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

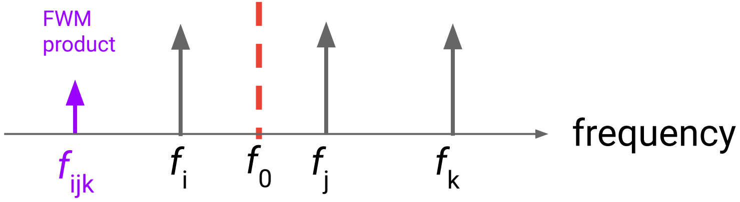
How to calculate FWM phase-matching factor with large frequency spacings

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

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

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

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



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

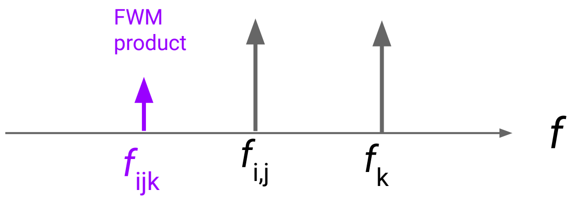
IEEE fiber CD model

Fiber group velocity dispersion coefficients

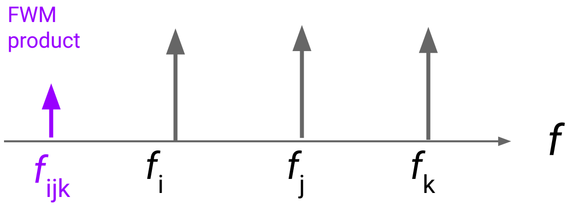
Fiber Zero dispersion frequency (ZDF)

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

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

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

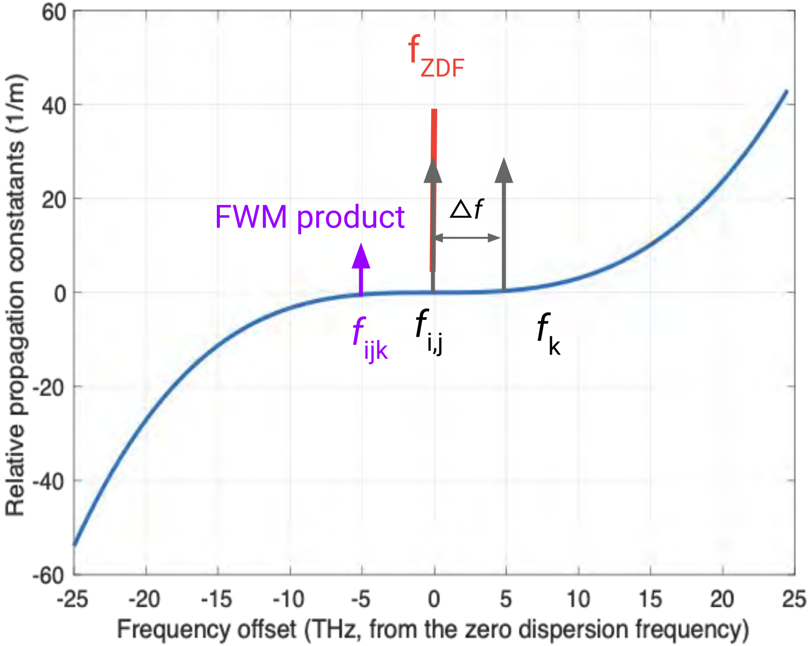
FWM efficiency:

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

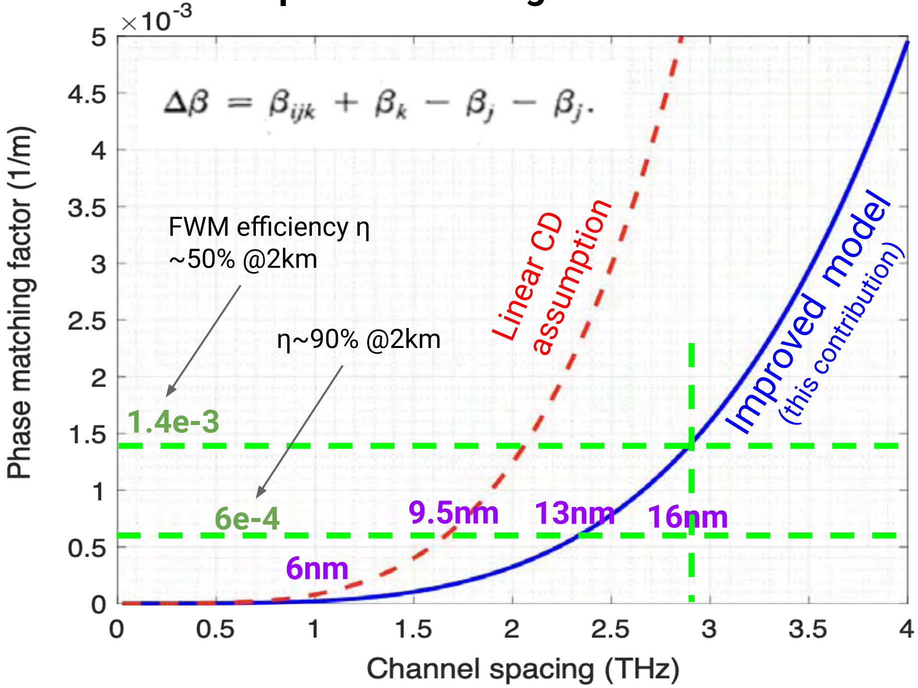
O-Band FWM Worst-Case Phase Matching Bandwidth

