FWM Simulations in O-band

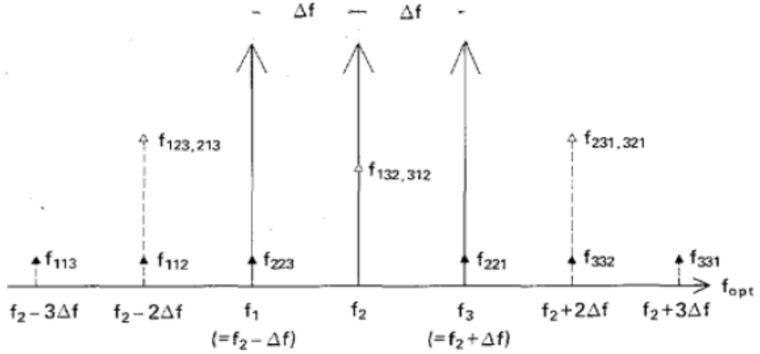
Dora van Veen & Vincent Houtsma, Bell Labs

dora.van_veen@nokia-bell-labs.com, vincent.houtsma@nokia-bell-labs.com,

Introduction

- FWM is a nonlinear process in which three waves of frequencies f_i , f_j , and f_k: (k # i , j) interact through the third-order electric susceptibility of the optical fiber to generate a fourth wave of frequency $f_{ijk}=f_i+f_j-f_k$
- For example 3 co-propagating waves generate 9 new waves (and 4 generate 24 new waves, etc.)
- The mixing products act as crosstalk (in band) and deplete power from the 3 main optical carriers

from [1] Chibata et al.



# λ's	3	4	6	8
# FWM products	9	24	90	224

Model of FWM around zero-dispersion wavelength

Taylor expansion around f_0 of propagation constant $\beta(f)$:

$$\beta(f) = \beta(f_0) + (f - f_0)\frac{\delta\beta}{\delta f}(f_0) + \frac{1}{2}(f - f_0)^2 \frac{\lambda^2\pi}{c} D_C(f_0) + (f - f_0)^3 \frac{\lambda^4\pi}{3c^2}\left\{\frac{2}{\lambda} D_C(f_0) + \frac{\delta D_C}{\delta\lambda}(f_0)\right\}$$

When f_0 is chosen at zero-dispersion wavelength the phase-mismatching $\Delta\beta$ is:

$$\Delta\beta = \beta(f_i) + \beta(f_j) - \beta(f_k) - \beta(f_F)$$

$$\Delta\beta = -\frac{\lambda^4\pi}{c^2}\frac{\delta D_C}{\delta\lambda}\{(f_i - f_0) + (f_j - f_0)\} \cdot (f_i - f_k)(f_j - f_k)$$

FWM efficiency η:

See also [2] Inoue et al. for further details

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

Satisfying phase-matching conditions around zero-dispersion wavelength

- Partially degenerate: one of wavelength channels on zero-dispersion wavelength (ZDW) with $f_0=f_i=f_j$ making $\Delta\beta=0$

- Completely non-degenerate case: Zero-dispersion wavelength in between two wavelengths:
  - From model: Zero-dispersion wavelength exactly in between two wavelength with $D_C(f0)=0$ and $(f_i-f_0)=-(f_j-f_0)$ making $\Delta\beta=0$ independent of grid spacing
  - More practical case: Zero-dispersion wavelength in between two wavelengths, positive and negative D_C in 2^{nd} order terms of expansion cancel each other (yellow-highlight on previous slide) also satisfying $\Delta\beta=0$

