Four-Wave Mixing Penalty for WDM-based Ethernet PMDs in O-band

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Outline

- Large Frequency Spacing FWM Model
  - Theory
  - Experimental verification
- FWM Power Penalty for PAM4
  - An approximate analytical model
  - Simulation results
- FWM Impacts for 800G (4x200G) IM-DD CWDM4
  - Uncooled laser
  - Cooled laser
- FWM Impacts for 1.6T (8x200G) IM-DD WDM8
  - 10nm-WDM8
  - LAN-WDM8 and others

FWM Model: Phase-Matching Factor

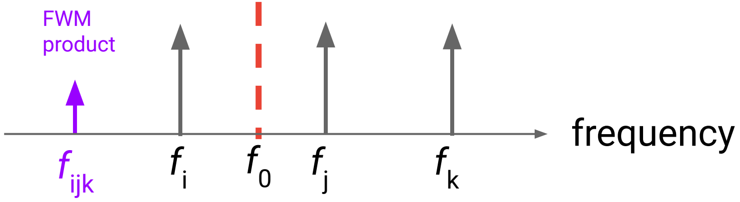
How to calculate FWM phase-matching factor with large frequency spacings

$$\Delta\beta = \beta(f_k) + \beta(f_{ijk}) - \beta(f_i) - \beta(f_j)$$

$$\Delta\beta = \int_{f_0}^{f_k}\int_{f_0}^{f_k}\beta_2(f)df + \int_{f_0}^{f_{ijk}}\int_{f_0}^{f_{ijk}}\beta_2(f)df - \int_{f_0}^{f_i}\int_{f_0}^{f_i}\beta_2(f)df - \int_{f_0}^{f_j}\int_{f_0}^{f_j}\beta_2(f)df$$

$$f_{ijk} = f_i + f_j - f_k$$

$$f_0 = \frac{1}{2}(f_i + f_j)$$



$$\beta_2(f) = \left(-\frac{23.25}{2\pi}\right)\left(\frac{C^2}{f^3}\right)\left[1 - \left(\frac{f}{f_{ZD}^4}\right)\right]$$

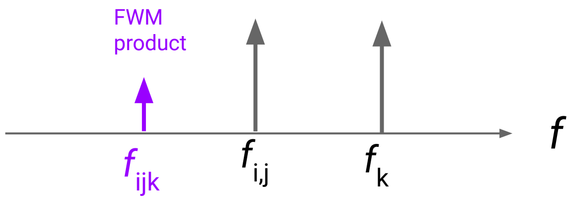
IEEE fiber CD model

Fiber group velocity dispersion coefficients

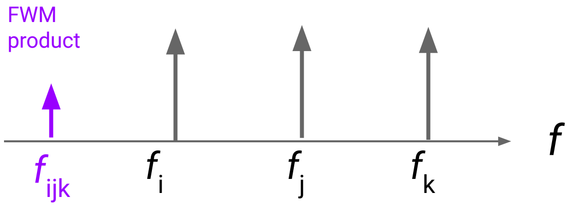
Fiber Zero dispersion frequency (ZDF)

FWM Model: FWM Products

$$f_{ijk} = f_i + f_j - f_k$$



Degenerate FWM



Non-degenerate FWM

Under aligned polarizations, FWM product in field given by

$$E_{ijk} = D\gamma \frac{1 - e^{-(\alpha + j\Delta\beta)L}}{\alpha - j\Delta\beta} E_i E_j E_k^* e^{-\alpha L/2}$$

Where

$$D = \begin{cases} 1, & Degenerate\ FWM \\ 2, & Non-degenerate\ FWM \end{cases}$$

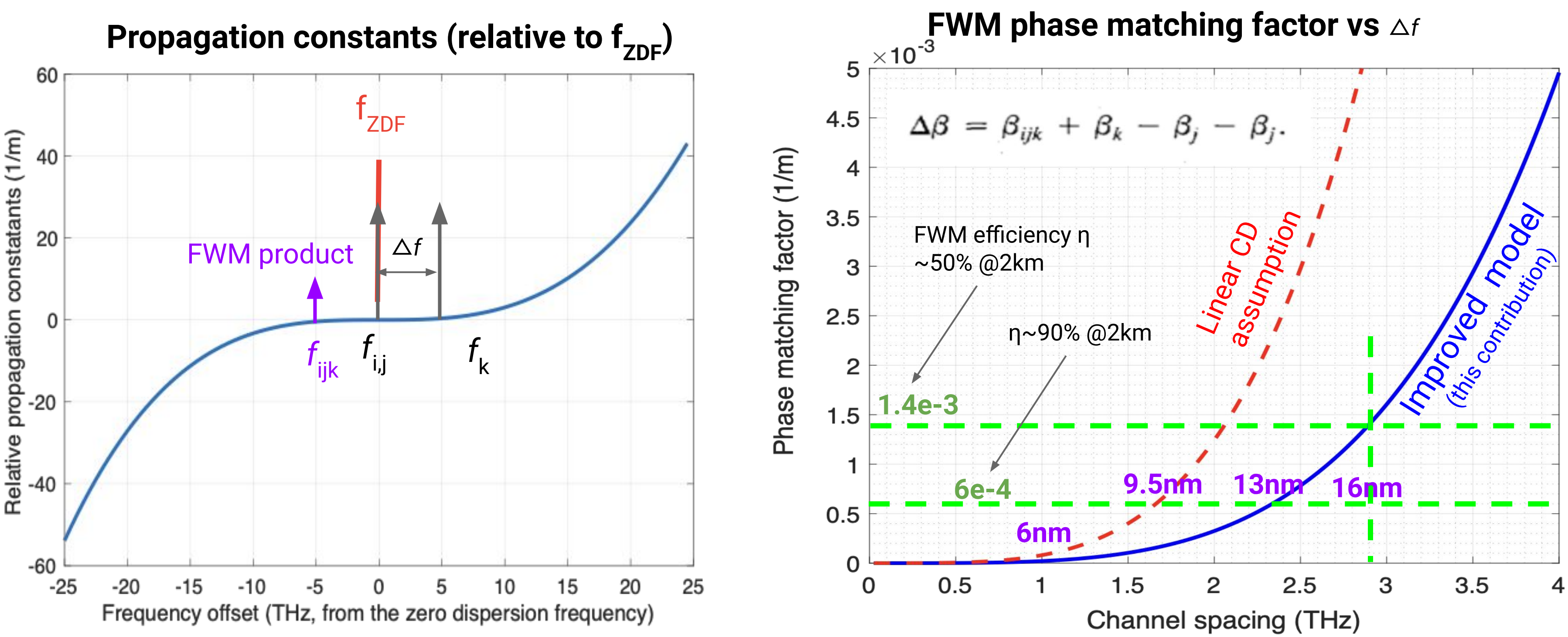
$$\gamma = \frac{2\pi f n_2}{cA_{eff}}$$