Degenerate FWM

Propagation constants (relative to f_{ZDF})



FWM phase matching factor vs Δf

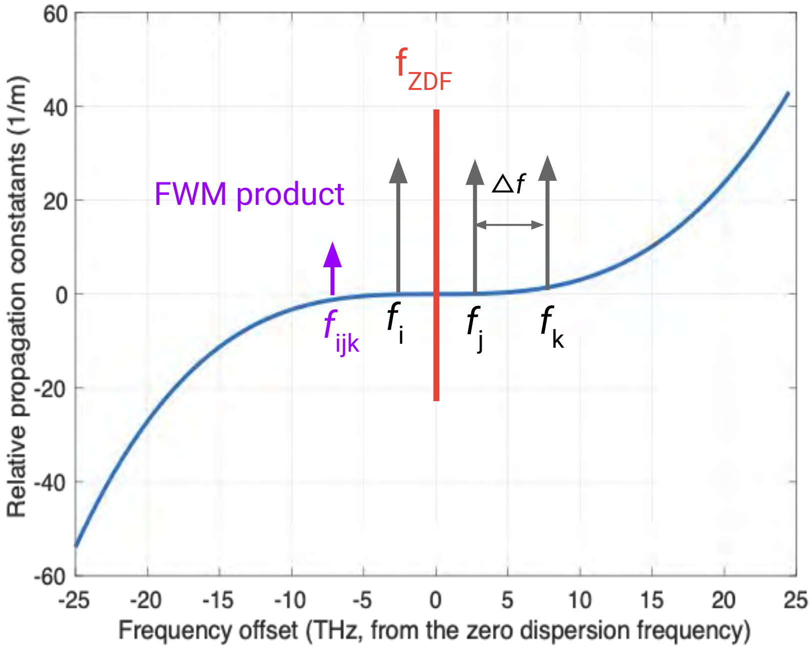


- Worst-case phase matching bandwidth: ~16nm @3dB.2km, ~13nm @0.5dB.2km

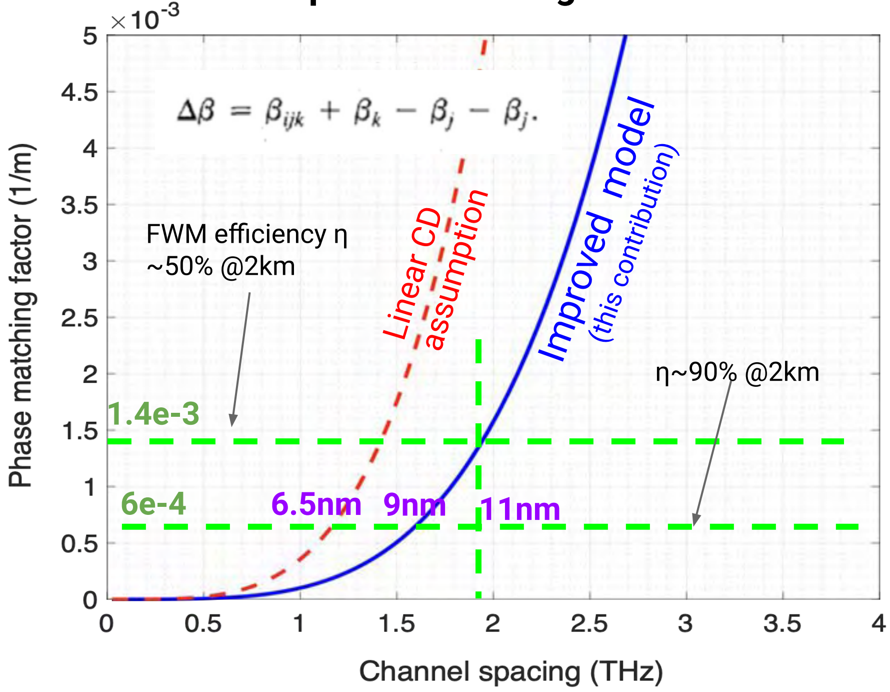
O-Band FWM Worst-Case Phase Matching Bandwidth

Non-degenerate FWM

Propagation constants (relative to f_{ZDF})



