Four-wave mixing in O-band for CW-WDM

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Four-wave mixing in O-band for CW-WDM grids

- This analysis uses the same formalism previously presented in IEEE 802.3ca contribution Johnson_3ca_1_0716.pdf for 25G-EPON wavelength plans.
- DWDM grid spacing in O-band has all of the ingredients for FWM to be a significant potential impairment
  - Requires co-polarization, which is typical for integrated DWDM transmitters
  - Is highly efficient when channels are on either side of the dispersion zero frequency
  - Is most efficient when channels are equally spaced in frequency
  - High channel count and small channel spacing increase the number of FWM tones generated
- In this contribution, using established analytical formulas, we look at the potential for FWM impairments in CW-WDM around the dispersion zero in O-band.

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CW-WDM grid proposal

VIEW 1	ITU-T G.694.1 c: 299792458 m/s						Anchor Freq: 193.1 THZ				Chris Cole 6/18/20	
Total Span	36nm						18nm					
# of λs	1 + 8		1 + 16		1 + 32		1 + 8		1 + 16		1 + 32	
Grid GHz	800		400		200		400		200		100	
Span nm	4 + 32		2 + 34		1 + 35		2 + 16		1 + 17		0.5 + 17.5	
Units	THz	nm	THz	nm	THz	nm	THz	nm	THz	nm	THz	nm
L-16					233.8	1282.26					232.2	1291.10
L-15					233.6	1283.36					232.1	1291.65
L-14					233.4	1284.46					232.0	1292.21
L-13					233.2	1285.56					231.9	1292.77
L-12					233.0	1286.66					231.8	1293.32
L-11					232.8	1287.77					231.7	1293.88
L-10					232.6	1288.88					231.6	1294.44
L-9					232.4	1289.98					231.5	1295.00
L-8			233.8	1282.26	232.2	1291.10			232.2	1291.10	231.4	1295.56
L-7			233.4	1284.46	232.0	1292.21			232.0	1292.21	231.3	1296.12
L-6			233.0	1286.66	231.8	1293.32			231.8	1293.32	231.2	1296.68
L-5			232.6	1288.88	231.6	1294.44			231.6	1294.44	231.1	1297.24
L-4	233.8	1282.26	232.2	1291.10	231.4	1295.56	232.2	1291.10	231.4	1295.56	231.0	1297.80
L-3	233.0	1286.66	231.8	1293.32	231.2	1296.68	231.8	1293.32	231.2	1296.68	230.9	1298.36
L-2	232.2	1291.10	231.4	1295.56	231.0	1297.80	231.4	1295.56	231.0	1297.80	230.8	1298.93
L-1	231.4	1295.56	231.0	1297.80	230.8	1298.93	231.0	1297.80	230.8	1298.93	230.7	1299.49
L0	230.6	1300.05	230.6	1300.05	230.6	1300.05	230.6	1300.05	230.6	1300.05	230.6	1300.05
L1	229.8	1304.58	230.2	1302.31	230.4	1301.18	230.2	1302.31	230.4	1301.18	230.5	1300.62
L2	229.0	1309.14	229.8	1304.58	230.2	1302.31	229.8	1304.58	230.2	1302.31	230.4	1301.18
L3	228.2	1313.73	229.4	1306.85	230.0	1303.45	229.4	1306.85	230.0	1303.45	230.3	1301.75
L4	227.4	1318.35	229.0	1309.14	229.8	1304.58	229.0	1309.14	229.8	1304.58	230.2	1302.31
L5			228.6	1311.43	229.6	1305.72			229.6	1305.72	230.1	1302.88
L6			228.2	1313.73	229.4	1306.85			229.4	1306.85	230.0	1303.45
L7			227.8	1316.03	229.2	1308.00			229.2	1308.00	229.9	1304.01
L8			227.4	1318.35	229.0	1309.14			229.0	1309.14	229.8	1304.58
L9					228.8	1310.28					229.7	1305.15
L10					228.6	1311.43					229.6	1305.72
L11					228.4	1312.58					229.5	1306.29
L12					228.2	1313.73					229.4	1306.85
L13					228.0	1314.88					229.3	1307.42
L14					227.8	1316.03					229.2	1308.00
L15					227.6	1317.19					229.1	1308.57
L16					227.4	1318.35					229.0	1309.14

CW-WDM MSA Grid Proposal 5-2.pdf

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Four-wave mixing (non-degenerate)

FWM frequency:

$f_{ijk} = f_i + f_j - f_k \qquad i \neq j \neq k$

FWM power:

$P_{ijk} = \left(\frac{D_{ijk}}{3}\gamma L e\right)^2 P_i P_j P_k e^{-\alpha L}\eta$, where $\gamma = \frac{2\pi n_2}{\lambda A_e}$ and $L_e = \frac{1-e^{-\alpha L}}{\alpha}$

FWM efficiency:

