Four-wave mixing in O-band for 100G EPON

John Johnson

IEEE 802.3ca Conference Call
July 6, 2016

Four-wave mixing in O-band

- Broadcom proposed keeping all upstream and downstream wavelengths in O-band in order to enable NRZ modulation format and avoid the need for dispersion compensation.
  - See May 2016 contribution: johnson_3ca_1b_0516
- FWM in the transmission fiber was brought up as a possible reason to avoid WDM in O-band for NG-EPON
  - FWM is most efficient when dispersion is zero (~1300-1324nm)
  - PON launch power is very high, and FWM impairment ~ P^2
  - Existing 100G CWDM and LWDM point-to-point transceivers are not as susceptible because they use much lower optical power.
- In this contribution, using established analytical formulas, we look at the potential for FWM impairments in 100G-EPON around the dispersion zero in O-band.

BROADCOM

Four-wave mixing (non-degenerate)

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

FWM power:

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

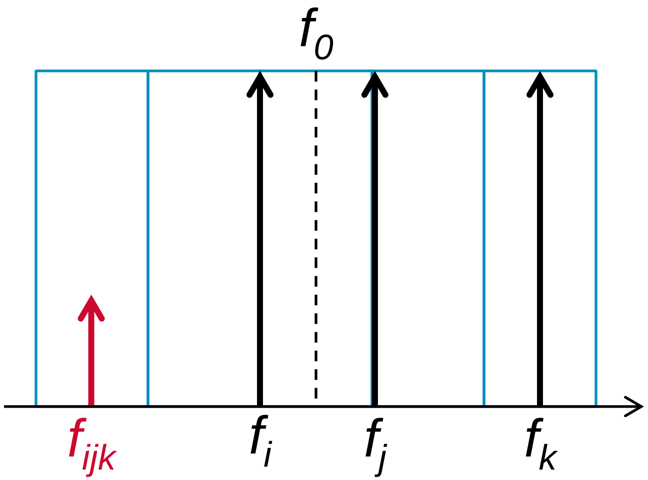
FWM efficiency:

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

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

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

D(λ) is the dispersion at λ and *dD/dλ* is the dispersion slope



Co-polarization is assumed.

FWM conversion efficiency is maximum for phase-matched condition, $\Delta\beta = 0$.

This occurs when the zero dispersion frequency, f_0, is centered between two of the input frequencies.

$D_{ijk} = 6$ for non-degenerate mixing (3 distinct inputs)

BROADCOM

Four-wave mixing (partially-degenerate)

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

FWM power:

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

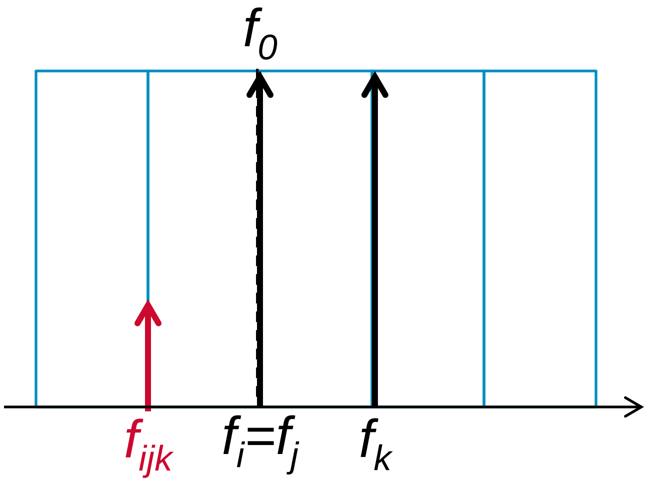
FWM efficiency:

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

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

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

D(λ) is the dispersion at λ and *dD/dλ* is the dispersion slope



Co-polarization is assumed.

FWM conversion efficiency is maximum for phase-matched condition, $\Delta\beta = 0$.

This occurs when the zero dispersion frequency, $f_0 = f_i$ or f_k.

$D_{ijk} = 3$ for partially-degenerate mixing (2 distinct inputs)

BROADCOM

Fiber properties

For standard transmission fiber, the dispersion zero for any fiber segment can range between ~1300nm and 1324nm. The dispersion slope at 1310nm is ~0.093 ps/nm^2 km. Propagation loss at 1310nm ~ 0.42 dB/km.