Simulations

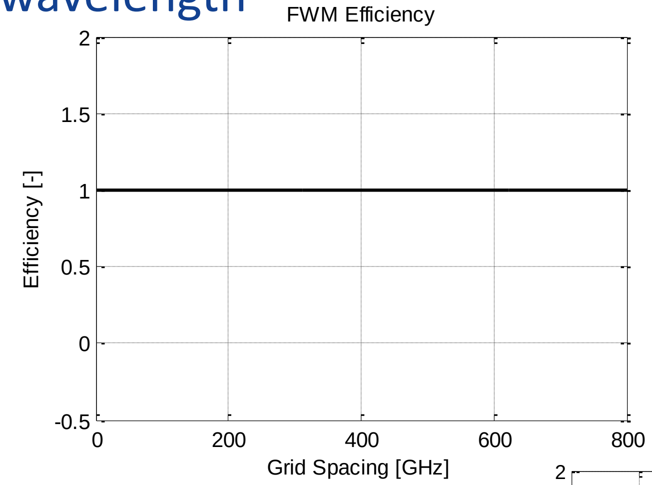
Two types of cases are simulated :

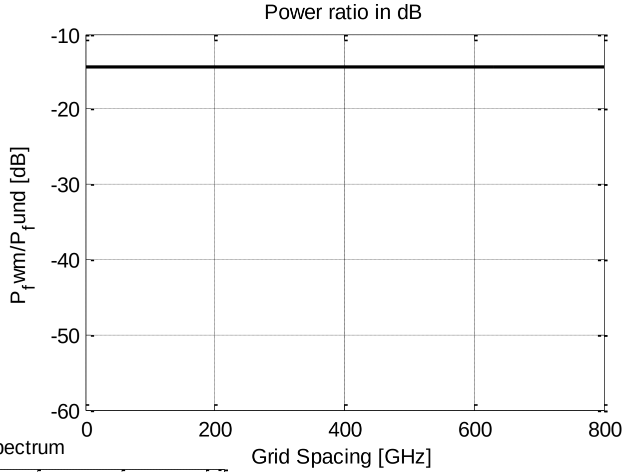
- Channels symmetric around the zero dispersion wavelength
- All channels on one side of the zero dispersion wavelength

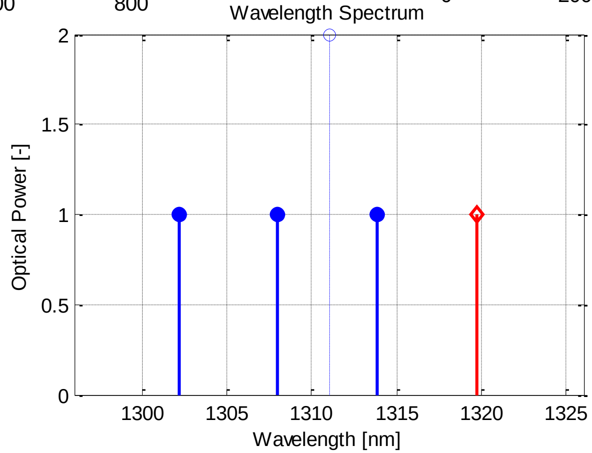
Simulation parameters

zero dispersion wavelength =1311 nm
+9 dBm optical transmission power
10 km of total fiber length
Wavelength grid spacing is varied

Simulation Case 1 : Wavelengths exactly symmetric around zero dispersion wavelength