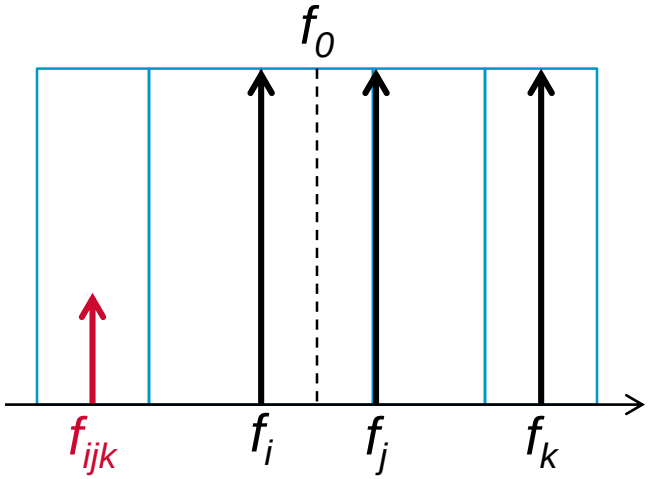
$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left(1 + \frac{4e^{-\alpha L}\sin^2(\Delta\beta L/2)}{(1-e^{-\alpha L})^2}\right)$$

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)

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Four-wave mixing (partially-degenerate)

FWM frequency:

$f_{ijk} = 2f_i - f_k$ $\quad\quad$ $i = j \neq k$

FWM power:

$P_{ijk} = \left(\frac{D_{ijk}}{3}\gamma L e\right)^2 P_i P_j P_k e^{-\alpha L}\eta$, where $\gamma = \frac{2\pi n_2}{\lambda A_e}$ and $L_e = \frac{1-e^{-\alpha L}}{\alpha}$

FWM efficiency:

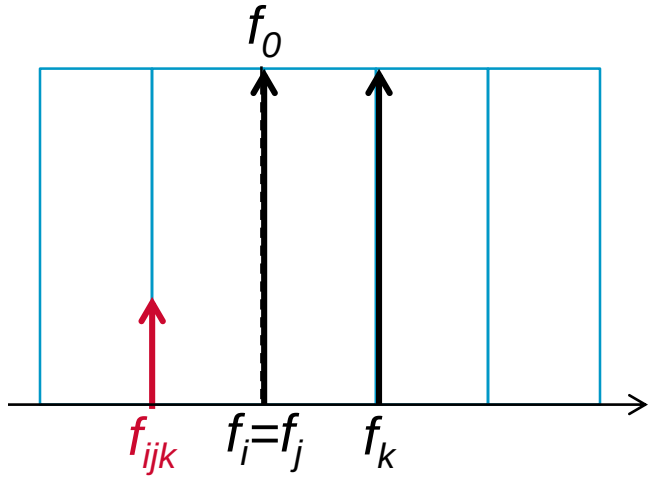
$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left(1 + \frac{4e^{-\alpha L}\sin^2(\Delta\beta L/2)}{(1-e^{-\alpha L})^2}\right)$$

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)

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

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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. Max propagation loss at 1310nm ~ 0.42 dB/km, but typical loss ~0.3 dB/km, resulting in slightly larger FWM power.

If all input powers = *P*, the ratio of FWM power to the transmitted signal is

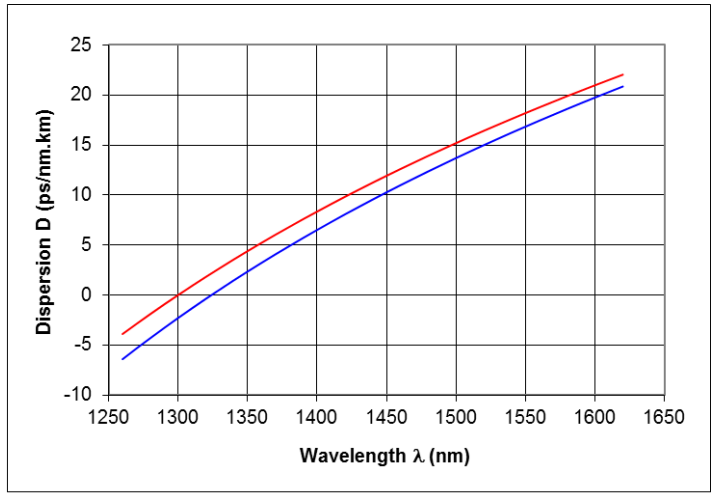
$$\frac{P_{ijk}}{P_L} = \left(\frac{D_{ijk}\gamma Le}{3}\right)^2 P^2 \quad \text{, where } P_L = P\, e^{-\alpha L}$$

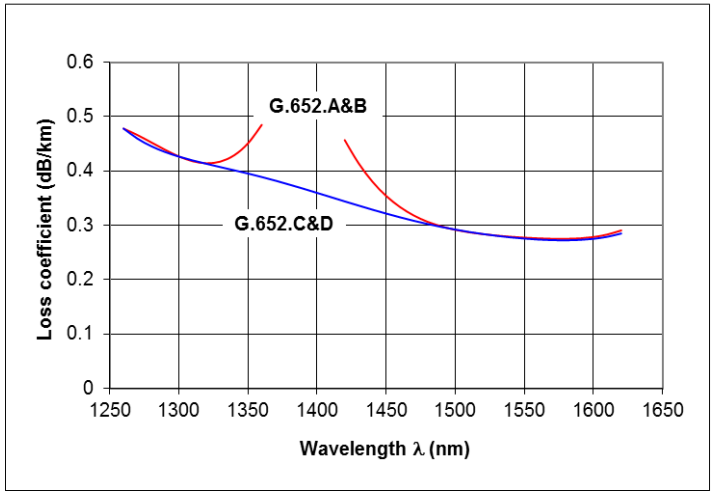
For short fibers, $L_e \sim L$ and for longer spans $L_e \sim 1/\alpha$. For $L > 1/\alpha$, standard transmission fiber and non-degenerate FWM*, the non-linear coefficient for power is approximately constant:

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

The value in O-band is similar.