For all input powers = *P*, the FWM power

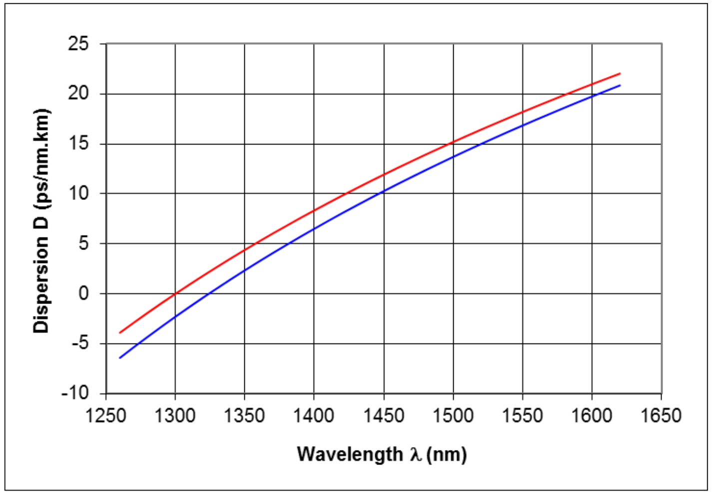
$$\frac{P_{ijk}}{P} = \left(\frac{D_{ijk}\gamma L}{3}\right)^2 P^2$$

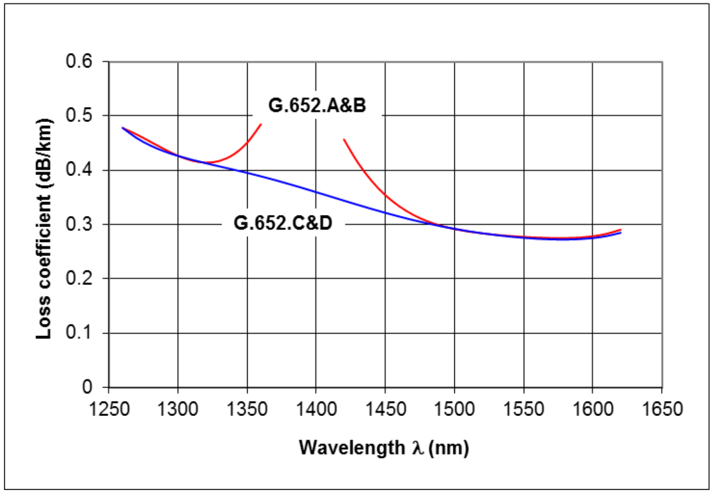
For 22km of standard transmission fiber and non-degenerate FWM*, the non-linear coefficient for power is:

$$\left(\frac{D_{ijk}\gamma L}{3}\right)^2 \approx 0.01\, mW^{-2}$$

This value is for C-band. It is slightly higher in O-band (smaller MFD), but it's close enough for our purposes.

*F. Forghieri, et. al., "Fiber non-linearities and their impact on transmission systems," in Optical Fiber Telecomunications IIIA, Academic Press, 1997.

