laboratory tests.

Monte-Carlo simulation of 200GBASE-LR4

- TX Frequency Accuracy
  - Normal, mean = 0, sigma = 56.7 GHz, Truncated at ±170 GHz
- TX OMA
  - Normal, mean = +0.6 dBm, sigma = 1.48 dB, Truncated at -0.4 and +5.1dBm
  - Extinction ratio = 4.5dB
- RX BW = 26 GHz
- Fiber
  - Length = 5km, attenuation = 0.3 dB/km
  - ZDF: Uniform,1300 to 1324nm

- 100,000 Monte-Carlo iterations
  - Count FWM tones within 53GHz of laser frequency and P_{FWM}/P_S > -30dB
  - TX channels with FWM impairment = 924 out of 400,000 (0.23%)
  - 4-ch TX with at least one impaired channel = 582 out of 100,000 (0.58%)



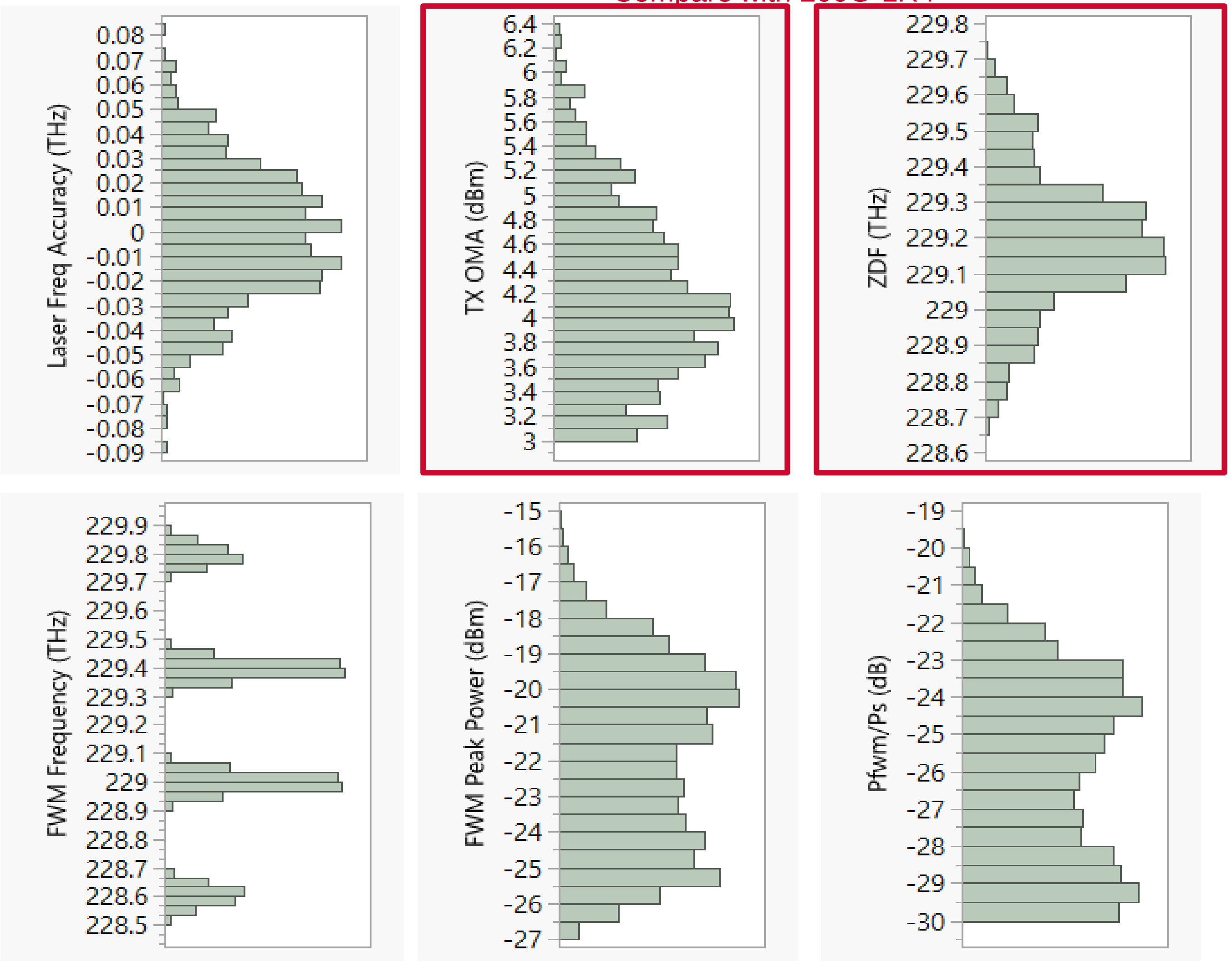
* Only the impaired channels are plotted