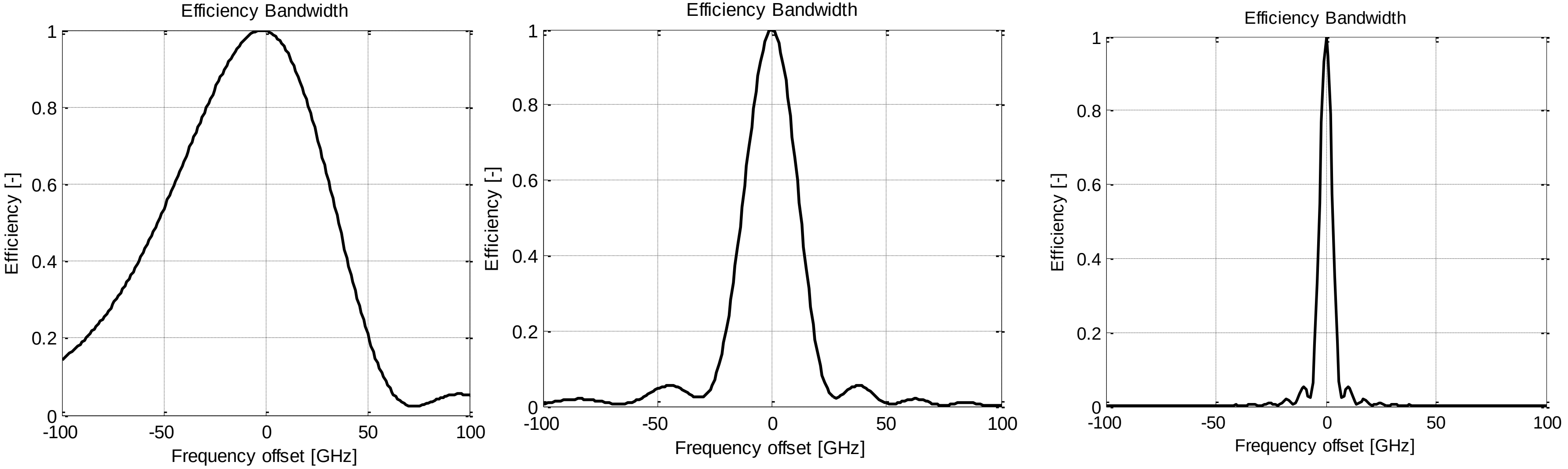






Simulation case 2 : Almost symmetric around zero dispersion wavelength

- Bandwidth of phase matching condition depends on grid spacing



500 GHz spacing   1000 GHz spacing   2000 GHz spacing

- Efficiency bandwidth versus frequency offset (from symmetrical around zero dispersion wavelength)

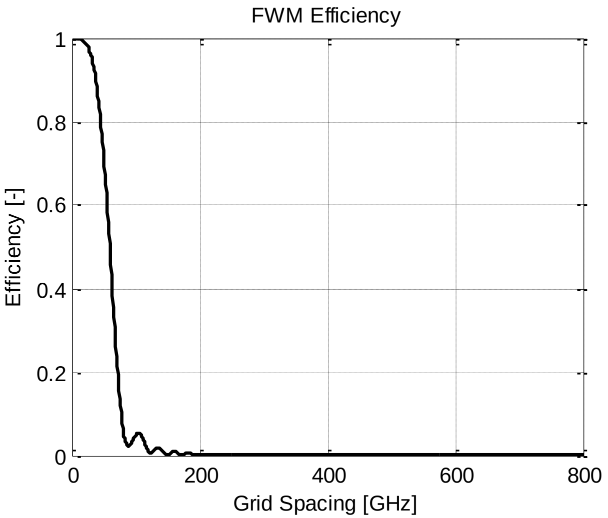
Simulation case 2 : Almost symmetric around zero dispersion wavelength

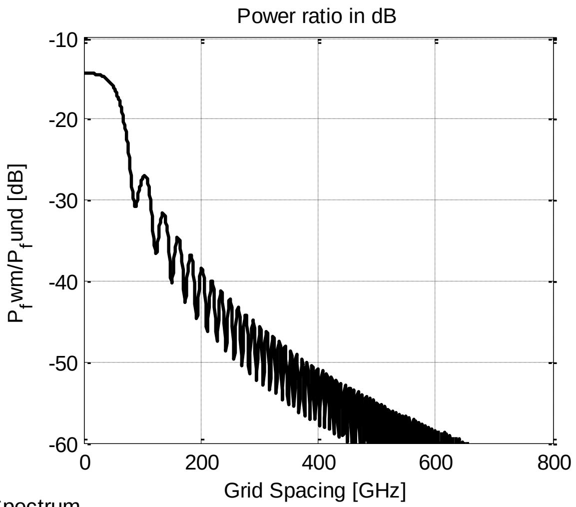
- If channels are exactly symmetric around zero dispersion, phase matching condition is always achieved independent of grid spacing