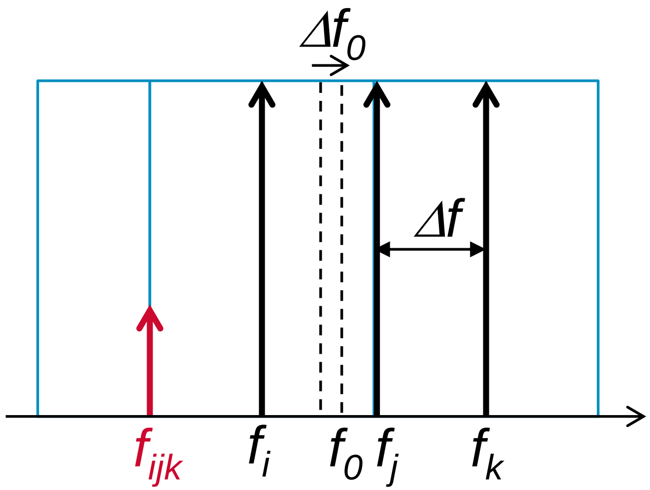


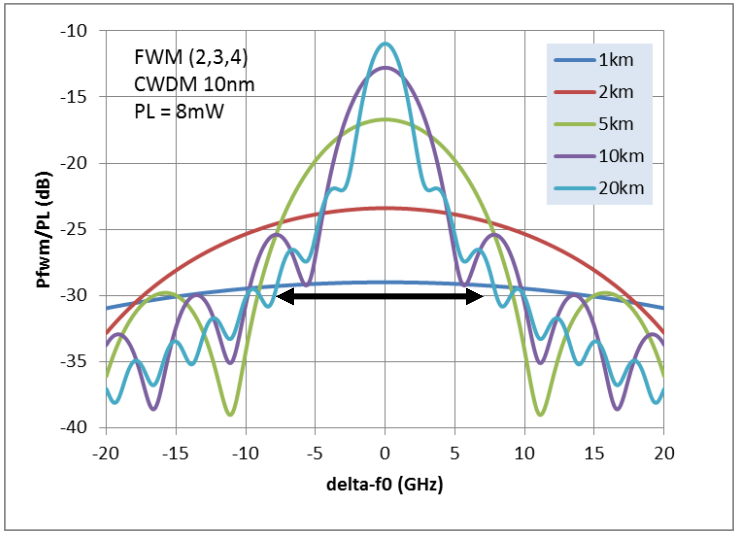


FWM power penalty

- For channels equally spaced in frequency, the FWM tone interferes *coherently* with the target channel
  - The actual frequency spacing must be equal to within the modulation bandwidth, R, for the beating to be in-band of the receiver.
  - For P_{FWM}/P_L = -20dB the ratio of electric fields is 10%, leading to noise on the one rail equal to 20% of the eye opening.
  - 20% eye closure results in roughly ~1dB power penalty
  - For P_{FWM}/P_L < -30dB the ratio of electric fields is 3.2%, resulting in < ~0.3dB power penalty which is manageable.
- For channels spaced equally in wavelength the frequencies are not exactly equal but for 10nm grid they are within ~25GHz.
  - Including the proposed laser wavelength tolerance of ~ ± 1nm, the frequencies can become equally spaced in frequency.
- If the FWM interference is more than 2R from the signal then the beat tones will be out of band of the receiver and the only penalty is due to power depletion of the source channels.
  - For 1dB penalty (20% signal depletion), P_{FWM}/P_L must be > -7dB, so this is not a major penalty.

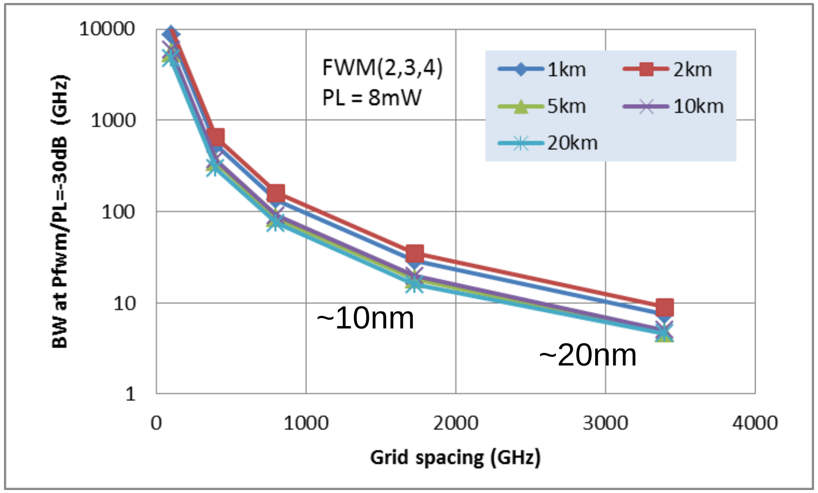
Effect of phase mismatch (non-degenerate)

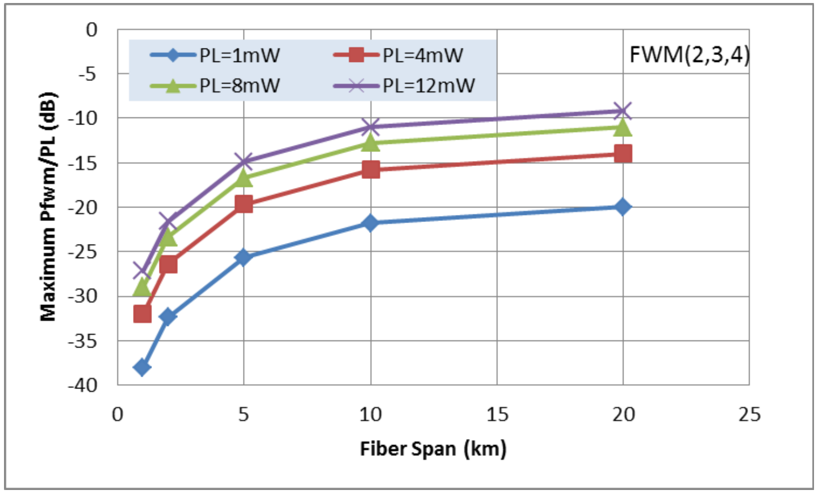




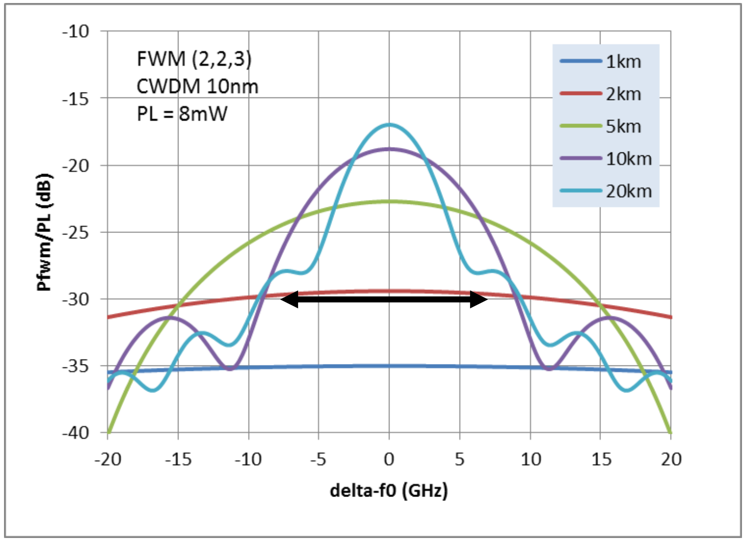
Peak FWM power increases for longer fiber spans and higher launch power, independent of grid.