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





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FWM power penalty

- For channels on an equally spaced frequency grid, the FWM tone interferes coherently with the target channel
  - The actual frequency spacing must be equal to within the receiver bandwidth, B_e, for the beat frequency to be in-band. Wider grid spacing may have larger random frequency offsets.
  - 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, resulting in ~1dB power penalty for NRZ
  - For P_{FWM}/P_L < -30dB the ratio of electric fields is 3.2%, resulting in < ~0.3dB power penalty for NRZ.
  - Penalties for PAM4 modulation will be higher due to reduced inner eye opening
- For short links, penalty due to power depletion is negligible.
- 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.

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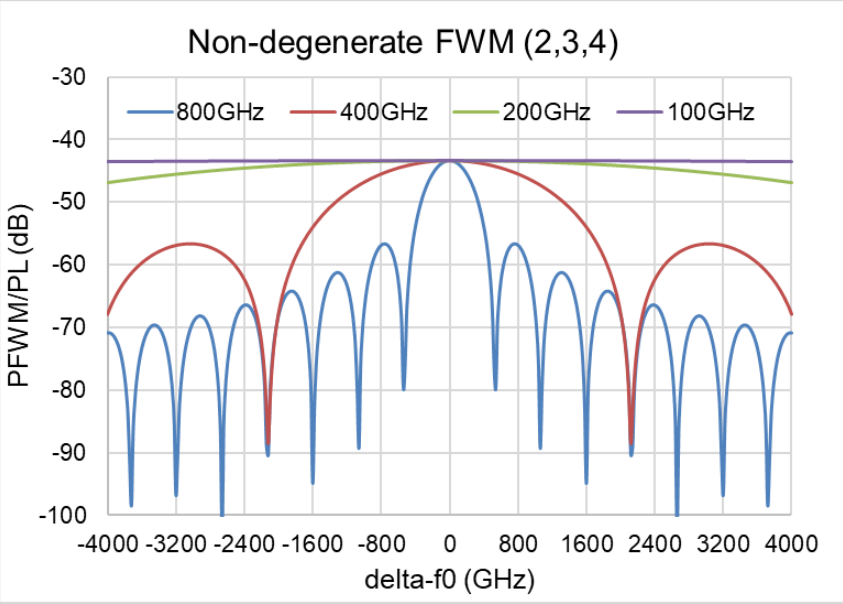
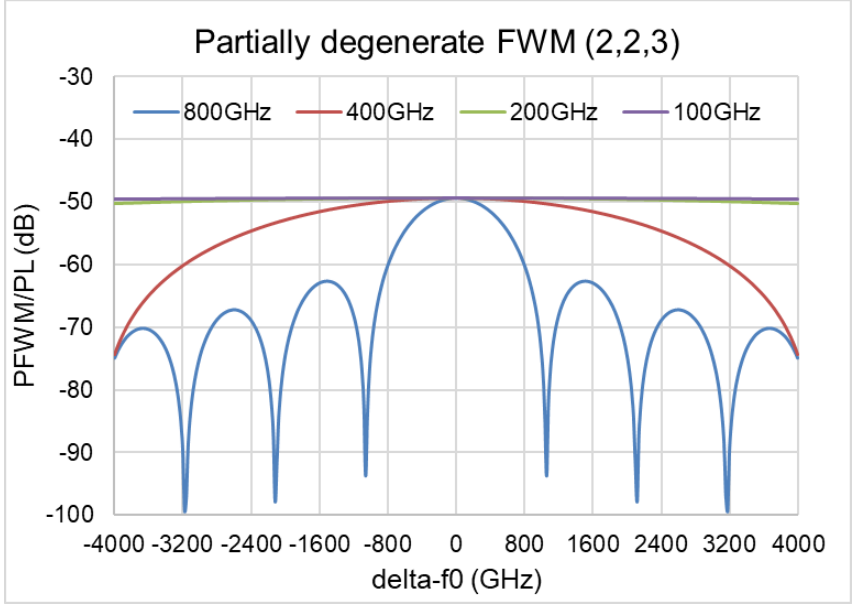
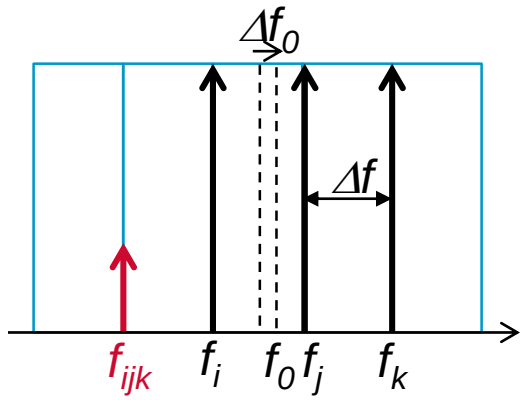
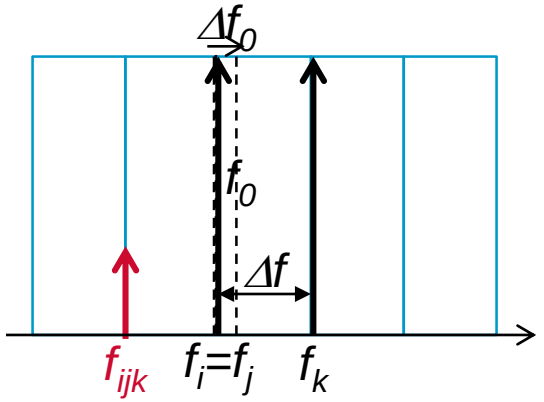
Effect of phase mismatch