Monte-Carlo simulation of 400GBASE-ER4-30 Straw Man

- TX Frequency Accuracy
  - Normal, mean = 0, sigma = 30 GHz, Truncated at ±90 GHz
- TX OMA
  - Normal, mean = +4 dBm, sigma = 0.85 dB, Truncated at +3.0 and +6.4 dBm
  - Extinction ratio = 5.5 dB
- RX BW = 53 GHz
- Fiber
  - Length = 5km, attenuation = 0.3 dB/km
  - ZDF: Uniform,1300 to 1324nm

- 10,000 Monte-Carlo iterations
  - Count FWM tones within 53GHz of laser frequency and P_{FWM}/P_S > -30dB
  - TX channels with FWM impairment = 3819 out of 40,000 (9.5%)
  - 4-ch TX with at least one impaired channel = 1405 out of 10,000 (14.0%)

Compare with 200G-LR4



* Only the impaired channels are plotted

Measuring and Detecting FWM

- Given the low probability of occurrence of FWM in a randomly selected combination of transmitters and fibers, measuring it takes extra effort in the lab:
  - The laser frequencies must be individually tuned to be on a fixed grid spacing
  - The entire WDM grid must be tuned to align with the known ZDF of the fiber. Different ZDF alignments will generate interference in different channels.
  - If an external MUX is used, the launch polarization of each laser must be aligned with the others
  - Max penalty will occur with the target channel at OMA(min) and other channels at OMA(max)
- In a datacenter environment, FWM may be difficult to distinguish from other issues
  - Observing the optical spectrum at the receiver end with the target laser off will reveal the interfering FWM tone – difficult when the TX and RX are >10km apart.
  - Blindly swapping out the TX module has a good probability of eliminating the FWM penalty.
    - If the “bad” TX is tried on a fiber with different ZDF, it has a high probability of working.
    - “Bad” TX returned to the vendor likely will have “no trouble found.” Are there any statistics on this?
  - A transmitter may work when installed but have FWM penalties later due to changes in laser frequency. Given typical cooled laser frequency stability, this is rather unlikely.

Discussion – Part 1

- Transmission penalties due to FWM need to be considered in two senses:
  - Maximum magnitude of FWM generation under worst-case conditions
  - Probability of occurrence of the conditions that result in significant FWM penalty
- Widely-deployed 100GBASE-LR4 is often cited as an example that FWM isn't an issue for 800GHz LAN-WDM grid in O-band. This observation is backed up by simulation:
  - 25Gb/s NRZ modulation and low OMA(min) lead to minimal BER penalties for 5km spans
  - Penalties can occur for contiguous 10km segments, but typical cable installation makes this unlikely.
  - More data on the actual distribution of cable segment lengths in DCI applications would be helpful.
- 100G/lane LR4/ER4 TX have higher launch OMA requirements that lead to significant FWM penalties under worst-case frequency alignment, even for 5km fiber segments
  - The observation of FWM penalties is predicted to be a low-probability event, on the order of 1% to 10% of randomly configured links.
  - Diagnosis of FWM in the field is difficult, but readily remedied by swapping out the transceiver
- The absence of FWM penalties can't be established by a small sample of link tests. Assessing worst case FWM penalties must be carried out with co-polarized launch, laser frequencies aligned with each other and with the fiber ZDF, and maximum launch power.
  - Carefully conducted FWM measurements should be conducted for new LAN-WDM channel plans