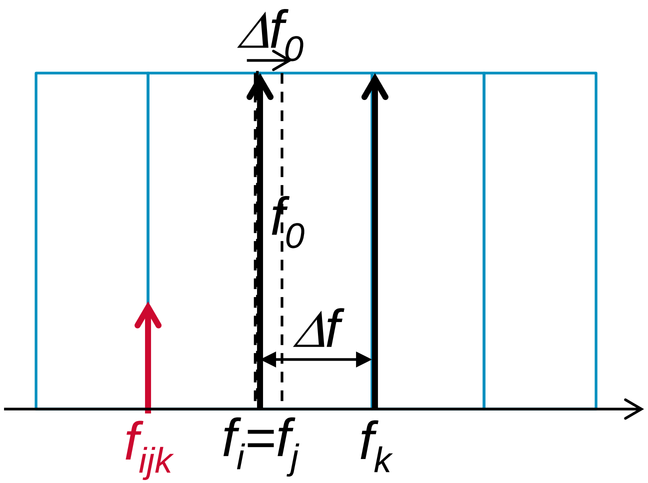
The phase-matching BW drops drastically as channel spacing and fiber span increase.



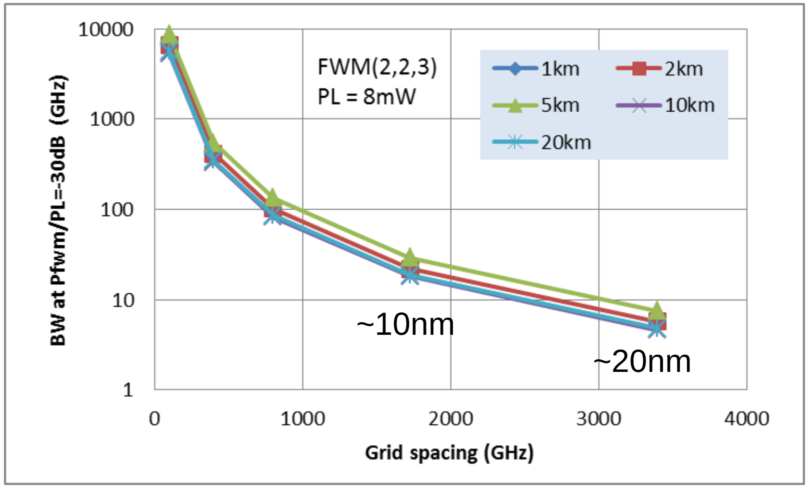


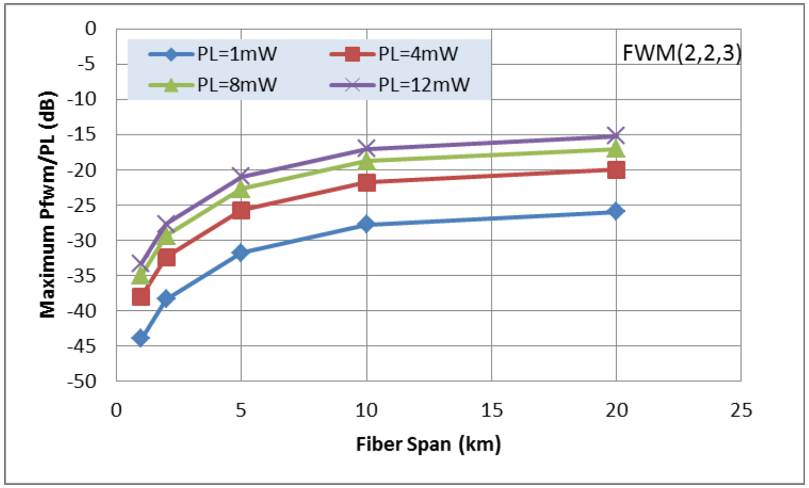
Effect of phase mismatch (partially degenerate)