For DWDM grid spacing, phase matching BW can be a significant fraction of the total channel range.

As a result, DWDM channels remote from the zero-dispersion frequency can mix efficiently and add together, resulting in more severe penalties than CWDM where the BW is narrow.

The results at left are for L = 500m and P = 2mW

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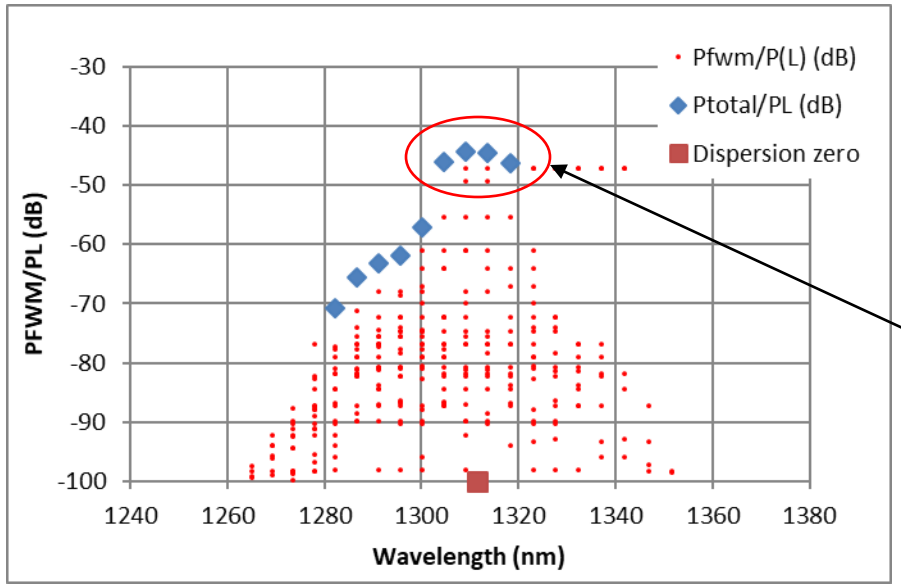
9 x 800GHz CWWDM grid

Non-degenerate

P = 3dBm, L = 500m, f_0 = 228.6 THz



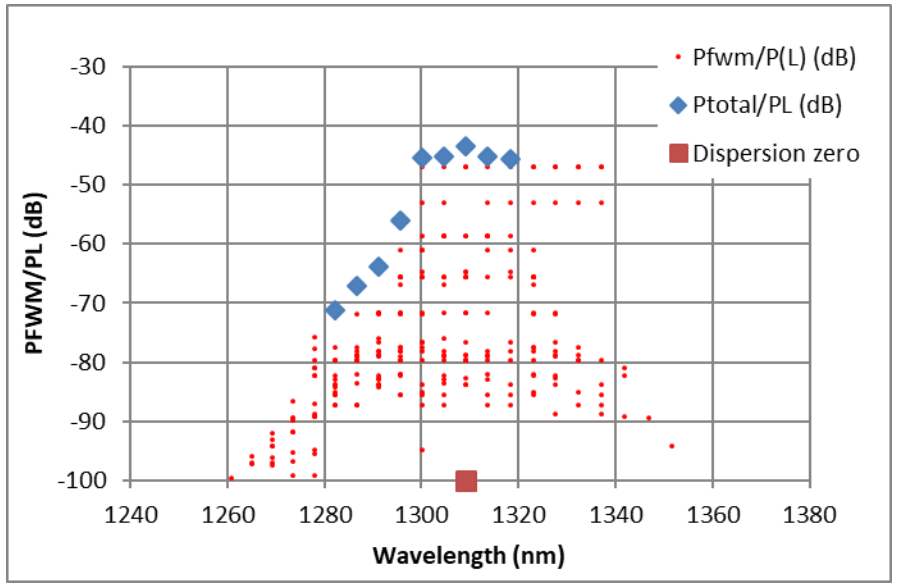
Note that the total FWM power is dominated by the tones with $\Delta\beta \sim 0$.