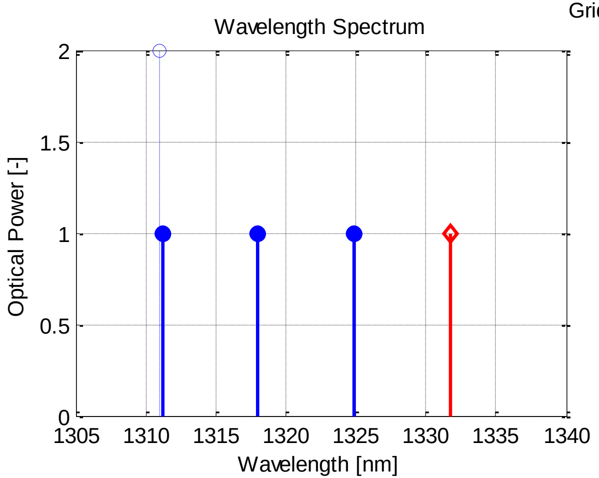
- Bandwidth of phase matching condition will however depend on channel spacing

- This condition is valid for the case where the contribution of dispersion slope to the phase matching is much larger than the dispersion contribution

Simulation case 3 : Wavelengths all on one side of the zero dispersion wavelength







Simulation case 3 : wavelengths all on one side of the zero dispersion wavelength

- From this case it can be observed that having a little bit of dispersion will help a lot to avoid phase matching condition

- Four wave mixing efficiency in this case will drop rapidly with increasing grid spacing

- Increasing the dispersion around the zero dispersion wavelength will only help in reducing the phase matching bandwidth

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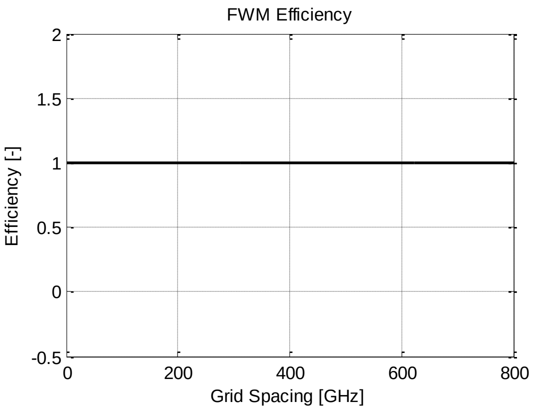
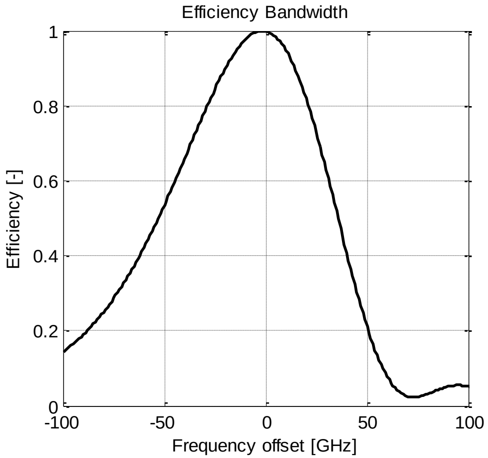
Simulation case 4: wavelengths symmetric around zero dispersion wavelength with ±Dc(f)

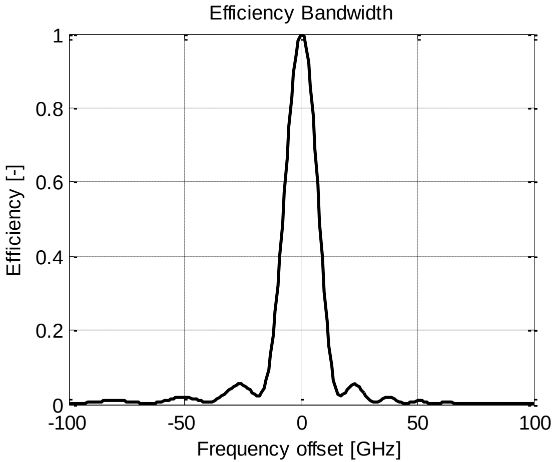
- Bandwidth of phase matching condition for 500 GHz grid spacing



Dc=Dc(f0) & ±Dc(f)