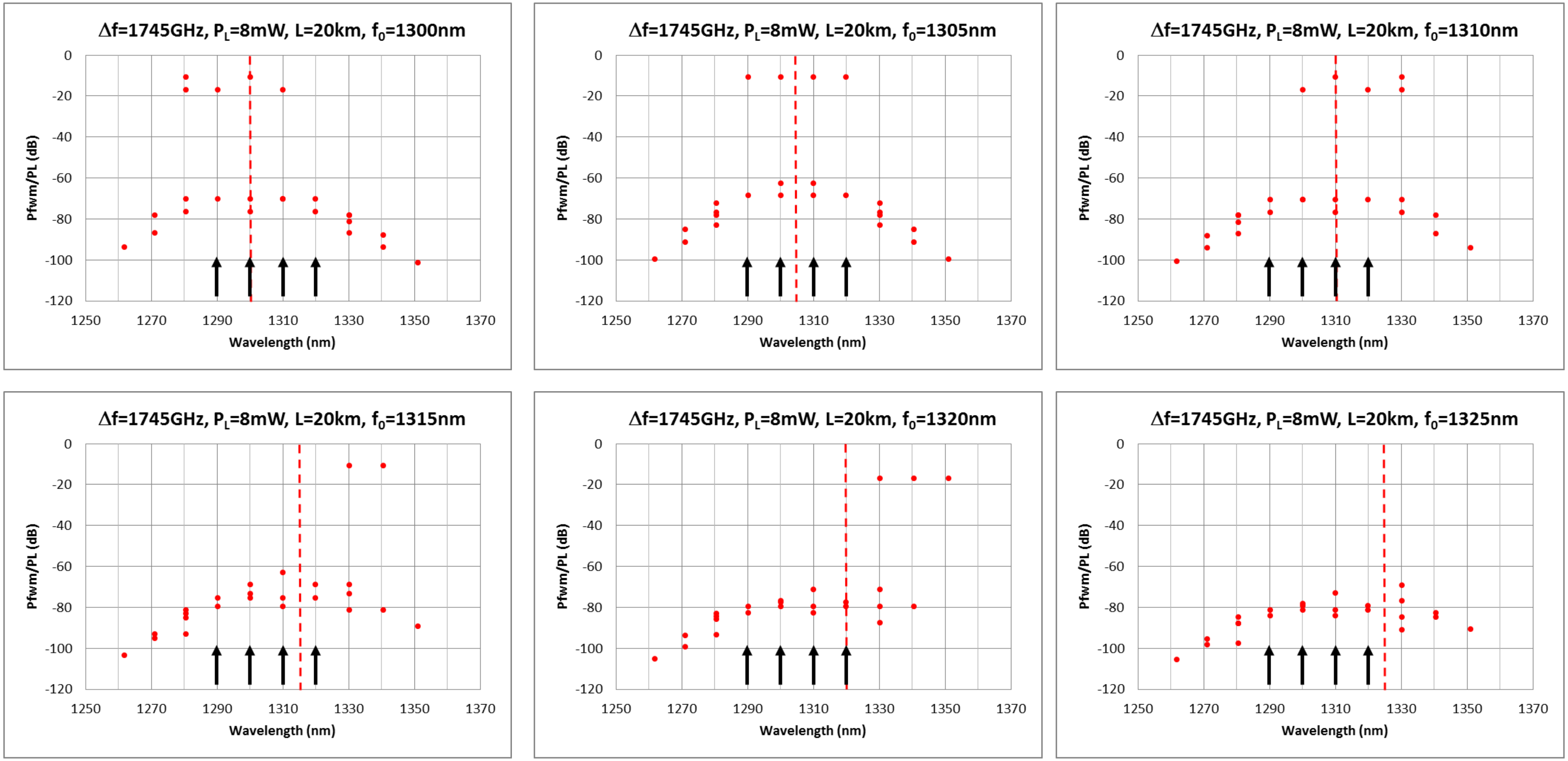
Same behavior as the non-degenerate FWM, but the peak FWM power is 6dB lower (4x smaller D_{ijk}^2).