Lane	WL (nm)	freq (Thz)	FWM tones*	Total Pfwm (mW)	Ptotal/PL (dB)
1	1282.26	233.800	0	1.62E-07	-70.77
2	1286.663	233.000	0	5.26E-07	-65.65
3	1291.096	232.200	0	9.17E-07	-63.24
4	1295.559	231.400	0	1.28E-06	-61.78
5	1300.054	230.600	0	3.75E-06	-57.12
6	1304.58	229.800	2	4.76E-05	-46.08
7	1309.137	229.000	3	7.03E-05	-44.39
8	1313.727	228.200	3	6.93E-05	-44.45
9	1318.349	227.400	2	4.54E-05	-46.29

* # of FWM tones with $\eta > 0.1$

Partially-degenerate

P = 3dBm, L = 500m, f_0 = 229.0 THz



Lane	WL (nm)	freq (Thz)	FWM tones*	Total Pfwm (mW)	Ptotal/PL (dB)
1	1282.26	233.800	0	1.46E-07	-71.23
2	1286.663	233.000	0	3.80E-07	-67.07
3	1291.096	232.200	0	8.10E-07	-63.78
4	1295.559	231.400	0	4.73E-06	-56.11
5	1300.054	230.600	2	5.60E-05	-45.38
6	1304.58	229.800	2	5.78E-05	-45.24
7	1309.137	229.000	2	8.56E-05	-43.54
8	1313.727	228.200	2	5.84E-05	-45.20
9	1318.349	227.400	2	5.36E-05	-45.57

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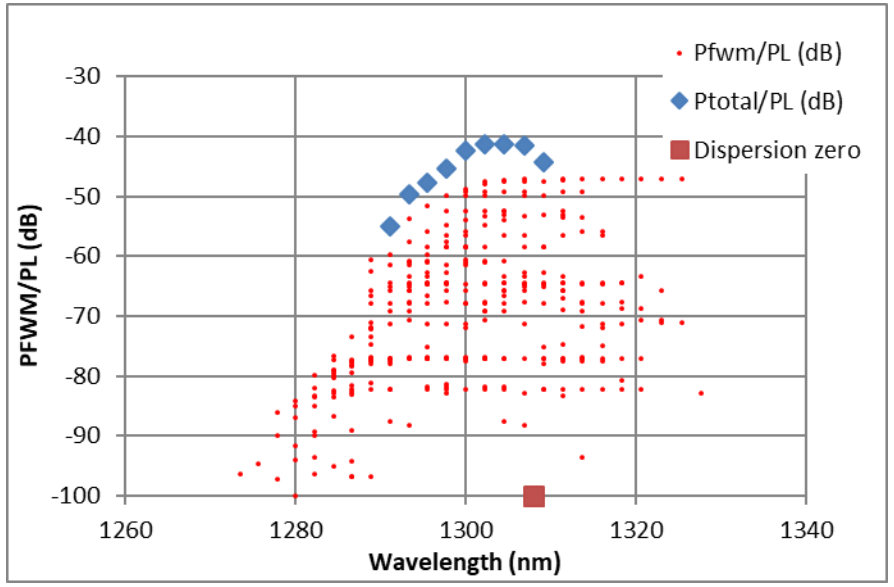
9 x 400GHz CWWDM grid