FWM efficiency:

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

O-Band FWM Worst-Case Phase Matching Bandwidth

Degenerate FWM

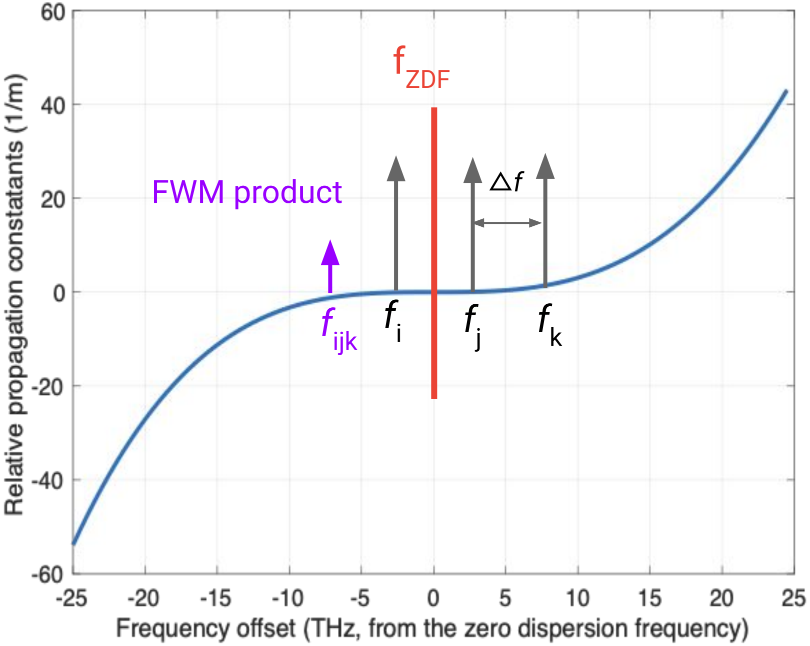


- Worst-case phase matching bandwidth: ~16nm @3dB.2km, ~13nm @0.5dB.2km

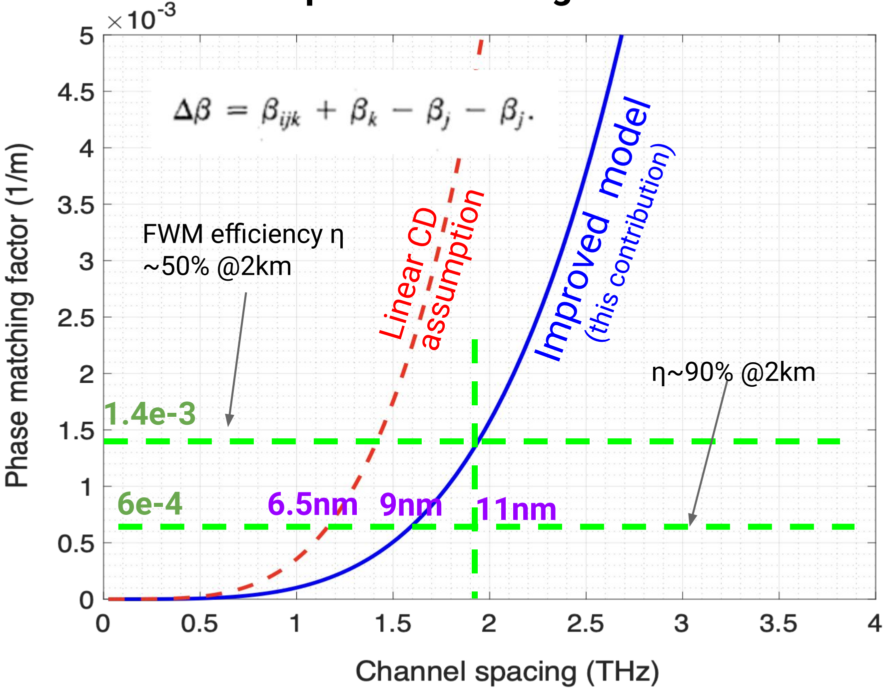
O-Band FWM Worst-Case Phase Matching Bandwidth

Non-degenerate FWM

Propagation constants (relative to f_{ZDF})