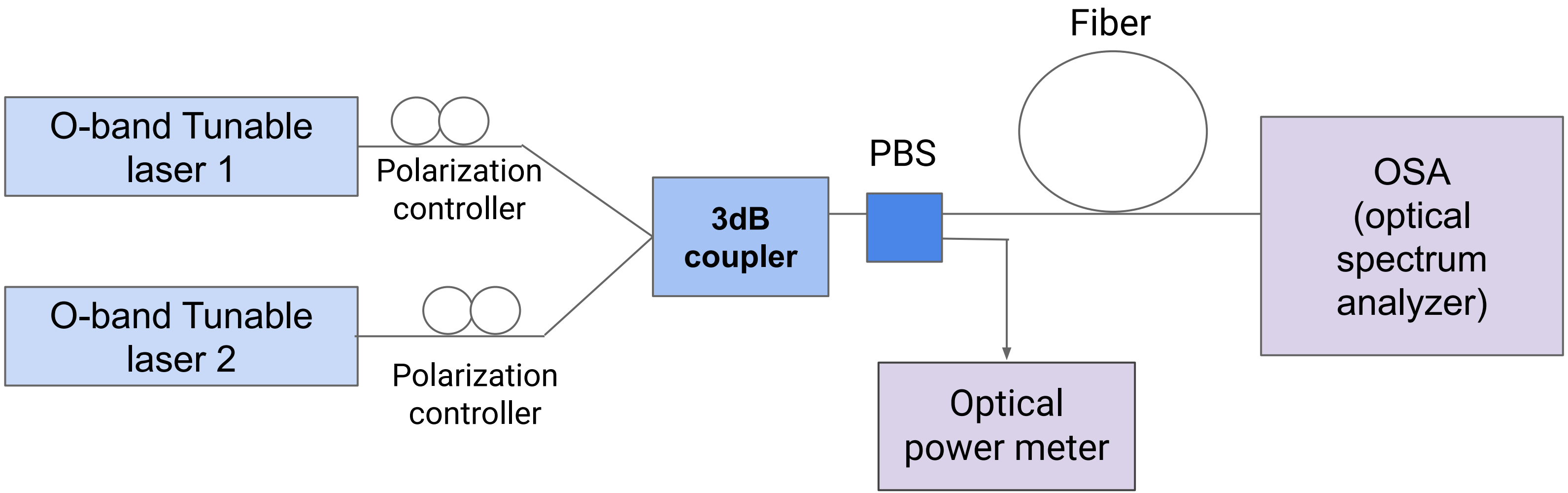
FWM phase matching factor vs $\triangle f$