Non-degenerate

P = 3dBm, L = 500m, f_0 = 229.2 THz

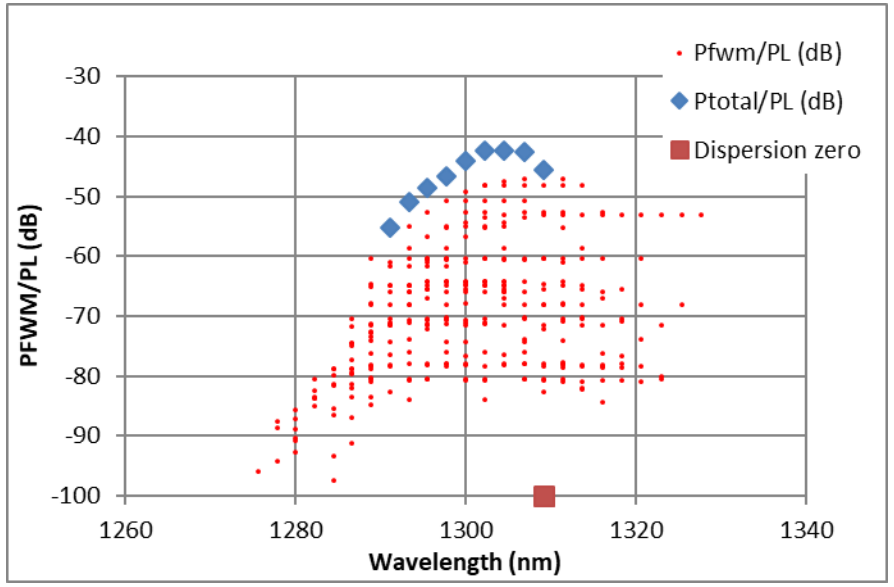


Lane	WL (nm)	freq (Thz)	FWM tones*	Total Pfwm (mW)	Ptotal/PL (dB)
1	1291.096	232.200	1	6.17E-06	-54.96
2	1293.324	231.800	2	2.13E-05	-49.58
3	1295.559	231.400	3	3.22E-05	-47.78
4	1297.803	231.000	5	5.64E-05	-45.35
5	1300.054	230.600	8	1.11E-04	-42.39
6	1302.313	230.200	7	1.43E-04	-41.30
7	1304.58	229.800	8	1.42E-04	-41.34
8	1306.855	229.400	6	1.36E-04	-41.52
9	1309.137	229.000	4	7.21E-05	-44.28

* # of FWM tones with $\eta > 0.1$

Partially-degenerate

P = 3dBm, L = 500m, f_0 = 229.0 THz



Lane	WL (nm)	freq (Thz)	FWM tones*	Total Pfwm (mW)	Ptotal/PL (dB)
1	1291.096	232.200	1	5.79E-06	-55.23
2	1293.324	231.800	2	1.58E-05	-50.89
3	1295.559	231.400	3	2.73E-05	-48.50
4	1297.803	231.000	4	4.19E-05	-46.64
5	1300.054	230.600	6	7.53E-05	-44.10
6	1302.313	230.200	7	1.13E-04	-42.33
7	1304.58	229.800	6	1.13E-04	-42.33
8	1306.855	229.400	5	1.07E-04	-42.55
9	1309.137	229.000	3	5.46E-05	-45.49

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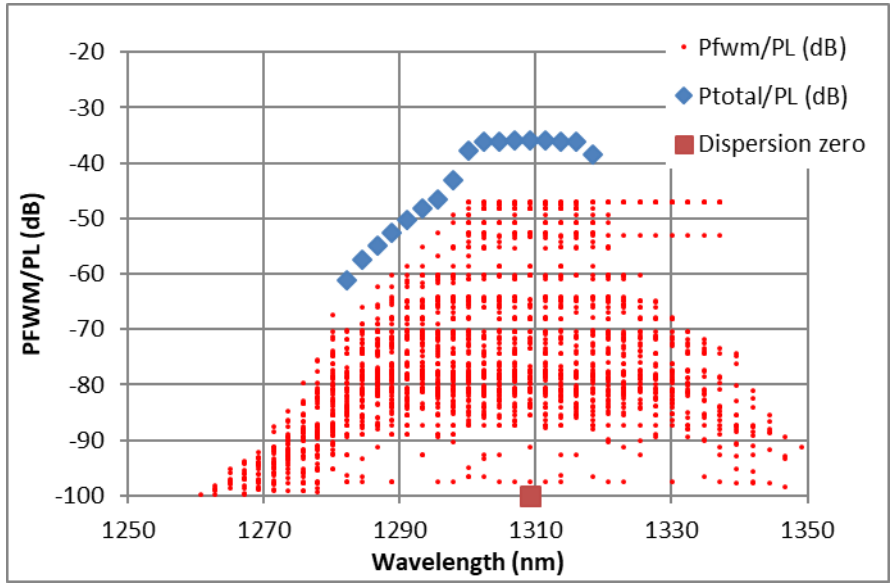
17 x 400GHz CWWDM grid

Partially-degenerate

P = 3dBm, L = 500m, f_0 = 229.0 THz



Lane	WL (nm)	freq (Thz)	FWM tones*	Total Pfwm (mW)	Ptotal/PL (dB)
1	1282.26	233.800	0	1.52E-06	-61.04
2	1284.458	233.400	0	3.41E-06	-57.54
3	1286.663	233.000	0	6.17E-06	-54.96
4	1288.876	232.600	0	1.05E-05	-52.65
5	1291.096	232.200	1	1.78E-05	-50.35
6	1293.324	231.800	2	2.90E-05	-48.24
7	1295.559	231.400	3	4.30E-05	-46.52
8	1297.803	231.000	7	9.38E-05	-43.14
9	1300.054	230.600	17	3.22E-04	-37.78
10	1302.313	230.200	22	4.59E-04	-36.24
11	1304.58	229.800	18	4.75E-04	-36.10
12	1306.855	229.400	20	4.91E-04	-35.95
13	1309.137	229.000	20	5.05E-04	-35.83
14	1311.428	228.600	20	4.89E-04	-35.96
15	1313.727	228.200	19	4.78E-04	-36.07
16	1316.034	227.800	21	4.65E-04	-36.18
17	1318.349	227.400	14	2.83E-04	-38.35

Non-degenerate case is similar.