FWM phase matching factor vs Δf



- Worst-case phase matching bandwidth: ~11nm @3dB.2km, ~9nm @0.5dB.2km

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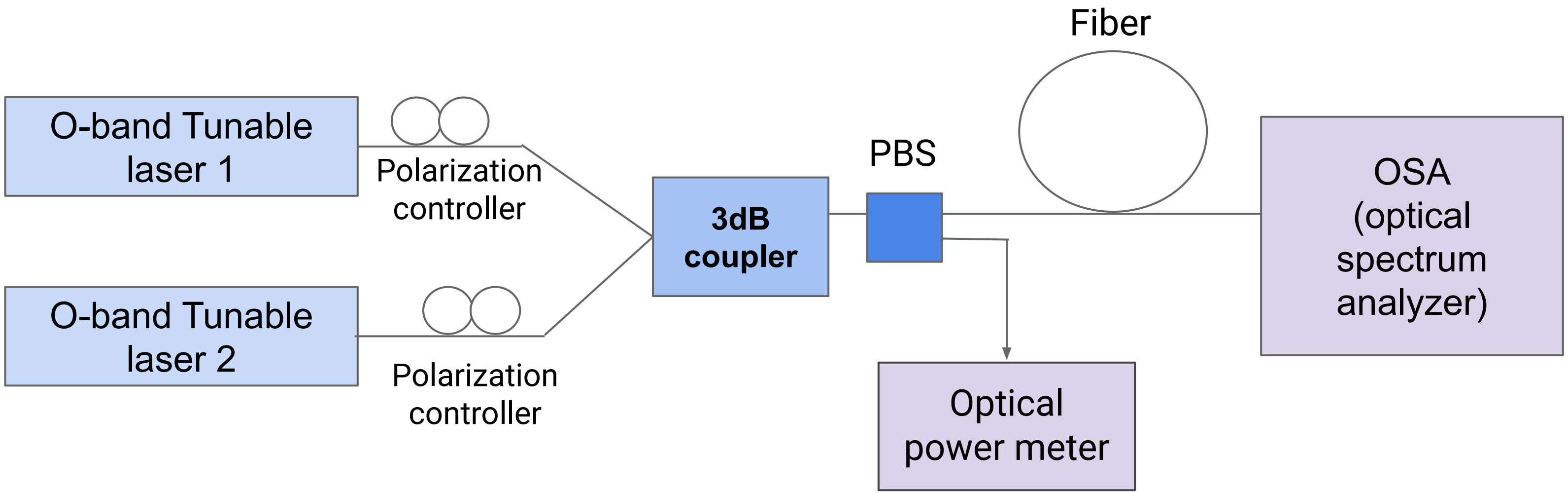
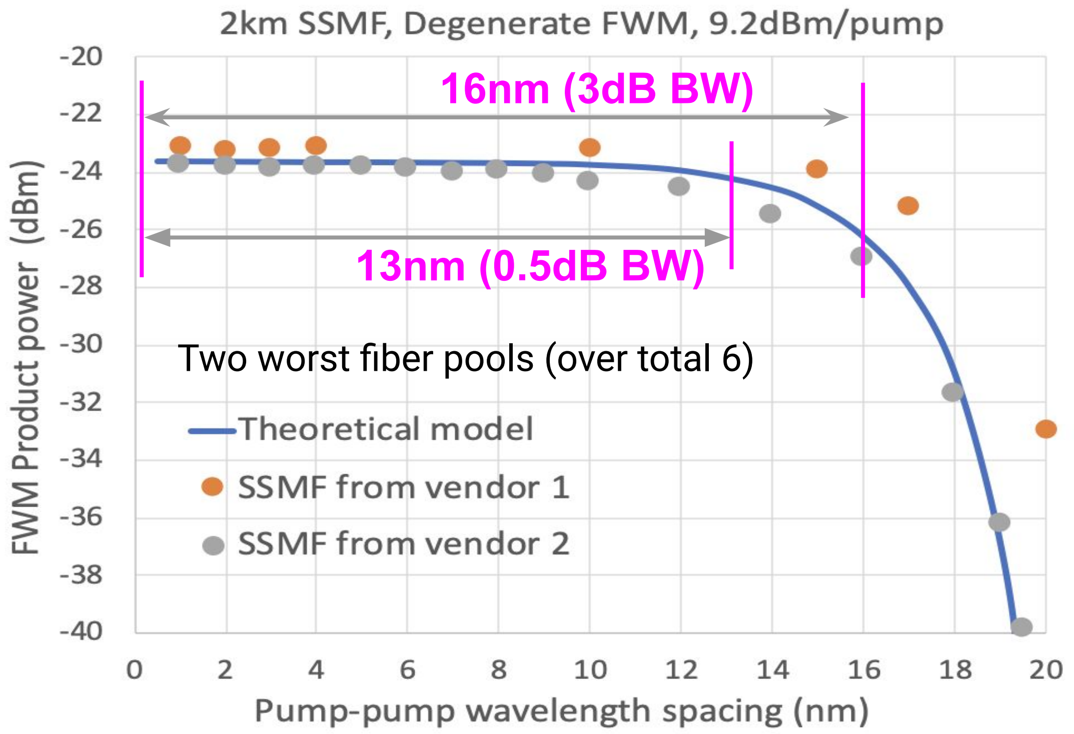
Experiment for FWM Model Verification

Degenerate FWM experimental setup



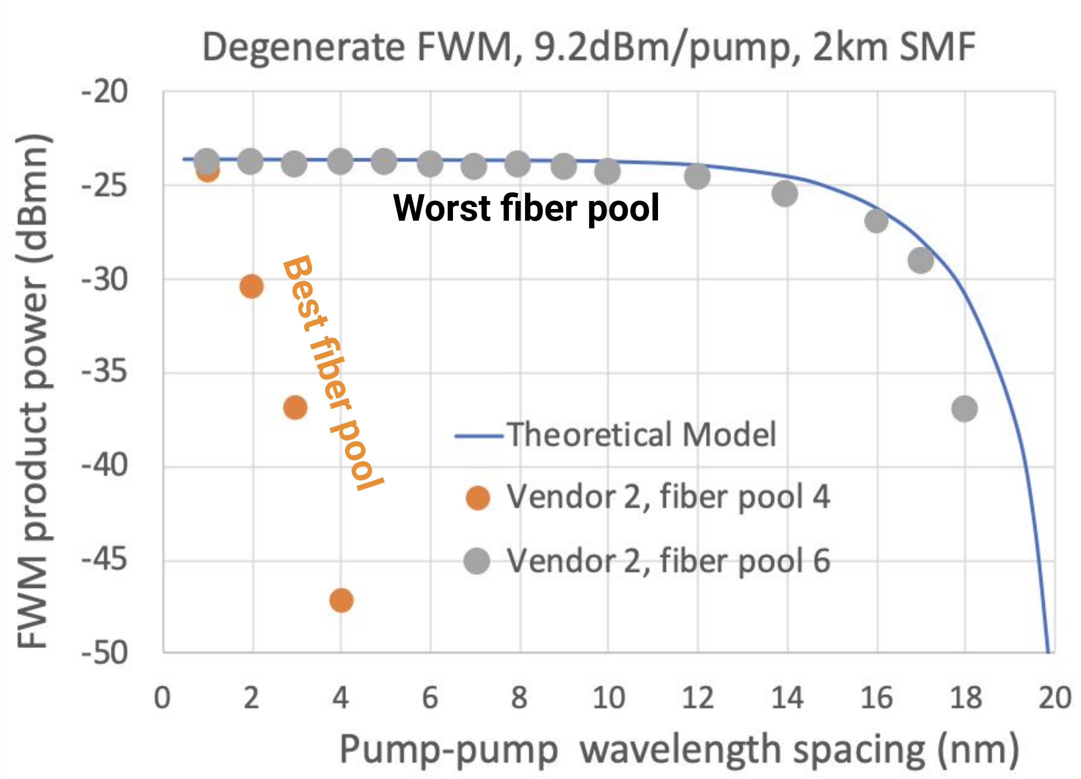
- Step 1: Find and set laser 1 at the Zero dispersion frequency of the fiber under test
- Step 2: Scan the frequency of laser 2 to measure the degenerate FWM product power vs the frequency spacing between the two pumps (laser 1 and laser 2)

Experimental Results: ‘Worst’ Fiber Pools



- **The developed worst-case model agrees with the ‘worst’ experimental results reasonably well**
  - **At ~13nm spacing, FWM power reduces by about 0.5dB**
  - **At ~16nm spacing, FWM power reduces by about 3dB**

Experimental Results: Pool by Pool Variation



- Large FWM efficiency variation from pool to pol observed
- Likely due to zero dispersion frequency variation over the 2km fiber length
  - 110GHz ZDF detuning will result in ~10dB FWM efficiency reduction