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

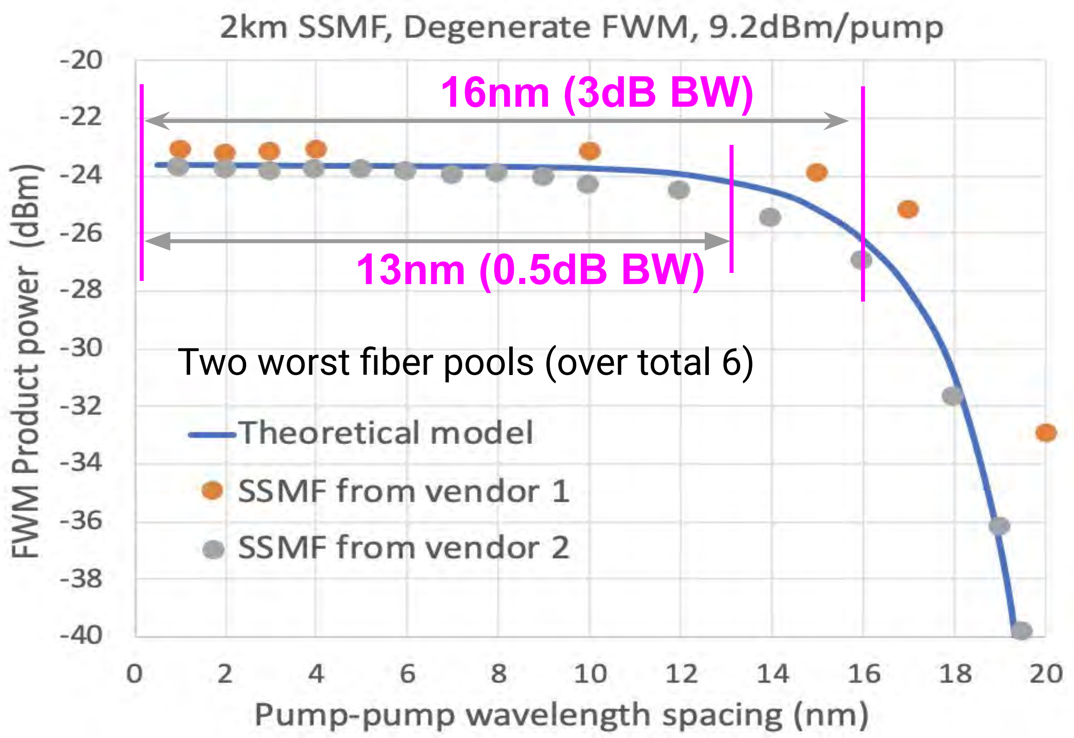
Experiment for FWM Model Verification

Degenerate FWM experimental setup



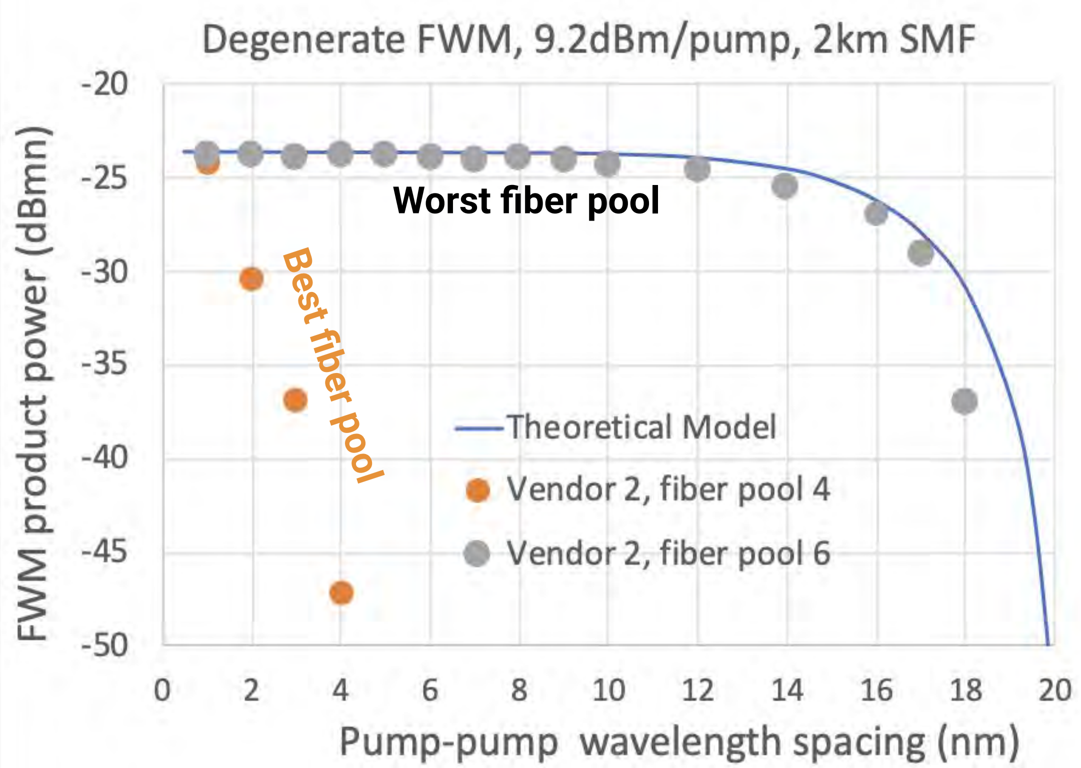
- Step 1: Find and set laser 1 at the Zero dispersion frequency of the fiber under test
- Step 2: Scan the frequency of laser 2 to measure the degenerate FWM product power vs the frequency spacing between the two pumps (laser 1 and laser 2)

Experimental Results: ‘Worst-Case’ Results



- **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

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 a 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

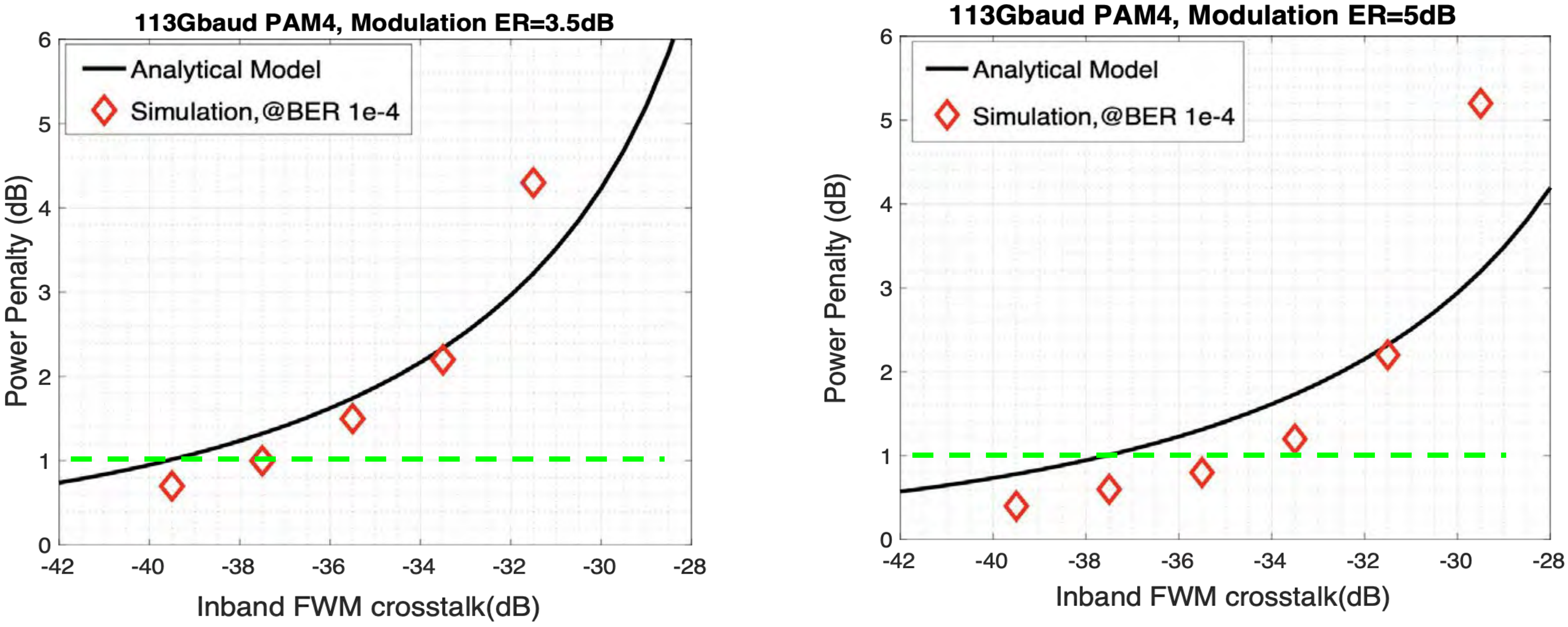
$$\varepsilon_{norm} \approx 2\sqrt{R}[1 + (2m - 3)E]/(E - 1)$$