* # of FWM tones with $\eta > 0.1$

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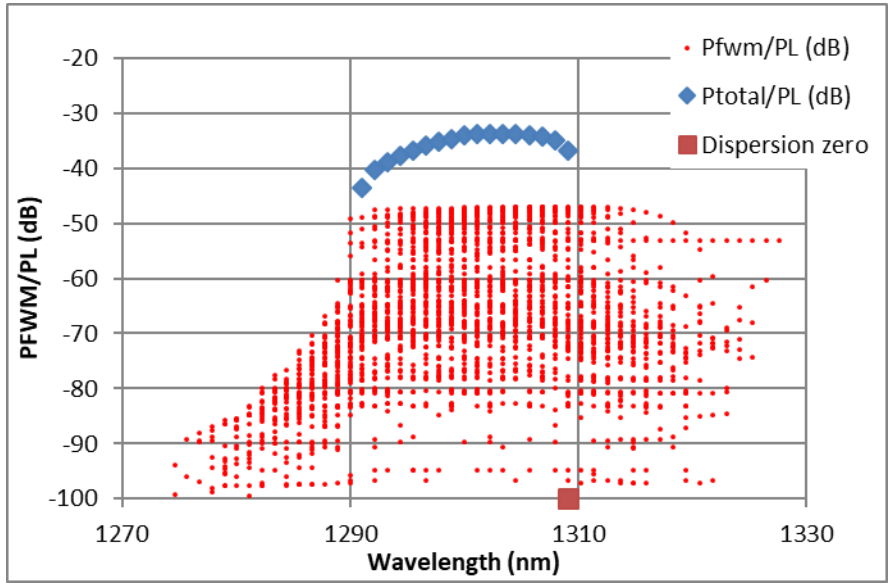
17 x 200GHz CWWDM grid

Partially-degenerate

P = 3dBm, L = 500m, f_0 = 229.0 THz



Non-degenerate case is similar.

Lane	WL (nm)	freq (Thz)	FWM tones*	Total Pfwm (mW)	Ptotal/PL (dB)
1	1291.096	232.200	5	8.33E-05	-43.65
2	1292.209	232.000	10	1.83E-04	-40.23
3	1293.324	231.800	14	2.42E-04	-39.02
4	1294.441	231.600	17	3.19E-04	-37.82
5	1295.559	231.400	24	3.99E-04	-36.85
6	1296.68	231.200	29	4.88E-04	-35.98
7	1297.803	231.000	33	5.77E-04	-35.25
8	1298.927	230.800	36	6.62E-04	-34.65
9	1300.054	230.600	37	7.52E-04	-34.10
10	1301.183	230.400	37	8.12E-04	-33.76
11	1302.313	230.200	36	8.26E-04	-33.69
12	1303.445	230.000	34	8.19E-04	-33.73
13	1304.58	229.800	34	7.93E-04	-33.87
14	1305.716	229.600	33	7.67E-04	-34.01
15	1306.855	229.400	29	7.10E-04	-34.34
16	1307.995	229.200	26	6.16E-04	-34.97
17	1309.137	229.000	18	4.04E-04	-36.79

* # of FWM tones with $\eta > 0.1$

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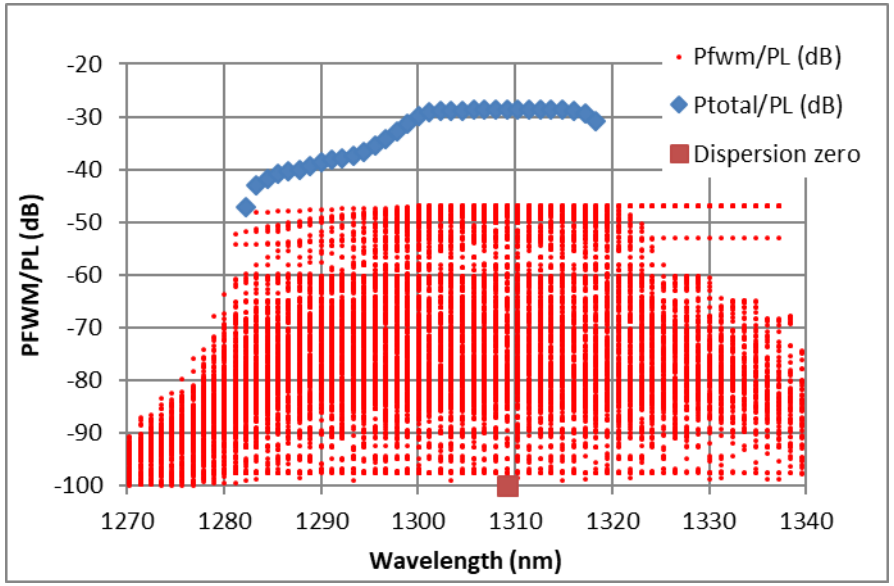
33 x 200GHz CWWDM grid

Partially-degenerate

P = 3dBm, L = 500m, f_0 = 229.0 THz



Non-degenerate case is similar.