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FWM Penalty: An Approximate Analytical Model

For PAM-m with amplitude A_1 to A_m, assuming that the FWM signal has similar peak to average power ratio (PAPR) as the original signal, then the worst (outmost) vertical eye closure distortion caused by an inband FWM crosstalk *R*, can be approximated as

$$\varepsilon_{eye} \approx 2\sqrt{R}\{|A_m|^2 + |A_m||A_{m-1}|\}$$

R=Inband FWM power / signal power

With modulation extinction ratio *E*, the normalized eye closure distortion is given by

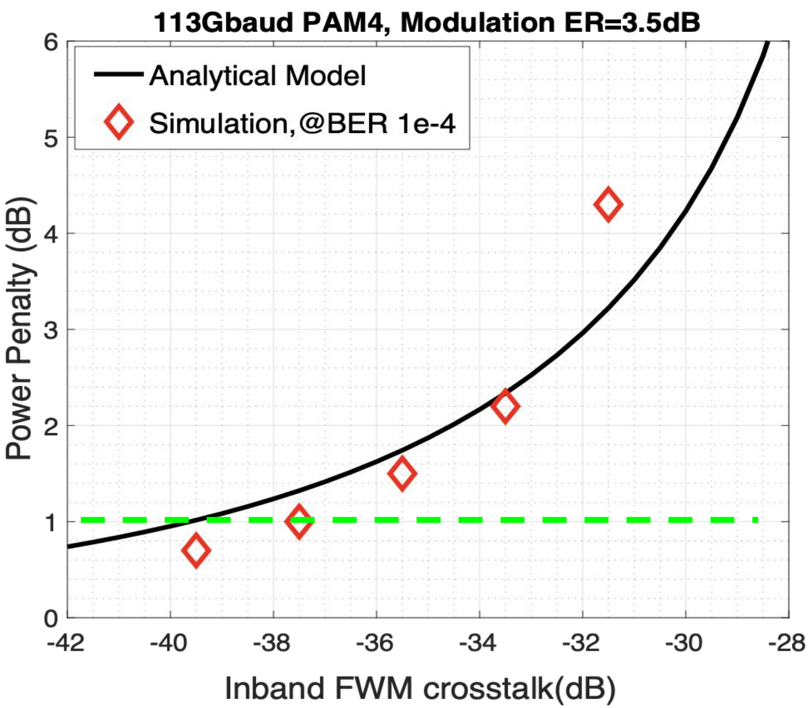
$$\varepsilon_{norm} \approx 2\sqrt{R}[1 + (2m - 3)E]/(E - 1)$$

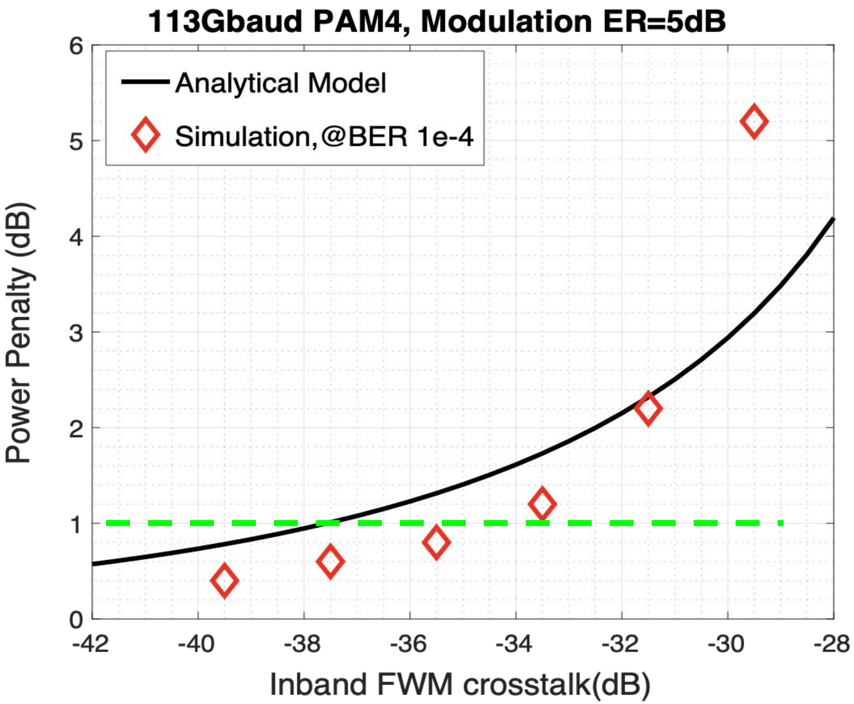
For an ideal transceiver operating at relatively low BER, optical power penalty can be approximated by

