Four-wave mixing impact in O-band

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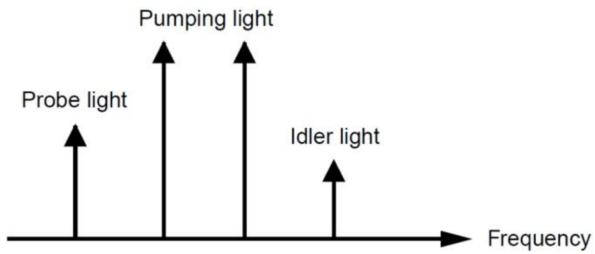
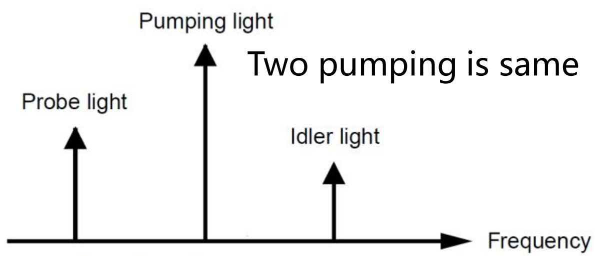
Four-wave mixing introduction

- Four-wave mixing (FWM) is a type of optical Kerr effect (third-order electric susceptibility nonlinear effect of optical fiber), and occurs when light of two or more different wavelengths is launched into a fiber.



a) 2-channel pump wave

$$f_{idler} = f_{p1} + f_{p2} - f_{probe}$$



b) 1-channel pump wave (degenerated FWM)

$$f_{idler} = 2f_{p} - f_{probe}$$

- FWM occurs when light of three wavelengths is launched into a fiber, giving rise to a new wave (know as an idler).
- When the frequencies of the two pumping waves are identical, it's called "degenerated four-wave mixing" (DFWM).

Origin of FWM

- Third order nonlinearity

$$P_{NL} = \varepsilon_0 \chi^{(3)} \vdots EEE$$

- Energy Conservation

$$\omega_4 = \omega_1 + \omega_2 - \omega_3$$

- Momentum Conservation—phase matching

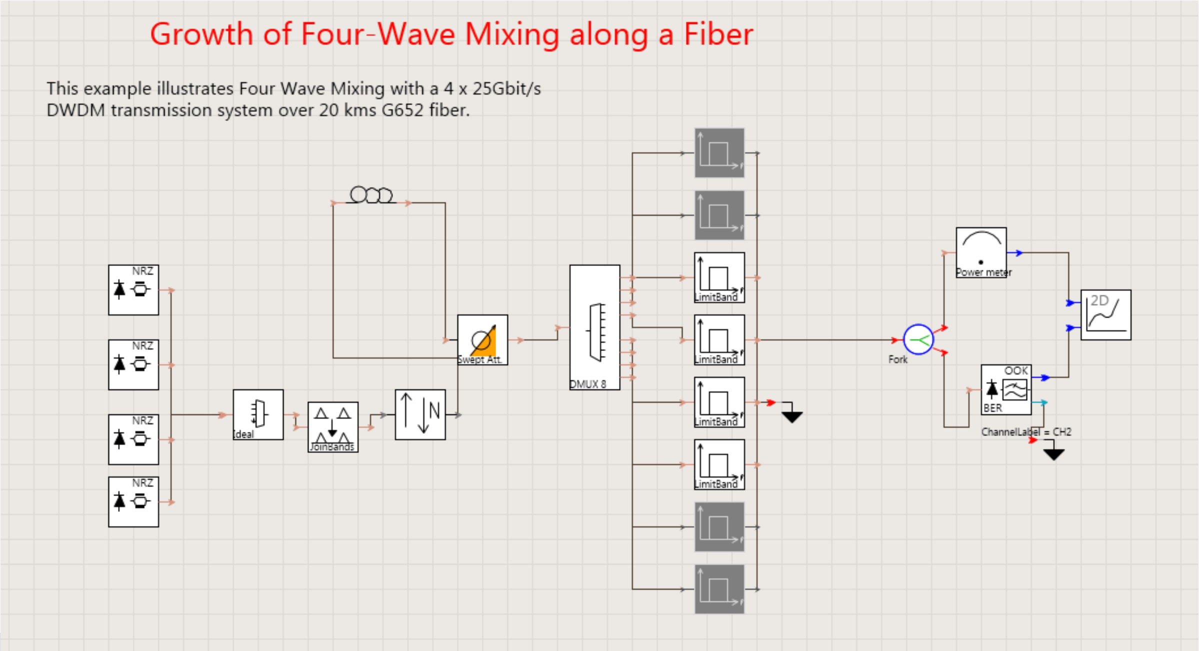
$$\beta_4 = \beta_1 + \beta_2 - \beta_3$$