Part 2 – Effects of Launch Polarization and PMD

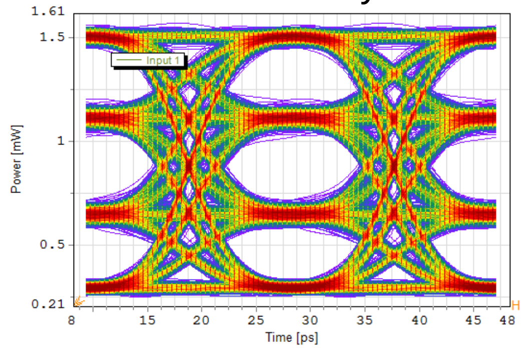
- The prior simulations assumed co-polarized launch and fiber without PMD
  - Aligned launch polarization is common for Ethernet WDM TX. Interleaved polarization would be possible with minor modifications.
  - PMD in the fiber will randomize the launch condition and reduce the generation of FWM
- Polarization interleaving has been suggested as a potential solution for FWM in LR4/ER4 systems, as documented in publications on FWM in C-Band DWDM systems [1-4].
  - If only four channels are present, interleaved polarization can be effective to reduce FMW
  - When PMD is present, the anti-polarized launch condition becomes randomized. This effect is larger for wider channel spacing (2nd order PMD)
  - The angle between the launch polarization and the (time-varying) principle state of polarization (PSP) and the total DGD of the fiber introduces an unavoidable random behavior into the FWM penalty
- This section attempts to address the ability of polarization interleaving to prevent the occurrence of significant FWM penalties in LAN-WDM links and assess the effect of PMD in the fiber for the 400G-ER4-30 straw man proposal

[1] K. Inoue, “Polarization Effect on Four-Wave Mixing Efficiency in a Single-Mode Fiber,” IEEE J. Quantum Electon., Vol. 28, No. 4. April 1992, pp. 883-894.
[2] J. Hansryd, et al, “Impact of PMD on Four-Wave-Mixing-Induced Crosstalk in WDM Systems”, IEEE Photon. Technol. Lett., Vol. 12, No. 9, Sept. 2000, pp. 1261-1263.
[3] S. Pachnicke, et al, “Impact of polarization-mode dispersion and fiber nonlinearities on four-wave mixing efficiency,” Proc. OECC 2006, 5F2-2-1.
[4] M. Gonzalez-Herraez et al., "Effects of polarization-mode dispersion on four-wave mixing efficiency," Symposium on Optical Fiber Meas., 2004, pp. 107-110

400G-ER4-30 Transmission Simulations

- 53GBd PAM4 transmission simulations were performed using the VPI Photonics Optical Systems design suite
- High BW TX and RX were assumed so that FFE were not required for simulation
- EML TX parameters:
  - Equal launch power in all channels (best case)
  - Linear polarization = 0 or 90 deg
  - TX ER = 7.1 dB (best case)
  - Linewidth = 1e6 Hz
  - RIN = -145 dB/Hz
- Fiber parameters:
  - Attenuation = 0.3e-3 dB/m
  - DispersionSlope = 0.093e3 s/m^3
  - NonLinearIndex = 2.6e-20 m^2/W
  - CoreArea = 55.0e-12 m^2
  - CorrelatLength = 20.0 m (PMD coarse step)
  - MeanStepWidth = 200 m (PMD coarse step)
- APD RX parameters:
  - DarkCurrentMultiplied = 300e-9 A
  - DarkCurrentNonMultiplied = 10e-9 A
  - AvalancheMultiplication = 8
  - IonizationCoefficient = 0.4
  - ThermalNoise = 20.0e-12 A/Hz^(1/2)