BROADCOM

Four channel 1745 GHz (~10nm) CWDM example



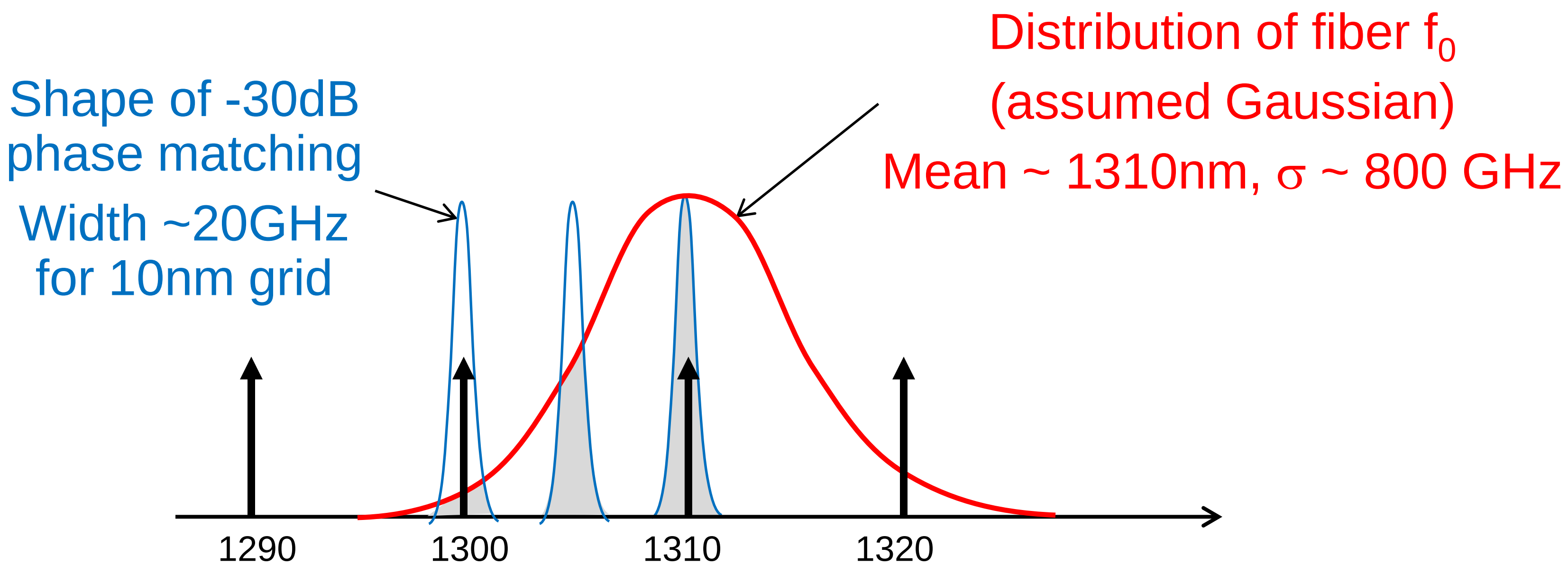
4 channels generate 24 distinct FWM tones. Most are not phase matched.

Here, the 6 precisely phase matched conditions for 1300nm < f_0 < 1325nm are shown.

Inclusion of 10G-EPON 1270nm channel would generate additional products.

BROADCOM

Likelihood of phase matching



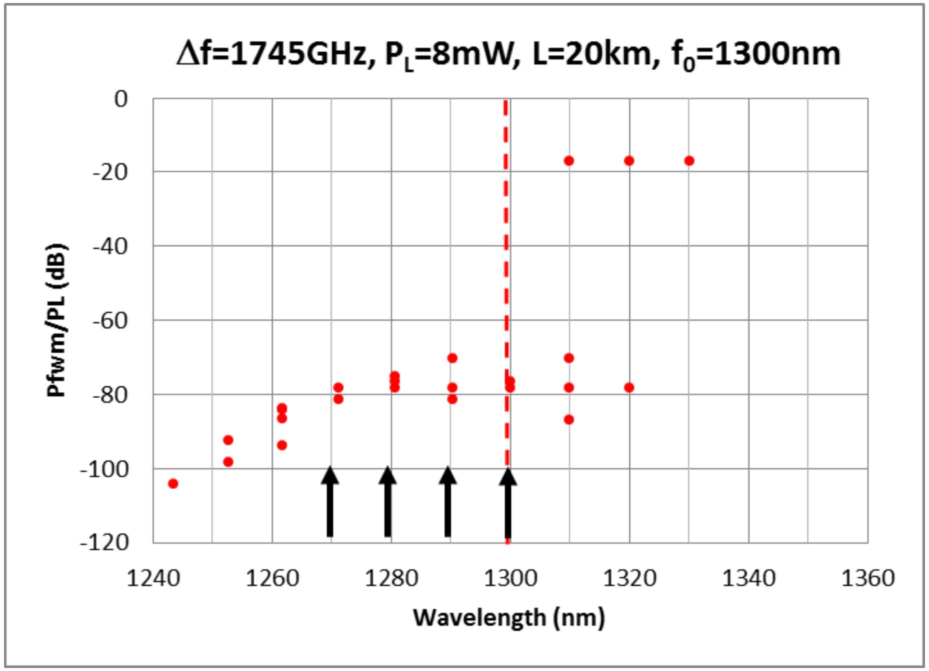
Since f0 is not known on any given fiber it's not possible *a priori* to avoid situations where precise phase matching will cause an impairment – there is always a finite probability of achieving phase matching.

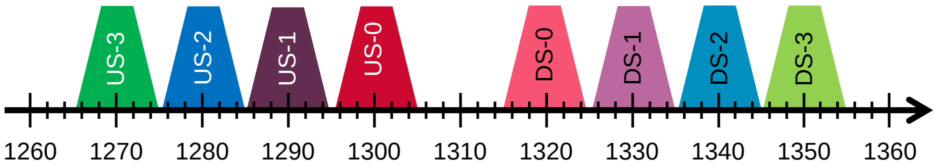
If channels are in the dispersion zero range, f_0 must align to laser frequency (or average of two frequencies) within the -30dB BW to cause impairment.