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

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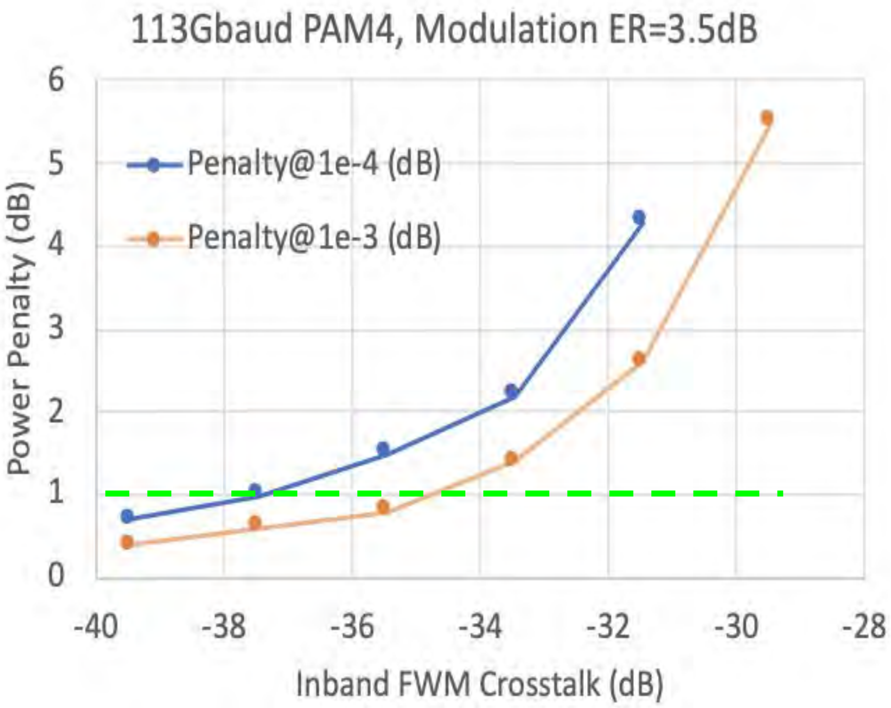
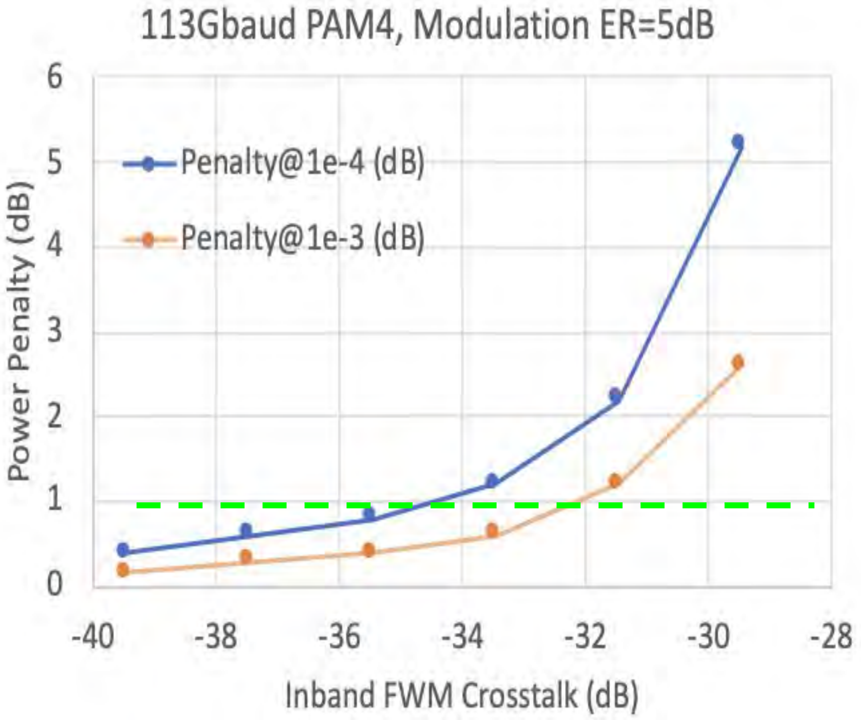
FWM Penalty: BER threshold and Mod. ER Impacts

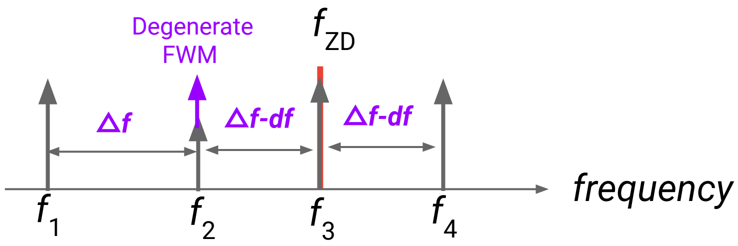
Simulation results, 113Gbaud PAM4





- 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)