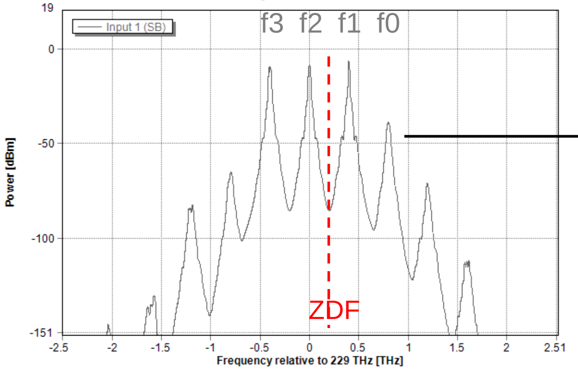
Pre-fiber eye



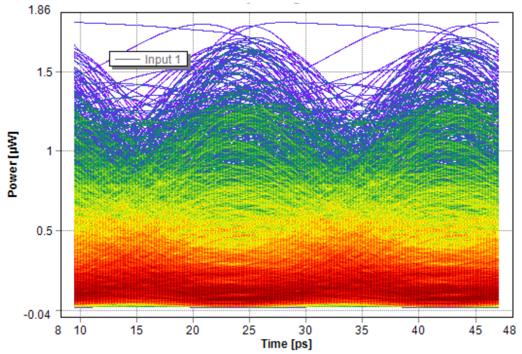
$f0 = f1 + f2 - f3$

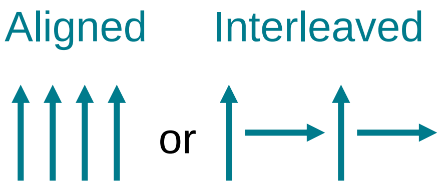
$ZDF = (f1 + f2)/2$

Post-fiber spectrum,TX0 off

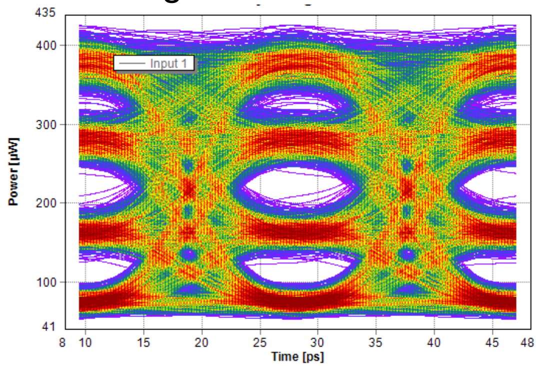


FWM at f0

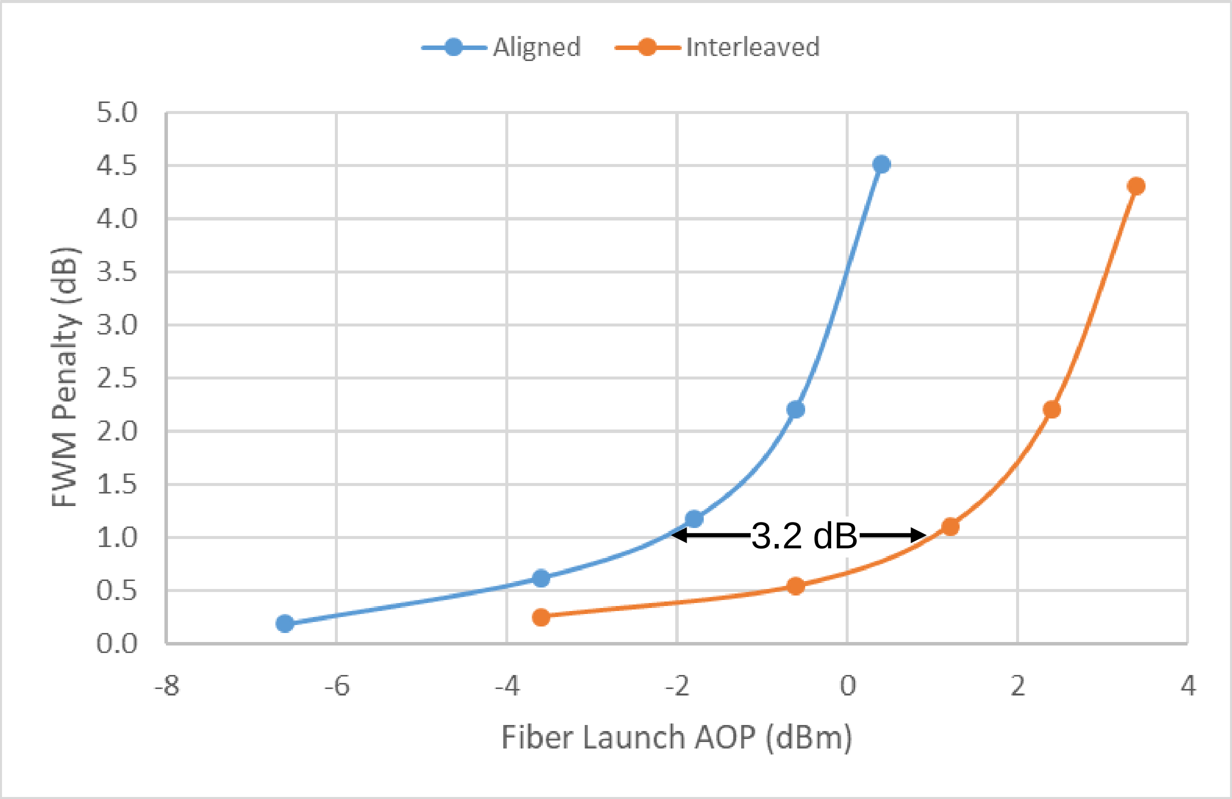




Signal + FWM at f0



10km, Zero PMD

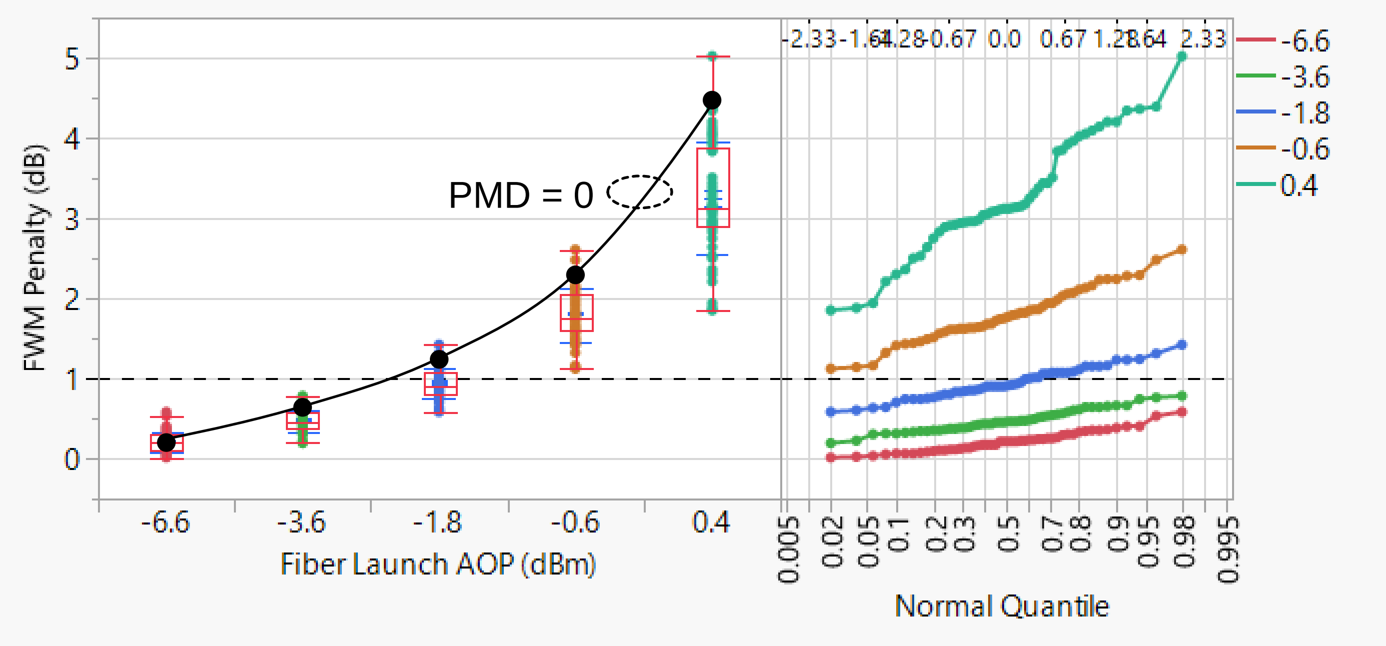


At ER=7.1dB, OMA = AOP + 1.3dB

- For aligned polarization, 1 dB FWM penalty occurs at low launch AOP = -2.3 dBm (OMA = -1.0 dBm), consistent with previous prediction on slide 11.
- This is less than required for the 400G-ER4-30 straw man (OMA minus TDECQ > +1.6 dBm)

- FWM is non-zero for interleaved polarization since $\chi^{(3)}_{1111} = \chi^{(3)}_{1212} = \chi^{(3)}_{1221}$ in isotropic media, but it is reduced relative to co-polarization
- For interleaved polarization, 1dB FWM penalty occurs at AOP = 0.9 dBm (OMA = 2.2 dBm), an improvement of 3.2 dB over aligned polarization.