$$P_{dB} \approx 10log10\left\{\frac{1}{1 - \varepsilon_{norm}}\right\}$$

Power Penalty by FWM: Analytical vs Simulations

113Gbaud PAM4, BER 1e-4

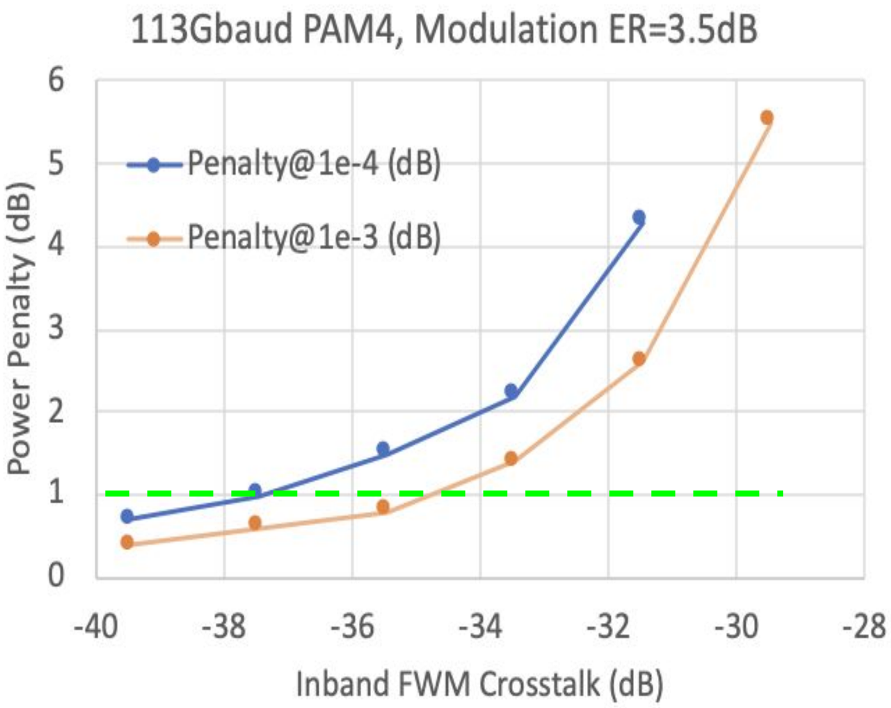


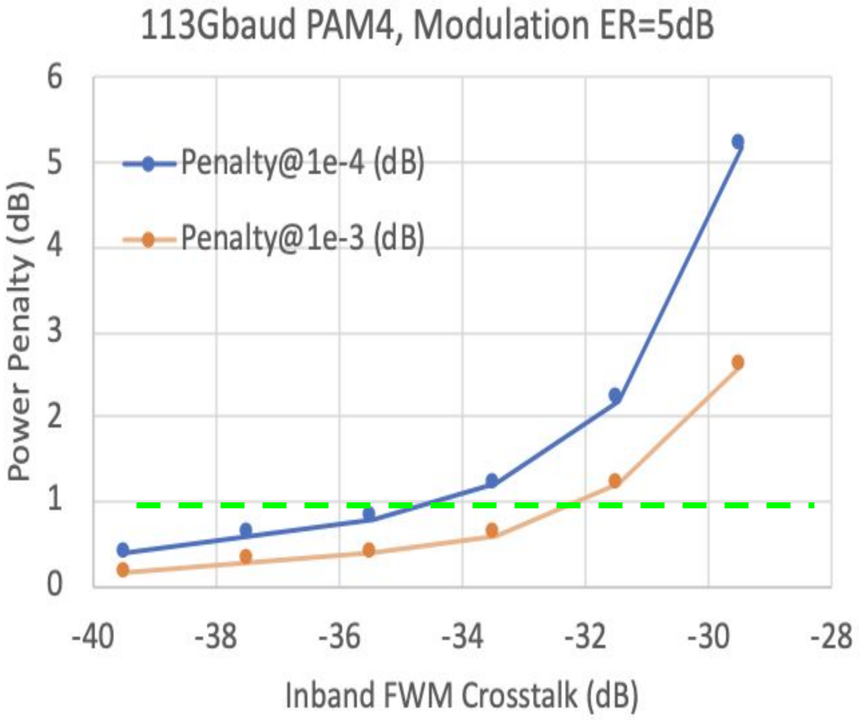


- Simulations based on a 4x200G LAN-WDM4 system over 2km of SSMF
- Assuming fiber ZDF in the middle of the four LAN-WDM4 wavelengths

FWM Penalty: BER threshold and Mod. ER Impacts

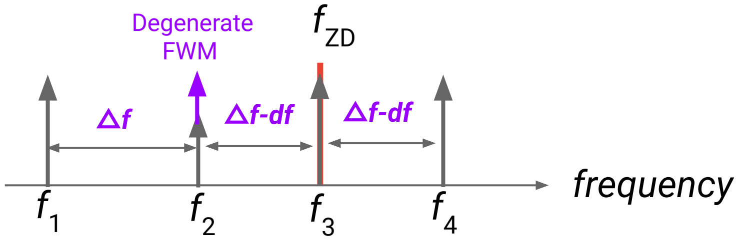
Simulation results, 113Gbaud PAM4





- Higher BER threshold (higher gain FEC) and higher mod. ER help in reducing FWM penalty
  - ~5dB FWM Xtalk tolerance increase from (1e-4 3.5dB) to (1e-3 5dB)

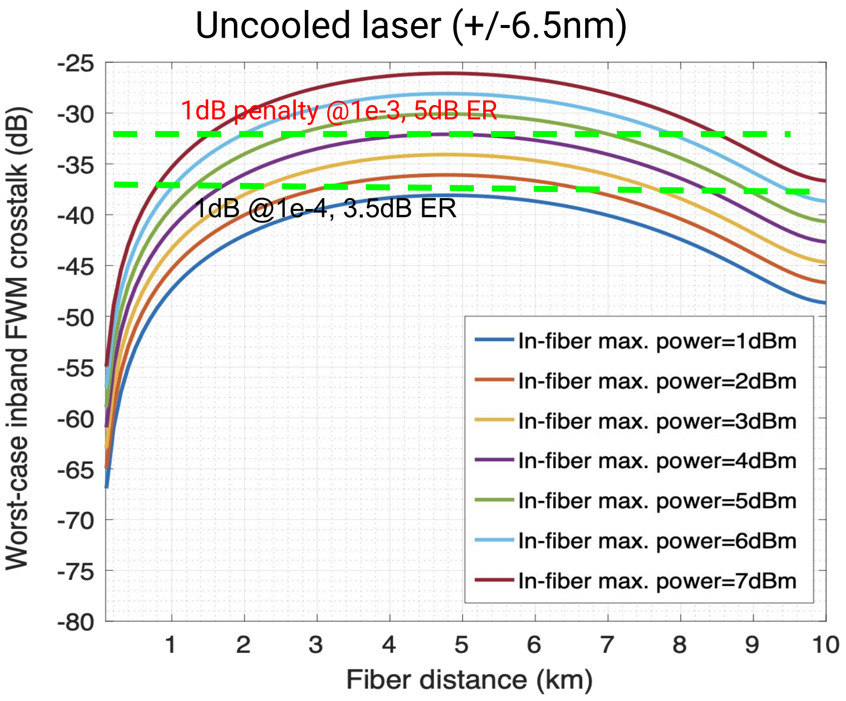
FWM Impacts for 800G (4x200G) IM-DD CWDM4