FWM effect on WDM systems:

- In WDM system, since all wave propagate in the same direction, the phase mismatch can be write as $\Delta\kappa = \beta(\omega_4) + \beta(\omega_3) - \beta(\omega_2) - \beta(\omega_1)$ (1)
  Where, $\beta(\omega)$is the propagation constant for an optical field with frequency ω. In the degenerate case , $\omega_2 = \omega_1$, $\omega_3 = \omega_1 + \Omega$, and $\omega_1 - \Omega$, Ω represents the channel spacing.
- the power transferred to the FWM component in a fiber of length L is given by
  $$P_F = |A_F(L)|^2 = \eta_F (d_F \gamma L)^2 P_i P_j P_k e^{-\alpha L} \quad (2)$$
  Where, γ is fiber nonlinear parameter, Pm m= i,j,k is the launched power in the m channel α is loss, dF = $2-\delta_{ij}$ is the degeneracy factor defined such that its value is 1 when i = j but doubles when i = j. P_F is the launched power in the m_{th} channel and η_F is a measure of the FWM defined as
  $$\eta_F = \left| \frac{1-\exp(-(\alpha + i\Delta k)L)}{(\alpha + i\Delta k)L} \right|^2 \quad (3)$$
- The FWM efficiency depends on the channel spacing through the phase mismatch governed by $\Delta k = \beta_F + \beta_k - \beta_i - \beta_j \approx \beta_2(\omega_i - \omega_k)(\omega_j - \omega_k)$ (4)
  where the propagation constants were expanded in a Taylor series around ω c = (ω i +ω j)/2 and β2 is the GVD parameter at that frequency

VPI simulation

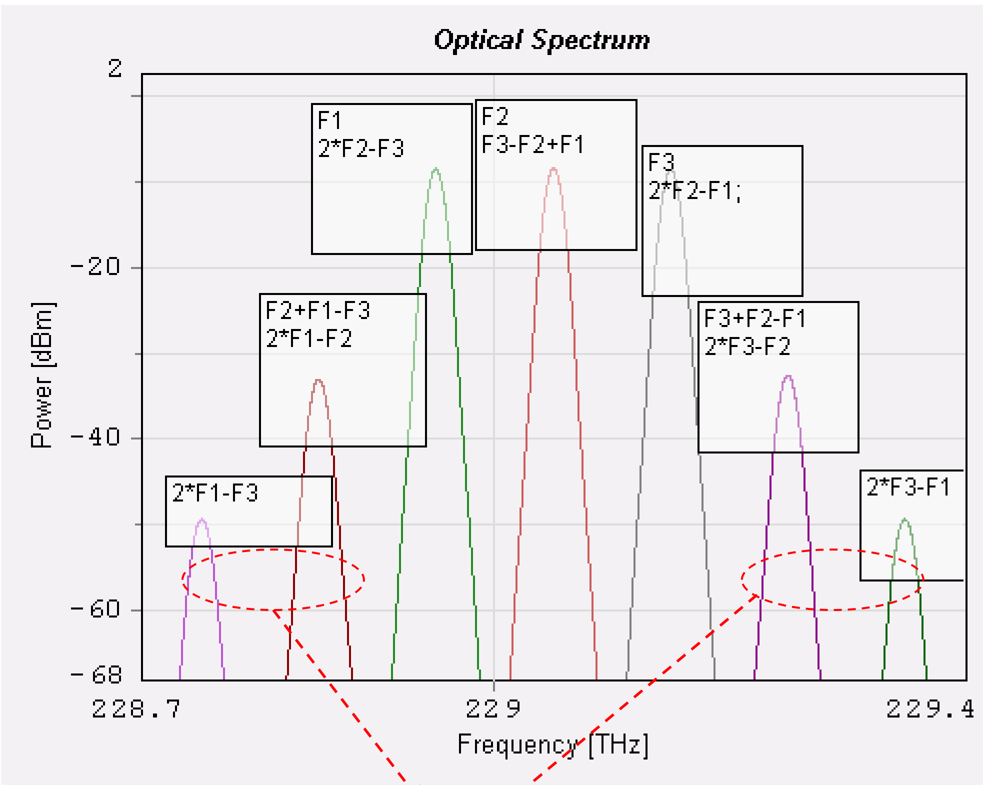
- Set up
  - 4 transmitters with equal channel spacing in O-band (from 100GHz ~ 400GHz)
  - Launch power : from 3dBm up to 10dBm
  - 20km G652 fiber
  - 25Gb/s NRZ modulation