Aligned Polarization: 10km, PMD = 0.1 ps/√km

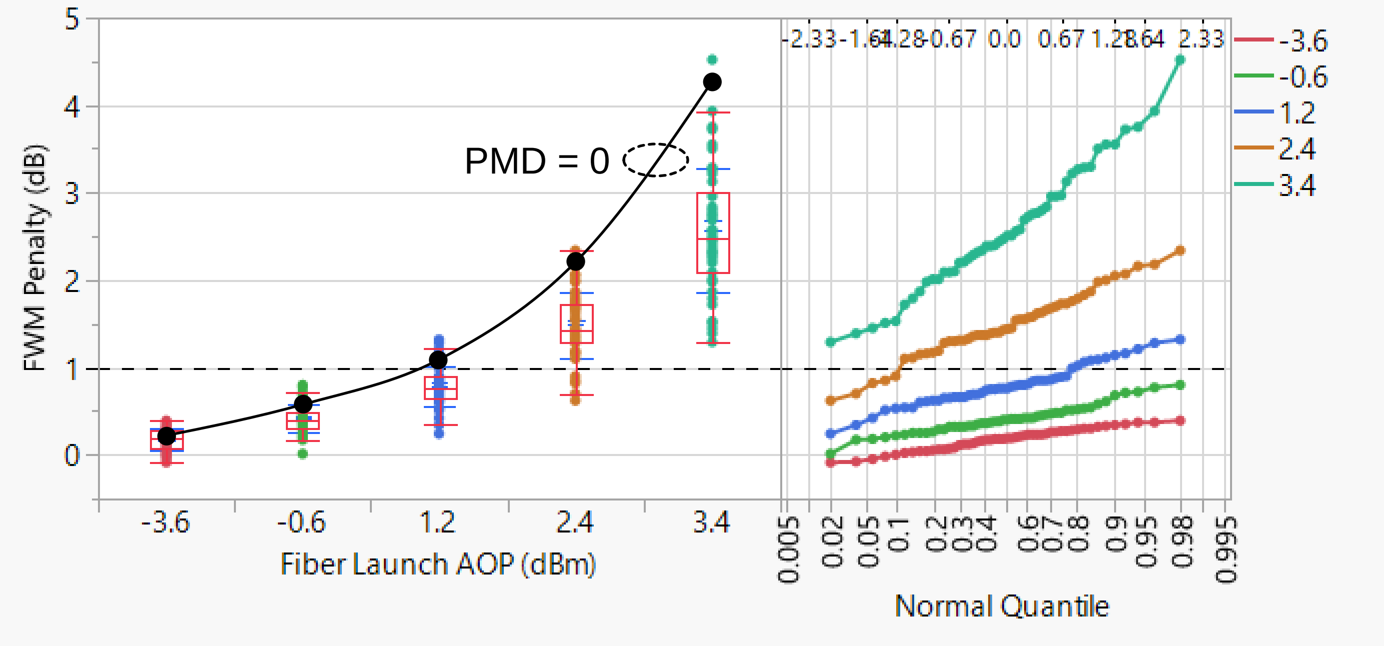


50 iterations of the coarse-step PMD model per AOP

PMD = 0 shown for reference

- Max PMD_Q for G.652D fiber is 0.2 ps/√km, but typical vendor specs are in the range of 0.05 to 0.1 ps/ √ km.
- As PMD increases, the FWM penalty is reduced and forms a distribution due to the randomness of total DGD and the orientation of the PSP vector relative to the launch polarization.
- The maximum penalty approaches the zero PMD case when the launch polarization aligns with the PSP, but the median penalty is lower, significantly so at high launch AOP.

Interleaved Polarization: 10km, PMD = 0.1 ps/√km



50 iterations of the coarse-step PMD model per AOP

PMD = 0 shown for reference

- The effect of PMD for interleaved polarization is the same as for aligned polarization.
- The 3.2 dB improvement in launch OMA still applies in the presence of PMD.

Discussion – Part 2

- 100G/lane ER4 transmission has multiple negative characteristics for FWM:
  - Fiber spans > 5km for efficient FWM generation
  - High optical launch powers, > +3dBm, due to the high link power budget
  - Narrow channel spacing due to limited chromatic dispersion tolerance of 100G PAM4 signals
  - WDM TX are typically integrated, with aligned launch polarizations
- Even with these characteristics, the probability of observing a FWM outage in the field is relatively low: on the order of 0.1% to 10%, depending on the channel spacing and TX OMA specs.
- Polarization interleaved launch reduces the generation of FWM over aligned polarization launch, but isn't sufficient to prevent > 1dB FWM penalty for the straw man 400G-ER4-30 proposal at the minimum launch OMA of +3dBm.
- PMD is a random variable affecting both the magnitude and probability of occurrence of transmission penalties due to FWM.
  - Non-zero PMD reduces the *average* FWM penalty at a given power
  - The highest penalty is similar to the zero PMD case, but is less likely to occur with non-zero PMD
  - PMD further complicates the accurate characterization of FWM due to its time-varying nature

Thank You!