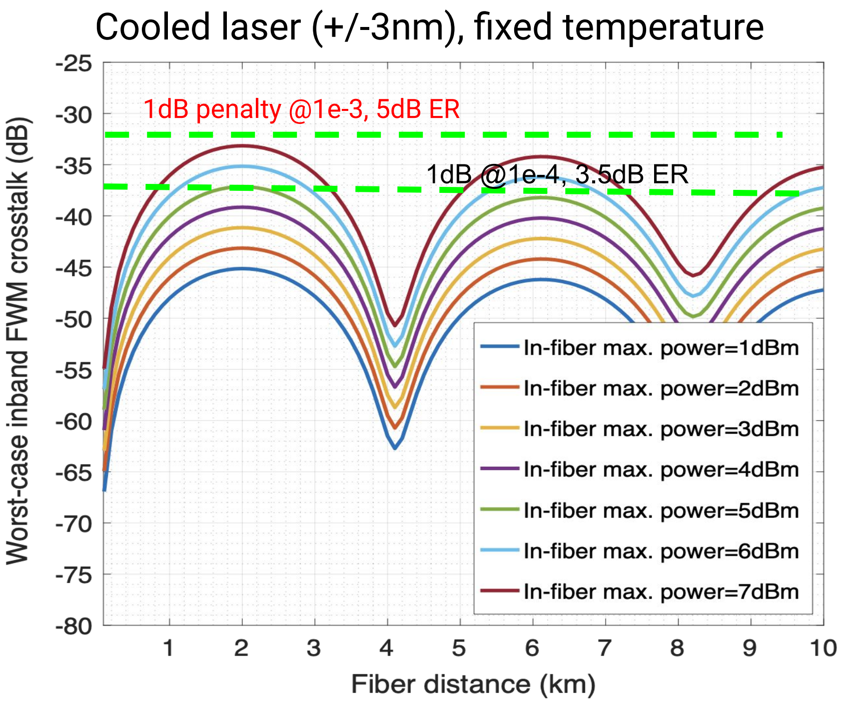


Δ*f* =nominal channel spacing (20nm for CWDM4)
***df*=Worst-case laser frequency drift (6.5nm for uncool lasers)**

- Based on one of the worst-case frequency distribution scenario
  - Ch. 2 (f_2) as the test channel
  - ZDF $f_{ZD}=f_3$
  - Ch 2, 3 and 4 have equal but narrowest spacing ***Δf-df,***
  - Allowing different spacing between channel 1 and 2 (e.g. **Δf**)
- Assume Tx power dynamic range<4dB (lane to lane)
  - The test channel lowest power
  - The other channel highest power
- Assume aligned polarizations

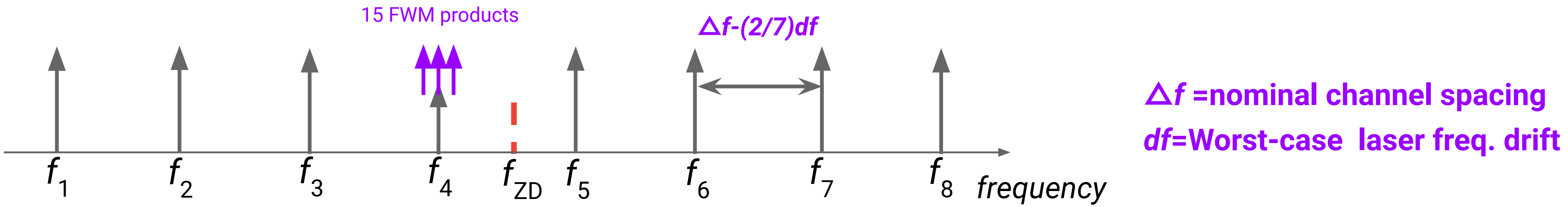
FWM Impacts on 20nm-Spaced CWDM4





- FWM cannot be neglected for >1km reach, especially for using uncooled lasers
- FWM crosstalk penalty manageable by
    - Cooled lasers and/or higher modulation ER + higher gain FEC

FWM Impacts for 1.6T (8x200G) IM-DD WDM8

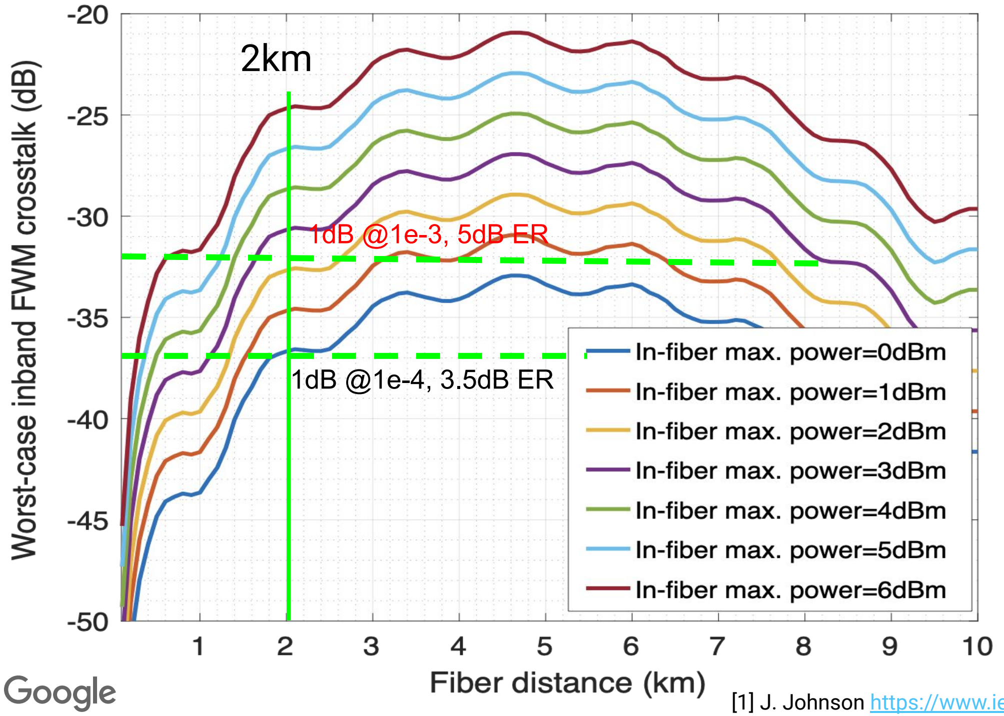


- Based on worst equal channel spacing scenario
  - Ch. 4 (f_4) as the test channel
  - Fiber ZDF in the middle of the 8 frequencies
  - Ch spacing=**Δ*f*-(2/7)*df***, the narrowest equal channel spacing possible
- Assume Tx power dynamic range<4dB (lane to lane)
  - Test channel lowest power
  - Other 7 channels highest power
- Assume aligned polarizations
- Coherent summation of 15 FWM products
  - EML laser coherent time (up to 1μs) longer than KP4 FEC frame length

FWM Impacts on 10nm-Spaced WDM8

Can 8x200G over 2km feasible ?