Dc=Dc(f0)



±Dc(f)

- Right figure : positive and negative dispersion added to wavelengths (±Dc(f)) which are symmetric around zero dispersion wavelength

Unequal spacing

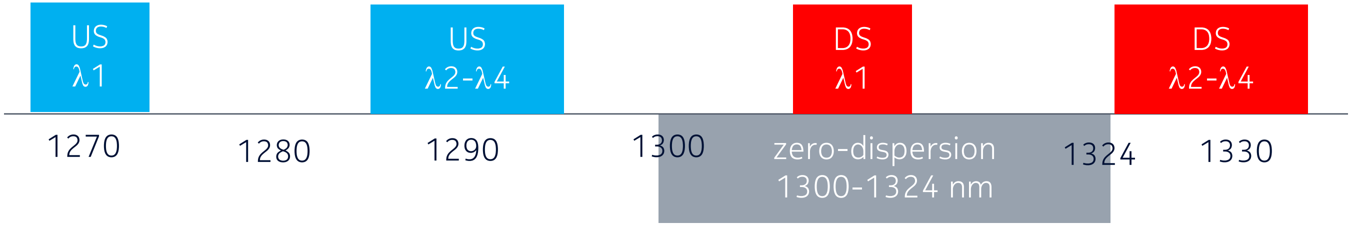
- If the frequency separation of any two channels of a WDM system is different from that of any other pair of channels, no FWM waves will be generated at any of the channel frequencies, thereby suppressing FWM crosstalk
- Even though the FWM waves do not interact with the channels, they are still generated at the expense of the transmitted power, so that ultimately the maximum launched power is limited by the channel depletion caused by the generation of the FWM waves

See also [3] Forghieri et al.

Design rules for wavelength plan NG-EPON driven by FWM

- Higher dispersion reduces FWM efficiency except when the zero-dispersion wavelength is in between wavelength channels, it is best to avoid zero-dispersion to avoid phase-matching
- Wider grid reduces FWM efficiency when sign of dispersion is same for all wavelengths
- Unequal grid reduces FWM crosstalk (still power depletion)

- Upstream wavelengths below 1300 nm (to avoid zero-dispersion) to enable DML at ONU (negative dispersion)
- First wavelength λ1 'far' away from 2^{nd}-4^{th} reduces FWM crosstalk (unequal grid) and also reduces cost of optical filters for first 25 Gbps wavelength
- Unequal grid for λ2-λ4 (for example skip 1 channel on 4-channel WDM)
- First downstream wavelength λ1, could possibly be in the zero dispersion wavelength window (between 1300-1324 nm) if it is far away from the other 3 wavelengths (unequal spacing and low bandwidth FWM efficiency)



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Conclusions and Factors reducing FWM efficiency

- Zero dispersion wavelength assumed same along whole fiber, multiple stretches of fiber with different ZDW will reduce FWM efficiency
- Same polarization assumed for all waves. Different polarizations will reduce average (not peak) FWM efficiency
- Unmodulated carriers simulated, modulated carriers will have reduced FWM efficiency.
- Phase matching bandwidth is narrow for grid spacing > 1000 GHz reducing likelihood of maximum FWM efficiency, however it is not infinite small.
- It is best to avoid zero dispersion wavelength region if possible, unequal channel spacing will be beneficial as well

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References

[1] N. Shibata, R. P. Braun, and R. G. Waarts, “Phase-mismatch dependence of efficiency of wave generation through four-wave mixing in a singlemode optical fiber,” *IEEE J. Quantum Electron.*, vol. 7, pp. 1205-1210, July 1987

[2] K. Inoue, “Four-wave mixing in an optical fiber in the zero-dispersion wavelength region,” *J. Lightwave Technol.*, vol. 10, pp. 1553-1561, Nov. 1992

[3] F. Forghieri, R. W. Tkach and A. R. Chraplyvy, "WDM systems with unequally spaced channels," in *Journal of Lightwave Technology*, vol. 13, no. 5, pp. 889-897, May 1, 1995

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