Backup Slides

Four-Wave Mixing: CW Theory

For modulated signals, the peak power is most relevant since $P_{FWM} \sim P^3$

FWM frequency:
$$f_{ijk} = f_i + f_j - f_k$$

$D(\lambda)$ is the dispersion at λ and $dD/d\lambda$ is the dispersion slope

Linear approximation is valid for grid spacing < 10nm in O-band

Phase matching condition:
$$\Delta\beta = \beta_i + \beta_j - \beta_k - \beta_{ijk}$$

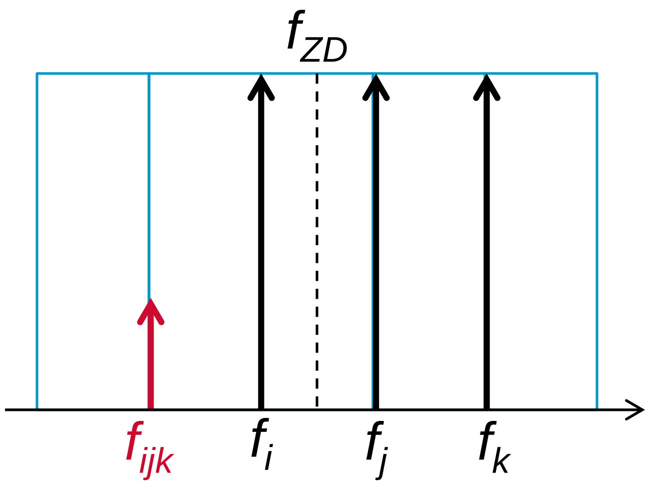
$$\Delta\beta \approx \frac{2\pi\lambda^2}{c}(f_i - f_k)(f_j - f_k)\left[D(\lambda) - \frac{\lambda^2}{c}\left(\frac{f_i + f_j}{2} - f_{ijk}\right)\frac{dD}{d\lambda}\right]$$

FWM efficiency:
$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left(1 + \frac{4e^{-\alpha L}\sin^2(\Delta\beta L/2)}{(1 - e^{-\alpha L})^2}\right)$$

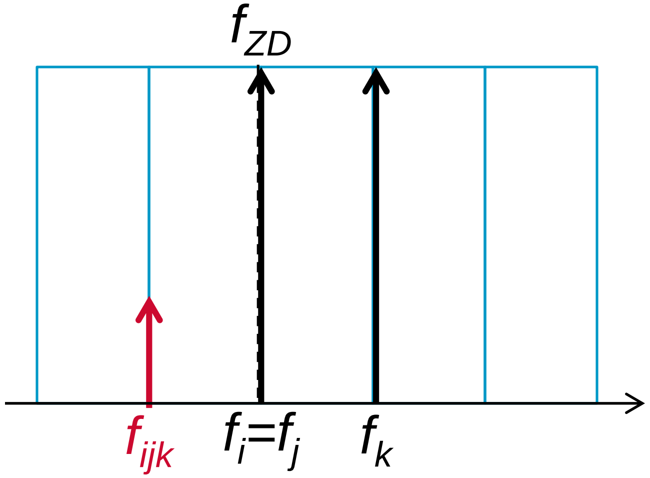
FWM efficiency = 1 when $\Delta\beta = 0$.

FWM power:
$$P_{ijk} = \left(\frac{D_{ijk}}{3}\gamma L e\right)^2 P_i P_j P_k e^{-\alpha L}\eta \text{ , where } \gamma = \frac{2\pi n_2}{\lambda A_e} \text{ and } L_e = \frac{1-e^{-\alpha L}}{\alpha}$$

$P_{FWM} \sim D_{ijk}^2$, so non-degenerate FWM tones are 4dB stronger than partially degenerate tones



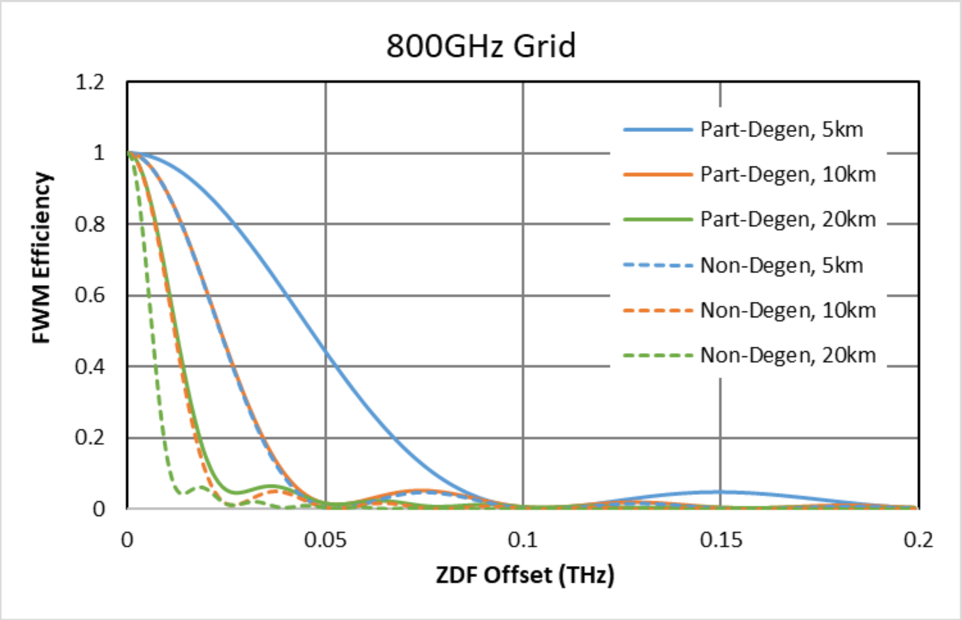
Non-degenerate, $i \neq j \neq k$, $D_{ijk} = 6$