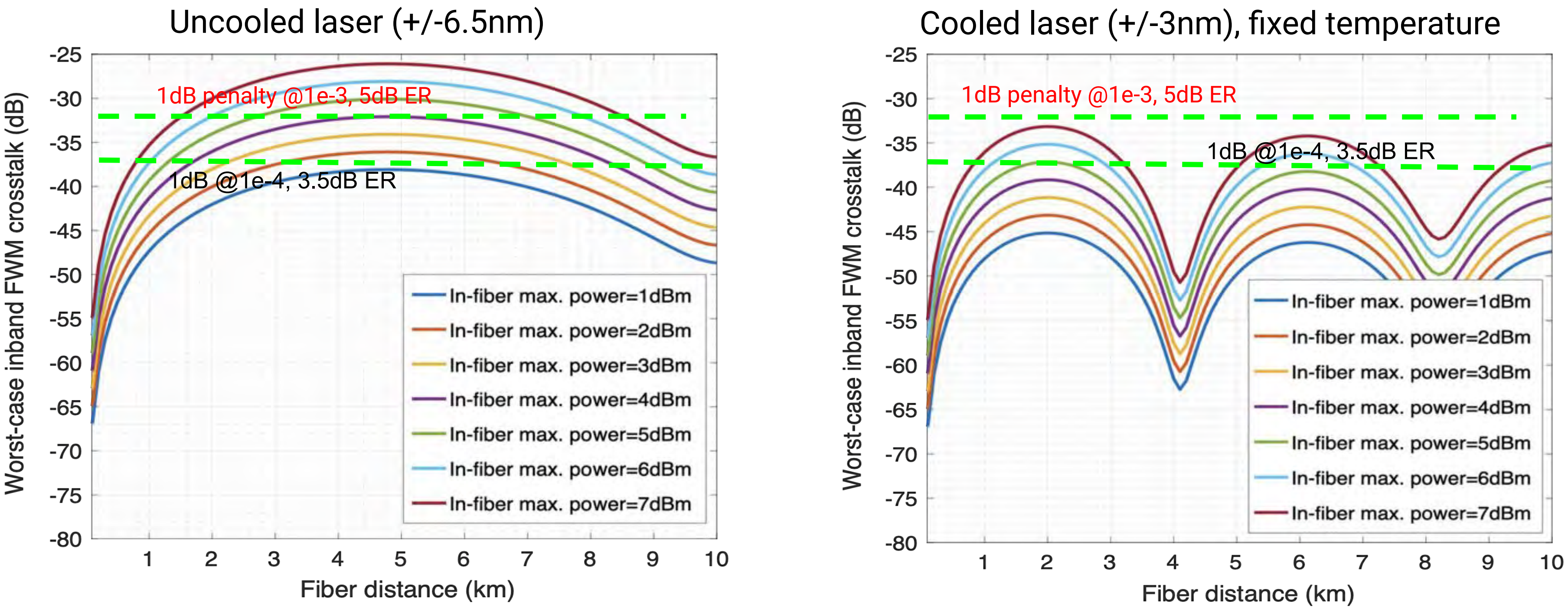
FWM Impacts for 800G (4x200G) IM-DD CWDM4



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

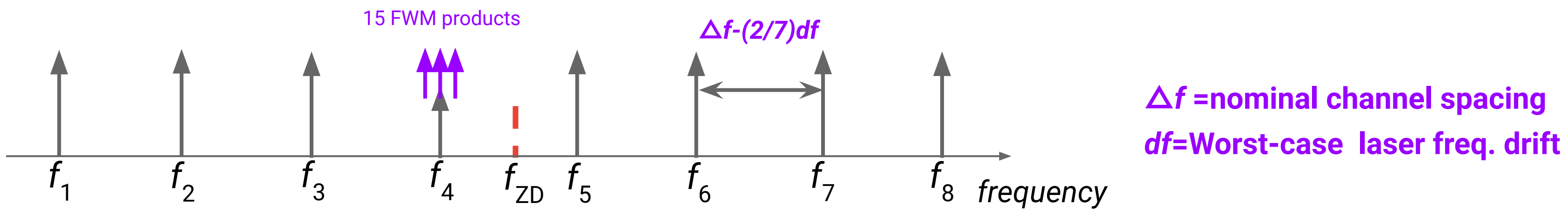
- Based on one of the worst-case frequency distribution scenario
  - Ch. 2 (f_2) as the test channel
  - ZDF $f_{ZD}=f_3$
  - Ch 2, 3 and 4 have equal but narrowest spacing ***$\Delta f\text{-}df$,***
  - Allowing different spacing between channel 1 and 2 (e.g. **Δf**)
- Assume Tx power dynamic range<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 up to Max 5dBm Tx power and 10km reach
    - Cooled lasers or higher modulation ER + higher gain FEC