Likelihood of that happening on any given piece of fiber is the overlap of the phase matching BW and the probability distribution for f_0. This is order ~1% for 10nm grid, which is still too high to be ignored.

BROADCOM

10nm CWDM US wavelength plan



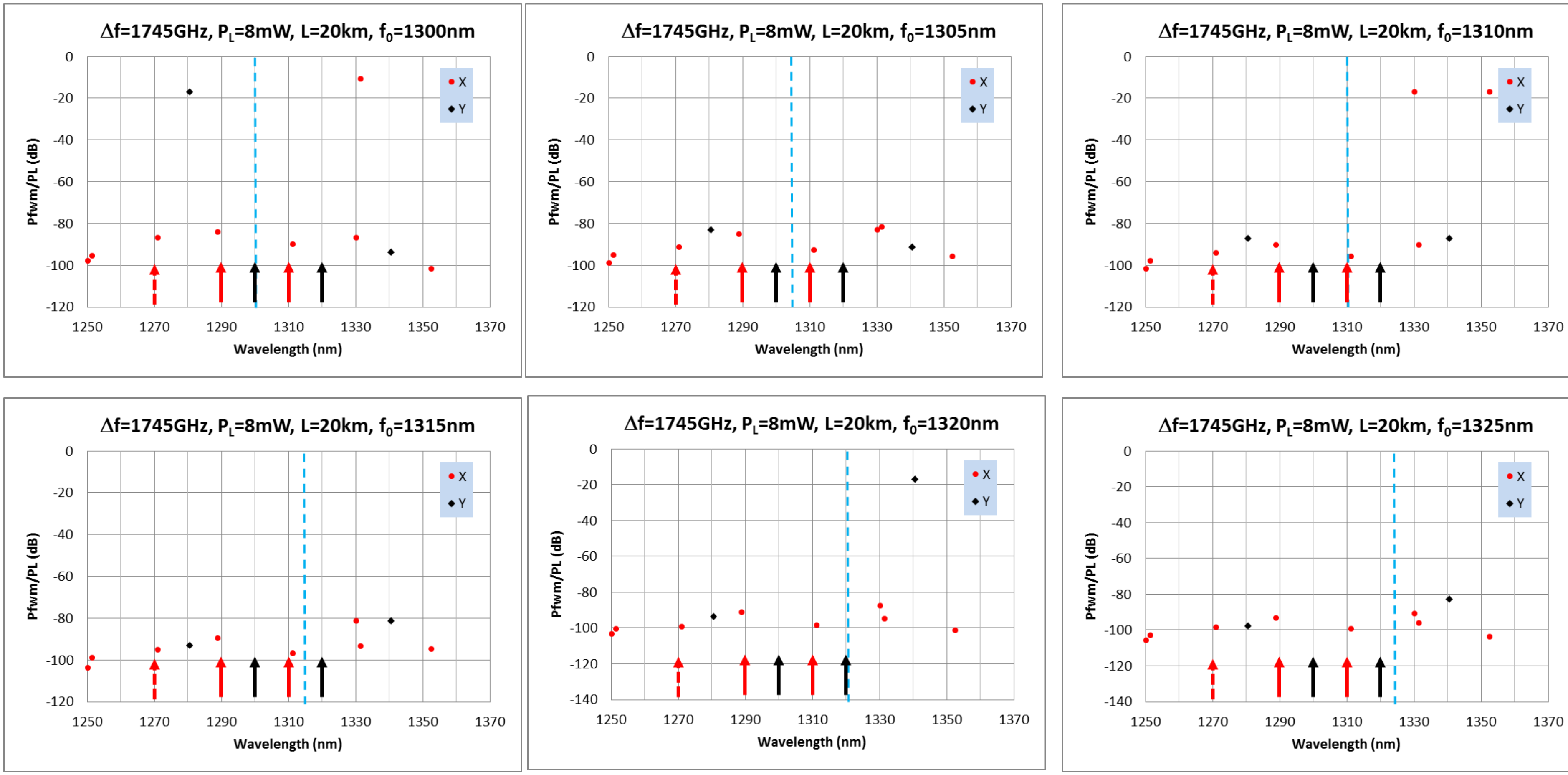


Choosing a wavelength plan lying outside of the zero dispersion window eliminates FWM impairments altogether.

For the 100G upstream wavelength plan with 10nm grid proposed in johnson_3ca_1b_0516, all of the phase matched FWM products are out of band of the upstream channels.

This wavelength plan maintains the widest possible channel spacing at the expense of giving up WDM 10G coexistence for networks with symmetric 100G ONUs.