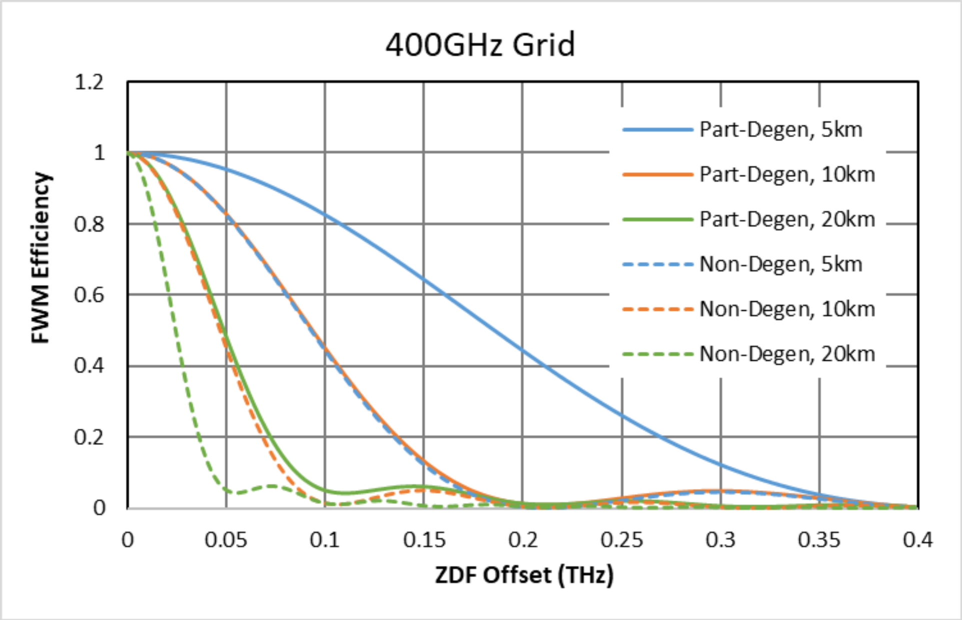


Partially degenerate, $i = j \neq k$, $D_{ijk} = 3$

F. Forghieri, R. W. Tkach and A. R. Chraplyvy, "Fiber Nonlinearities and Their Impact on Transmission Systems, Optical Fiber Telecommunications IIIA, I. P. Kaminow and T. L. Koch Eds., pp. 196-264, Academic Press, 1997.

Effect of phase mismatch





- Phase matching bandwidth represents how far ZDF can be offset from the ideal frequency
- Narrower grid spacing decreases the frequency span and $\Delta\beta$, so PM bandwidth increases
- Partially degenerate FWM uses a smaller frequency span, so PM bandwidth is 2x wider than non-degenerate FWM
- Longer fiber increases the magnitude of $\Delta\beta L$, so PM bandwidth decreases
- As mentioned, >10 km spans may be characterized by shorter cable segment lengths

FWM combinations

- N WDM channels potentially generate $N_{ijk} = ½\ N^2(N\text{-}1)$ combinations of FWM frequencies for a given value of ZDF.
- Phase matching can only occur if the ZDF is aligned with or halfway between the channel frequencies in the zero dispersion range.
- Of the N_{ijk} possible FWM tones, only a fraction will be phase matched and also align with another channel.
  - For N = 4 channels, N_{ijk} = 24 possible combinations to produce FWM
  - Only 3 choices of ZDF result in phase matching: aligned with channel 2 or 3, or halfway between them
  - Only 10 FWM tones land on active channels

Potential interfering FWM tones for N=4

	ZDF "Channel“ for Phase Matching					
	2		2.5	3		
Target Channel	D=3	D=6	D=6	D=3	D=6	Grand Total
1	1		1			2
2		1	1	1		3
3	1		1		1	3
4			1	1		2
Grand Total	2	1	4	2	1	10