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

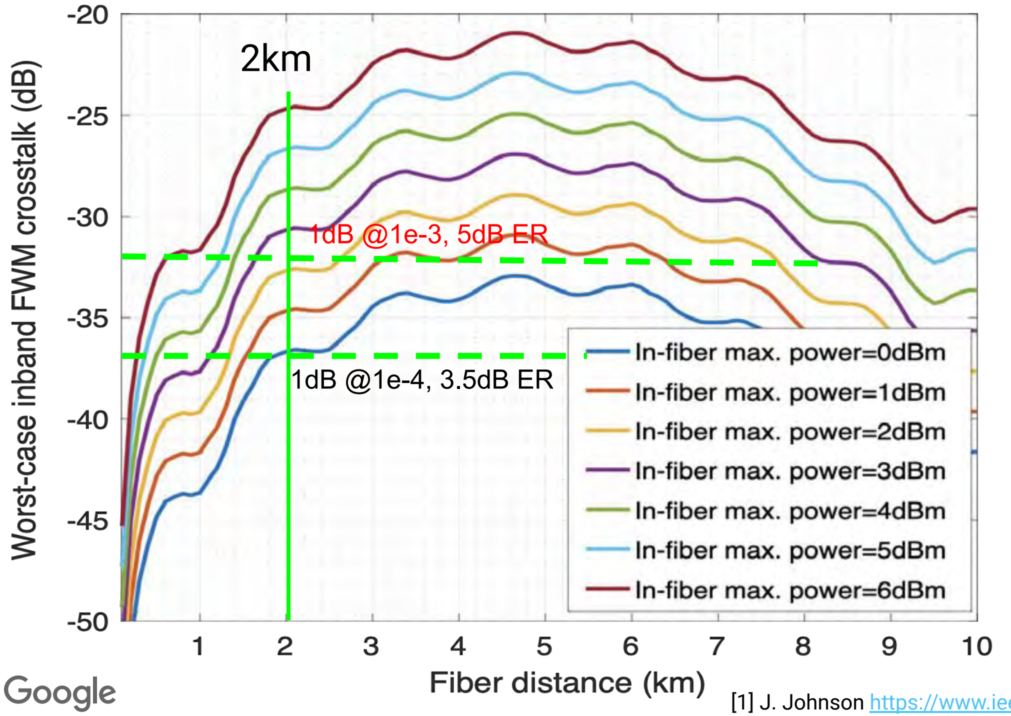


- Based on worst equal channel spacing scenario
  - Ch. 4 (f_4) as the test channel
  - Fiber ZDF in the middle of the 8 frequencies
  - Ch spacing=***Δf-(2/7)df*** , the narrowest equal channel spacing possible
- Assume Tx power dynamic range<4dB (lane to lane)
  - Test channel lowest power
  - Other 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 ?

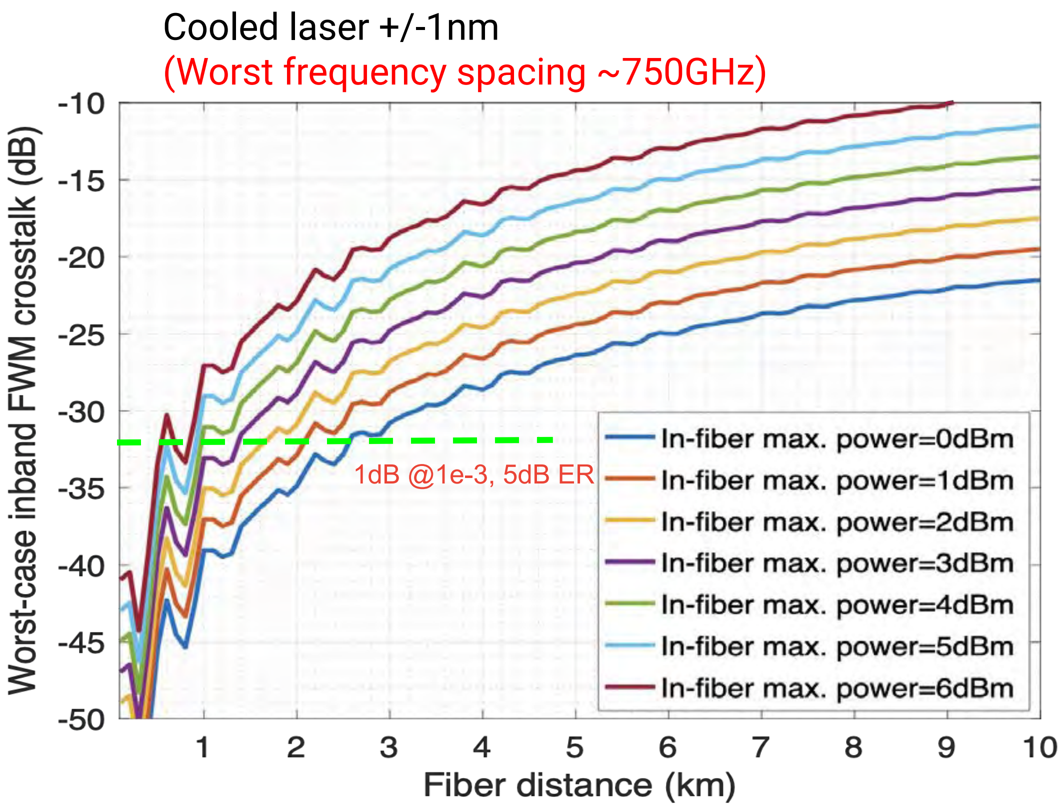
Cooled laser +/-3nm, fixed temperature
(worst equal wavelength spacing ~9.2nm)



- ***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)