Polarization interleaving



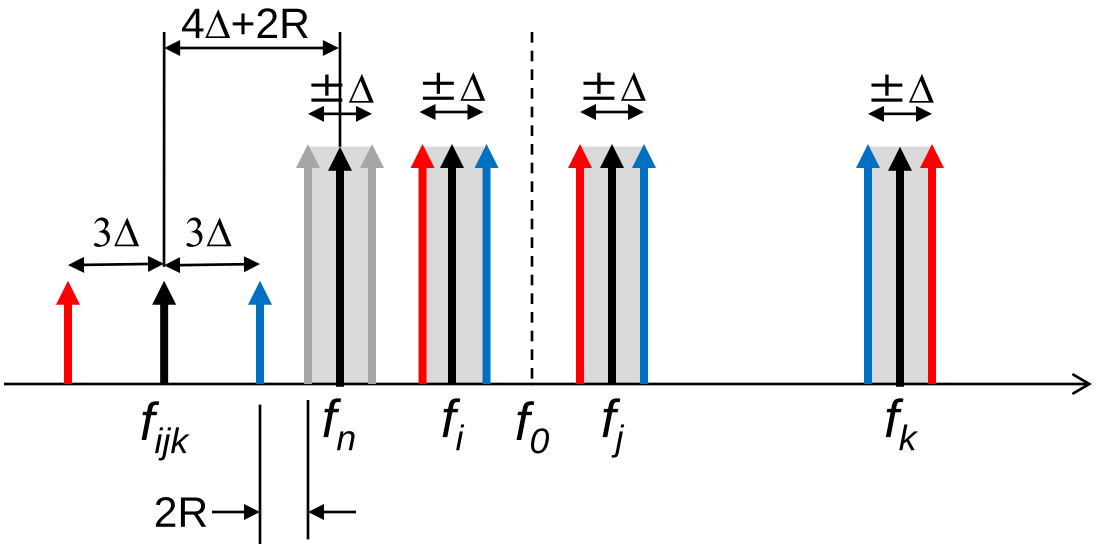
Interleaving polarization between CWDM channels effectively pushes any phase matched tones out of the US CWDM band. However PMD in the transmission fiber prevents maintaining the orthogonal polarizations. While not completely effective, it will reduce the FWM impairment somewhat since channels are partially orthogonal for first few kilometers.

BROADCOM

Uneven channel spacing

- Uneven channel spacing has been used in DWDM systems to reduce the accumulation of FWM but leads to less efficient use of fiber spectrum, which is very limited in O-band for wider grids.
- To prevent in-band interference the difference between any pair of channel <u>spacings</u> must be greater than 4Δ+2R, where R = the modulation bandwidth and Δ = the laser frequency accuracy.
  - For 25 Gb/s NRZ, R ~ 25 GHz
  - In johnson_3ca_1b_0516, Δ = 1nm was proposed to reduce laser operating temperature range and manufacturing cost so 4Δ+2R ~ 4.5nm.
  - Adding >4.5nm to the channel spacings makes it impossible to keep both US and DS channels in O-band.
- In order to make unequal channel spacing practical, tighter laser frequency accuracy is required, possibly at the expense of laser wavelength yield.
  - For future study.

Unequal channel spacing tolerance



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

$f_n - f_{ijk} = (f_k - f_j) - (f_i - f_n) > 4\Delta + 2R$

The frequency range of the FWM products is 3x the frequency tolerance of the signals.

The difference between any two channel spacings must be > 4Δ+2R to prevent coherent interference under worst case alignment

Factors reducing probability or severity of FWM impairments for channels in the zero range

- The phase matching bandwidth for 10nm grid is very narrow, making maximum FWM efficiency an unlikely event in any given path.
  - Operators won't accept any finite probability of FWM impairment unless that impairment in the worst case is small and accounted for in the link budget.
  - Cooled transmitters could be adjusted to avoid precise phase matching, but requires calibration/setup of the ONU wavelengths from the OLT.
  - If DS channels are located above 1330nm the dispersion zero is out of band so there is no phase matching and minimal FWM impairment.
- The PON splitter has high loss, so FWM is only effective between the transmitter and the splitter.
  - In most cases the splitter is close to ONU so US FWM will usually be low. However, the standard must cover "homerun" installations with splitter near OLT.
- These simulations assume the same f_0 along the entire span, co-polarization and cw signals (no modulation or chirp)
  - In reality the path is made up of several dissimilar pieces of fiber which reduces the maximum FWM efficiency by averaging over shorter spans with different f_0.
  - In practice PMD will effectively scramble the relative polarizations of each signal reducing the average (but not peak) efficiency of FWM generation. Interleaved launch may help.
  - Modulation reduces average overlap of "ones" in time and chirp reduces the overlap of frequencies in time reducing the worst case FWM impairment.
- Including these effects may bring the worst case impairment to manageable levels.
  - More rigorous simulation is needed to quantify these effects.

BROADCOM

Thank You