Cooled laser +/-3nm, fixed temperature
(worst equal wavelength spacing ~9.2nm)



- ***1dB FWM penalty @1e-4 & ER=3.5dB***
  - Allow Max Tx power ~0dBm without Pol. interleaving
  - Allow Max Tx power ~3dBm with Pol. interleaving [1]
- ***1dB FWM penalty @1e-3 & ER=5dB***
  - Allow Max Tx power ~2dBm without pol interleaving
  - Allow Max Tx power ~5dBm with Pol interleaving[1]
- ***2km reach feasible***
  - Pol intealeving
  - Higher gain FEC (>1e-3)
  - Higher modulation ER (~5dB)

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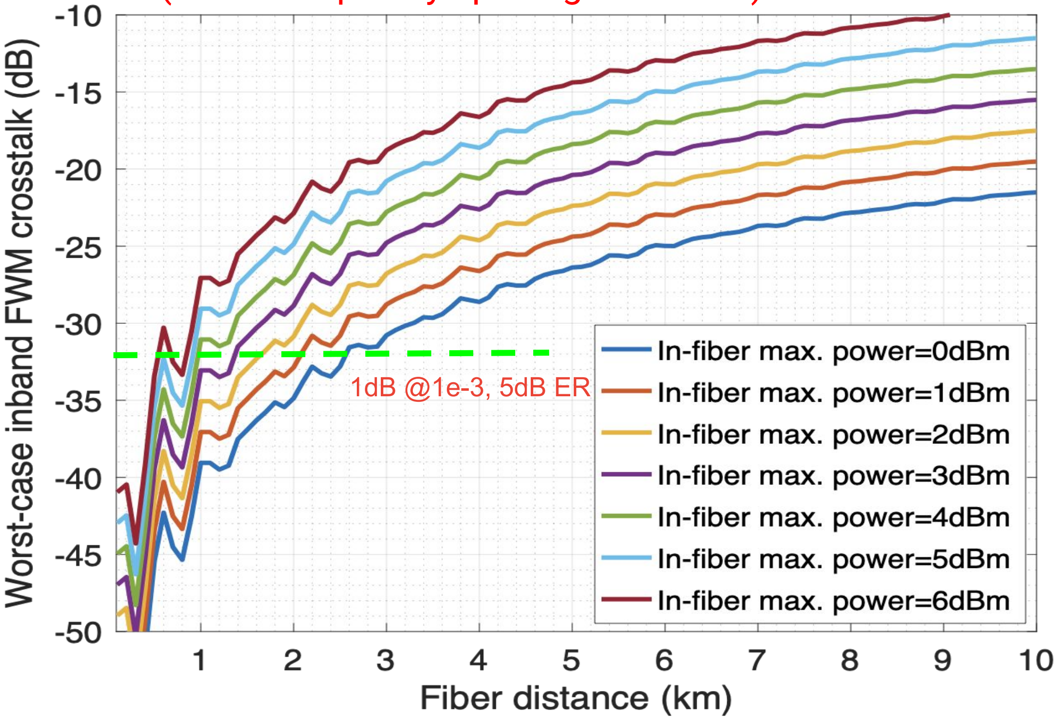
[1] J. Johnson https://www.ieee802.org/3/df/public/adhoc/optics/0422_OPTX/johnson_3df_optx_01_220414.pdf

FWM Impacts on 800GHz-Spaced LAN-WDM8

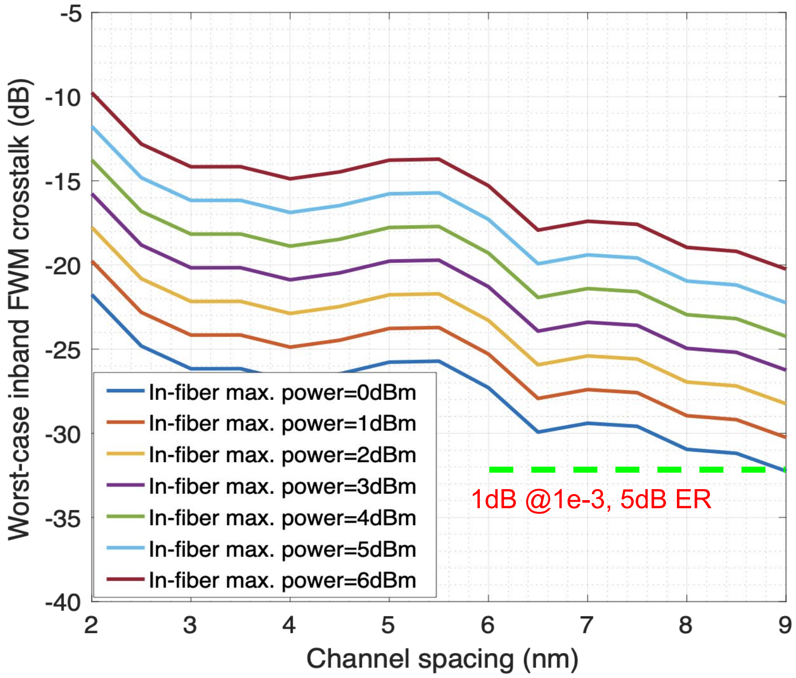
Cooled laser +/-1nm
(Worst frequency spacing ~750GHz)



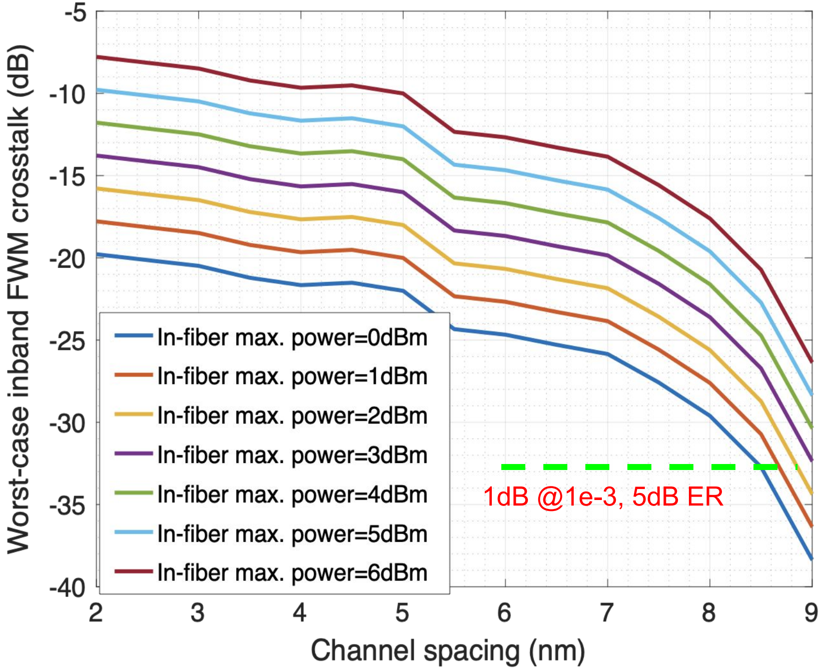
- FWM too strong for LAN-WDM with equal channel spacing
  - Allowable Max Tx power ~0dBm @ 3km