[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



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

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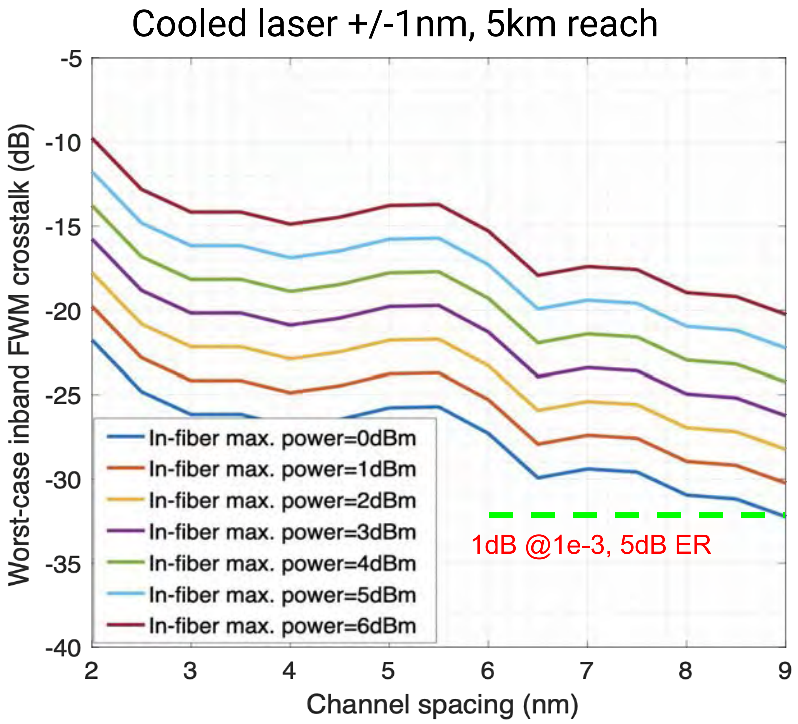
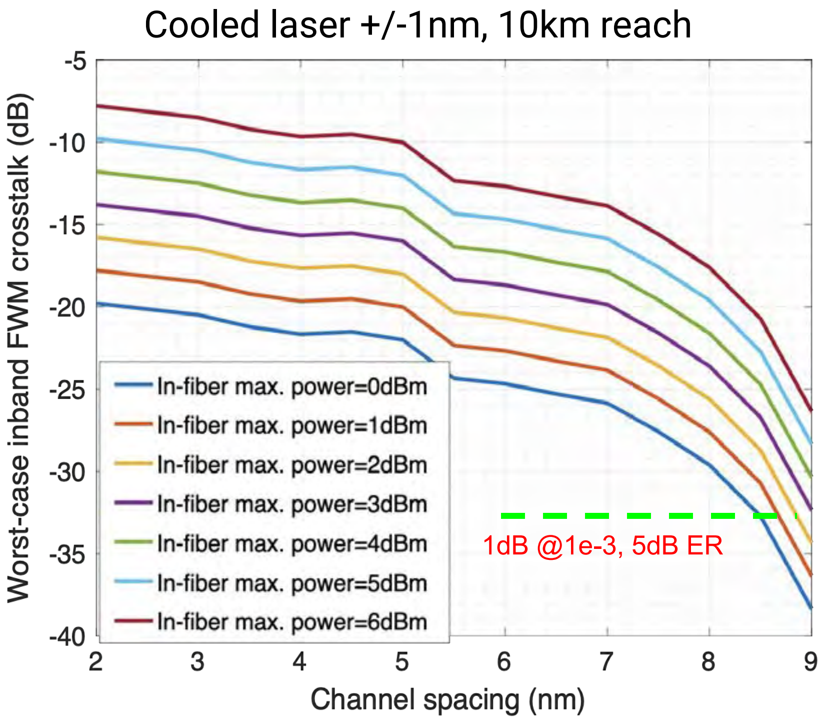
FWM Impacts on WDM8: Other Channel Spacings



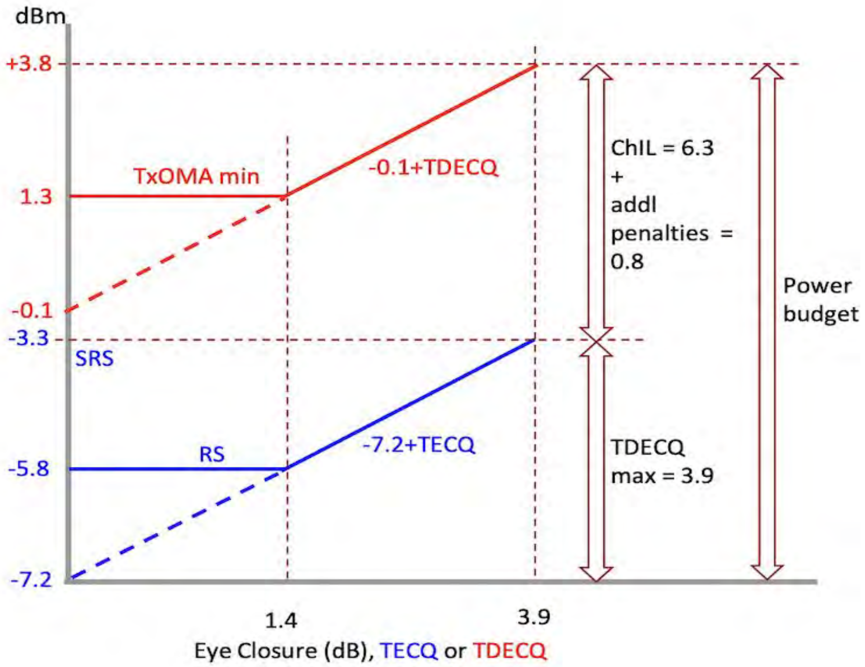


- FWM too strong with equal channel spacing
  - Allowable Max Tx power <0dBm at 5km

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

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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 manageable up to 5dBm Max Tx power
      - Cooled lasers 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)