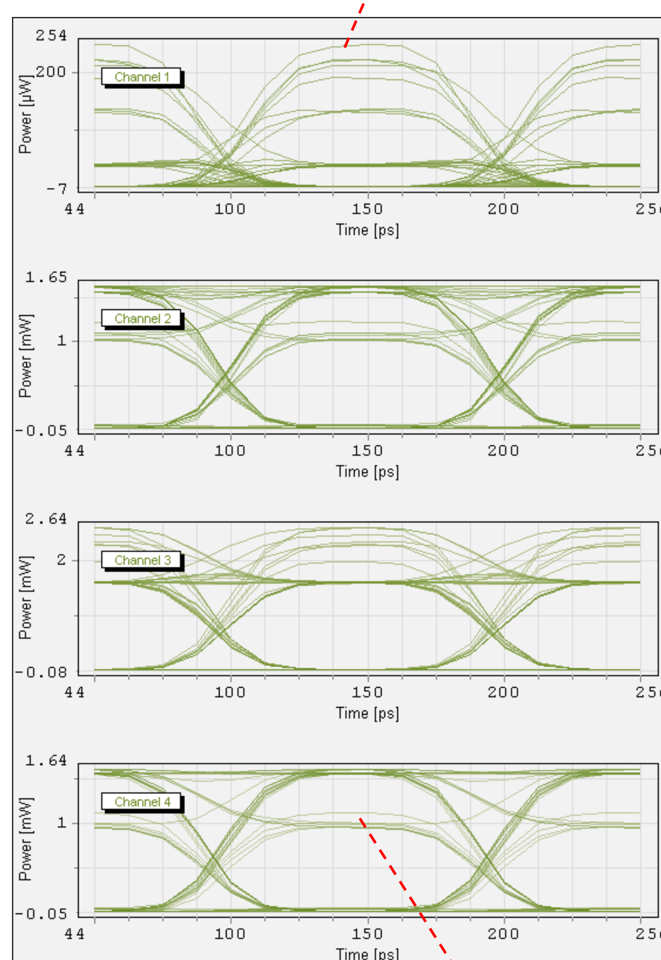


FWM crosstalk example

f0= 228.85 Thz   Disable Tx (to observe the crosstalk)
f1= 228.95 Thz   P=2dBm
f2= 229.05 Thz   P=2dBm
f3= 229.15 Thz   P=ddBm