FWM Impacts on WDM8: Other Channel Spacings

Cooled laser +/-1nm, 5km reach



Cooled laser +/-1nm, 10km reach

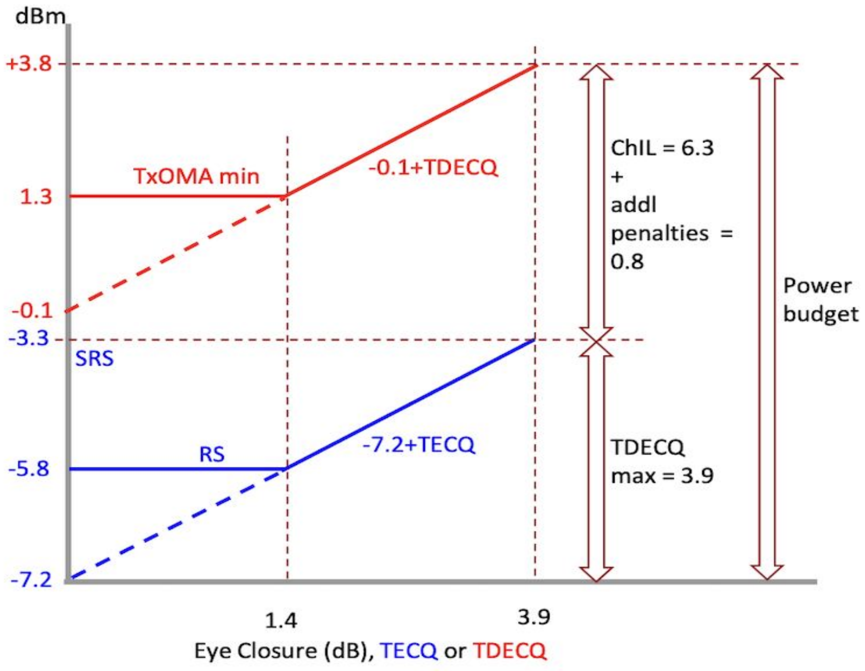


- FWM too strong with equal channel spacing
  - Allowable Max Tx power <0dBm at 5km

How Much Tx Power Needed for 1.6T-10km-WDM8

800G-LR4: Example Link Budget

(source: https://www.ieee802.org/3/df/public/22_03/rodes_3df_01a_220329.pdf)



- ~3.8dBm Tx OMA needed to support 10km
  - Assume 3.9dB TDECQ
- Assume Tx dynamic range (lane to lane) <4dB
  - Max Tx (average) power ~9dBm/lane @ ER=3.5dB
  - Max Tx (average) power ~7.8dBm/lane @ER=5dB

Can FWM be Mitigated for 1.6T-10km-WDM8 ?

- **Polarization interleaving**
  - Allow launch power increase by ~3dB [1]
  - Still not enough to support 10km with <10nm channel spacing
    - At 10nm+ spacing, reach limited by fiber CD[2]
- **Unequal channel spacing**
  - Complex laser frequency distribution design
    - Need to mitigate 84 possible combinations of FWM products
  - Require significantly larger optical bandwidth
    - Optical bandwidth increased by ~70% for the unequal 800G WDM-4 design proposed in [2] as compared to the LAN-WDM4
    - Fiber CD will become the limiting factor

[1] J. Johnson https://www.ieee802.org/3/df/public/adhoc/optics/0422_OPTX/johnson_3df_optx_01_220414.pdf
[2] R. Rodes et al, https://www.ieee802.org/3/df/public/22_03/rodes_3df_01a_220329.pdf

Conclusions

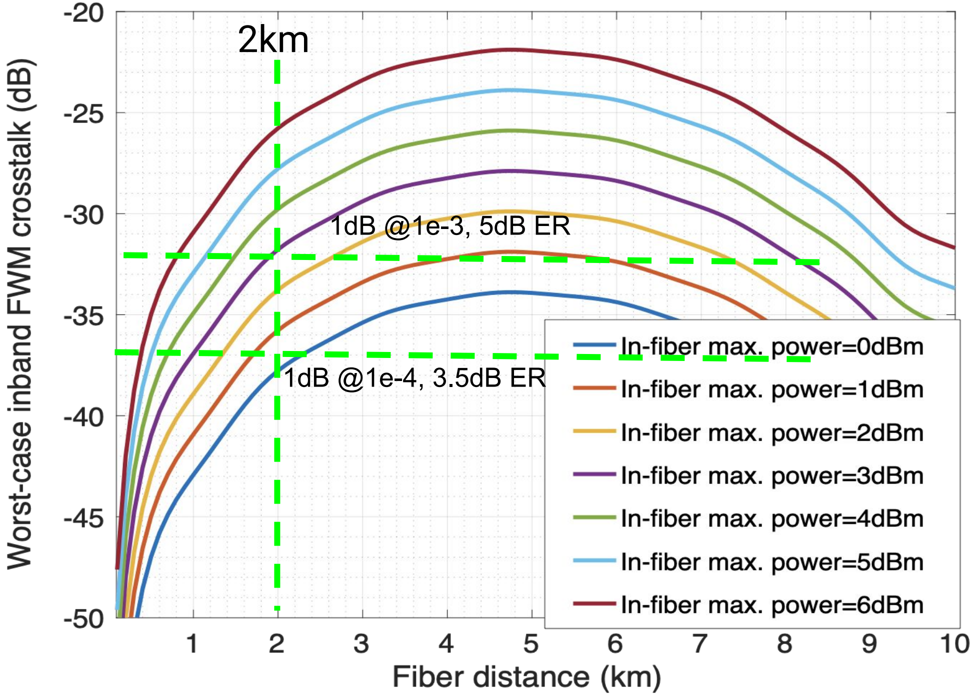
- A theoretical model capable of modeling large frequency spacing FWM proposed and verified by experiments
- FWM caused power penalty for PAM4 quantified through both analytical model and simulation studies
- Impact of FWM effects on both 800G CWDM4 and 1.6T WDM8 investigated
    - 800G CWDM4
        - FWM cannot be neglected for >1km reach
        - But FWM penalty still manageable by
            - Cooled lasers and/or higher modulation ER + higher gain FEC
    - 1.6T WDM8
        - Very challenging to support 10km reach
        - But ~2km reach could be feasible by using polarization interleaving

Appendix

FWM Impacts on 10nm-Spaced WDM8

Incoherent summation of 15 FWM products

Cooled laser +/-3nm, fixed temperature
('worst' channel spacing ~9.2nm)



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