Crosstalk signal

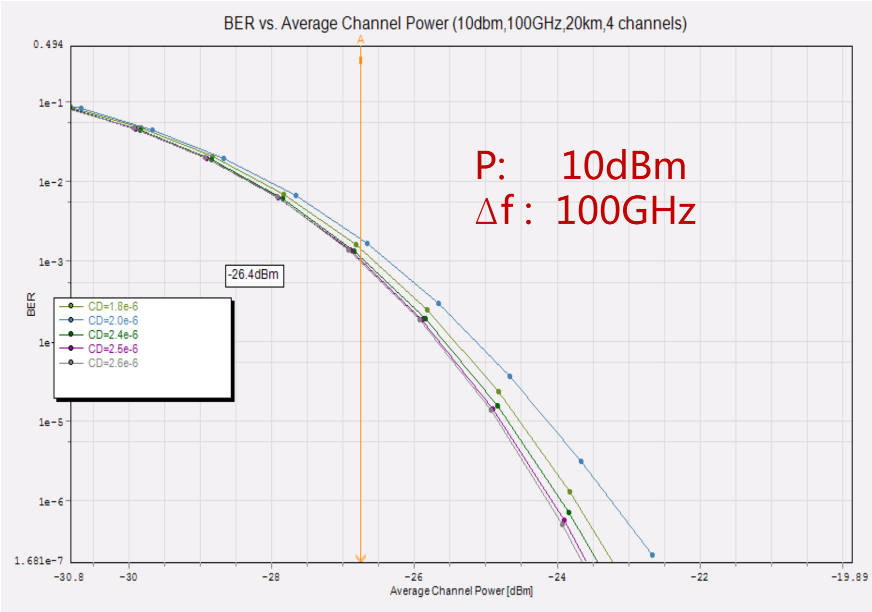


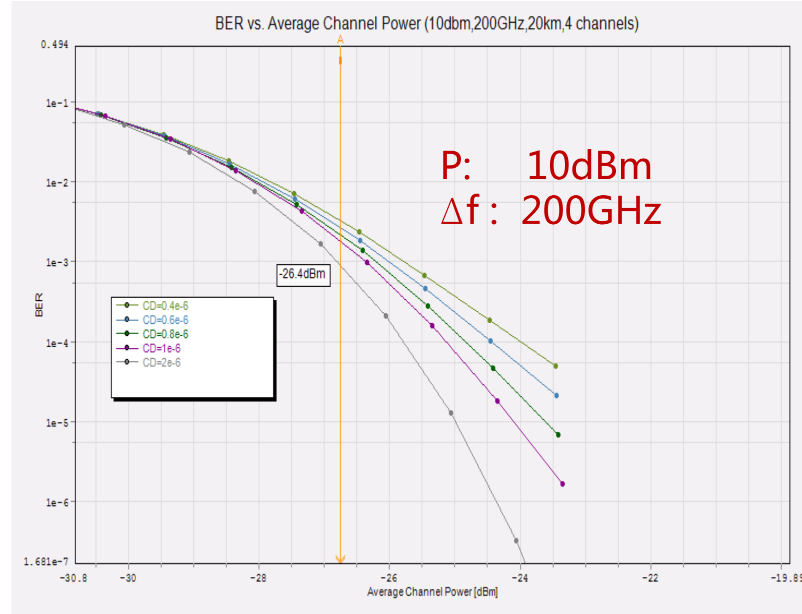


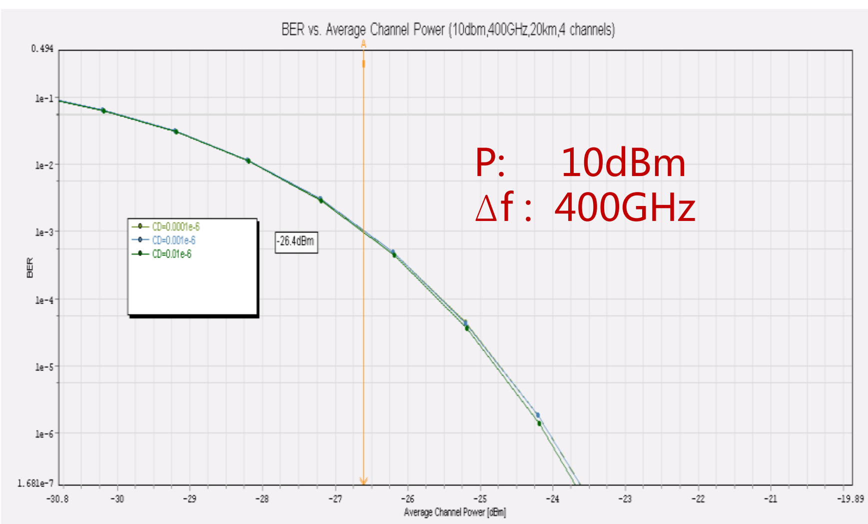
New crosstalk frequency due to FWM

Signal depletion

FWM penalty vs fiber dispersion







- FWM decreases as dispersion coefficient increases
- FWM increases as launch power increases
- FWM decreases quickly as channel spacing increases, is negligible when channel spacing more than 400GHz

Summary

Required fiber dispersion D (ps/nm/km) for <0.2dB FWM penalty:

launched power (dBm)	100 GHz (ps/nm/km)	200 GHz (ps/nm/km)	400G Hz (ps/nm/km)
3	>0.5	>0.1	0
6	>2.0	>0.18	0
8	>2.4	>0.3	0
10	>2.6	>2	0(>0.1e-3)
13	-	-	>0.8

Wavelength band restricted by FWM:

launched power (dBm)	100 GHz (ps/nm/km)	200 GHz (ps/nm/km)	400G Hz (ps/nm/km)
3	λ0±5.37nm	λ0±1.07nm	NA
6	λ0±21.5nm	λ0±1.93nm	NA
8	λ0±25.8nm	λ0±3.22nm	NA
10	λ0±27.9nm	λ0±21.5nm	NA (λ0±0.1nm)
13	-	-	λ0±8.6nm

λ0: zero dispersion wavelength 1300~1320nm

Thank you

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