Lane	WL (nm)	freq (Thz)	FWM tones*	Total Pfwm (mW)	Ptotal/PL (dB)
1	1282.26	233.800	2	3.81E-05	-47.05
2	1283.358	233.600	4	9.41E-05	-43.13
3	1284.458	233.400	7	1.28E-04	-41.79
4	1285.559	233.200	9	1.62E-04	-40.76
5	1286.663	233.000	9	1.77E-04	-40.37
6	1287.768	232.800	10	1.93E-04	-40.00
7	1288.876	232.600	11	2.22E-04	-39.40
8	1289.985	232.400	13	2.62E-04	-38.67
9	1291.096	232.200	14	3.01E-04	-38.07
10	1292.209	232.000	16	3.18E-04	-37.83
11	1293.324	231.800	17	3.47E-04	-37.46
12	1294.441	231.600	22	4.15E-04	-36.68
13	1295.559	231.400	32	5.38E-04	-35.55
14	1296.68	231.200	43	7.31E-04	-34.22
15	1297.803	231.000	54	9.91E-04	-32.90
16	1298.927	230.800	70	1.40E-03	-31.41
17	1300.054	230.600	85	1.94E-03	-29.98
18	1301.183	230.400	96	2.35E-03	-29.14
19	1302.313	230.200	96	2.53E-03	-28.84
20	1303.445	230.000	93	2.55E-03	-28.79
21	1304.58	229.800	93	2.55E-03	-28.79
22	1305.716	229.600	97	2.57E-03	-28.76
23	1306.855	229.400	94	2.60E-03	-28.71
24	1307.995	229.200	97	2.63E-03	-28.67
25	1309.137	229.000	99	2.63E-03	-28.65
26	1310.282	228.800	98	2.63E-03	-28.67
27	1311.428	228.600	95	2.60E-03	-28.71
28	1312.576	228.400	97	2.58E-03	-28.75
29	1313.727	228.200	94	2.56E-03	-28.77
30	1314.879	228.000	93	2.56E-03	-28.78
31	1316.034	227.800	93	2.49E-03	-28.89
32	1317.19	227.600	87	2.23E-03	-29.38
33	1318.349	227.400	68	1.55E-03	-30.94

* # of FWM tones with $\eta > 0.1$

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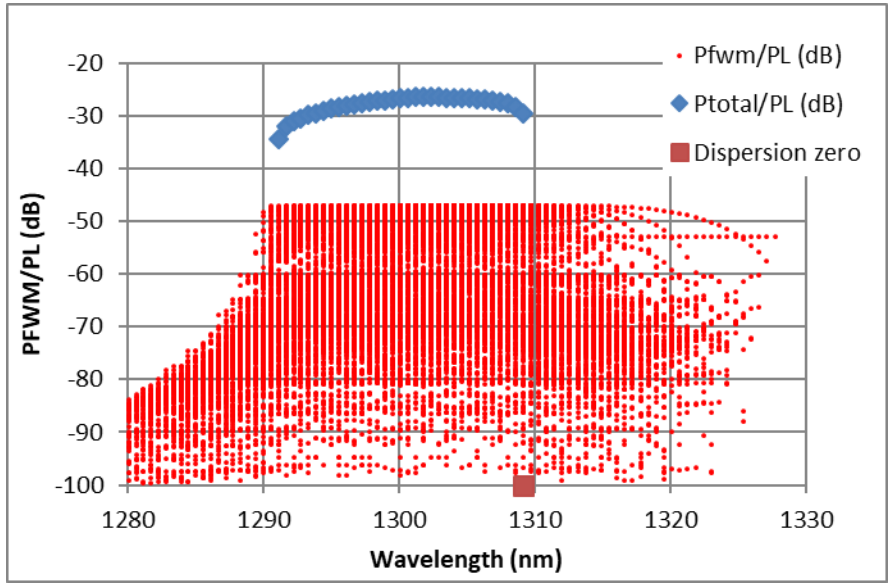
33 x 100GHz CWWDM grid

Partially-degenerate

P = 3dBm, L = 500m, f_0 = 229.0 THz



Non-degenerate case is similar.

Lane	WL (nm)	freq (Thz)	FWM tones*	Total Pfwm (mW)	Ptotal/PL (dB)
1	1291.096	232.200	38	6.89E-04	-34.48
2	1291.652	232.100	69	1.21E-03	-32.02
3	1292.209	232.000	83	1.51E-03	-31.08
4	1292.766	231.900	87	1.75E-03	-30.44
5	1293.324	231.800	96	1.96E-03	-29.93
6	1293.882	231.700	100	2.19E-03	-29.46
7	1294.441	231.600	105	2.40E-03	-29.06
8	1295	231.500	114	2.61E-03	-28.70
9	1295.559	231.400	123	2.80E-03	-28.38
10	1296.12	231.300	133	2.98E-03	-28.11
11	1296.68	231.200	139	3.16E-03	-27.86
12	1297.241	231.100	149	3.34E-03	-27.63
13	1297.803	231.000	152	3.50E-03	-27.42
14	1298.365	230.900	160	3.67E-03	-27.22
15	1298.927	230.800	165	3.84E-03	-27.02
16	1299.49	230.700	172	4.01E-03	-26.83
17	1300.054	230.600	176	4.16E-03	-26.67
18	1300.618	230.500	176	4.28E-03	-26.54
19	1301.183	230.400	174	4.35E-03	-26.47
20	1301.748	230.300	172	4.38E-03	-26.44
21	1302.313	230.200	169	4.37E-03	-26.46
22	1302.879	230.100	168	4.34E-03	-26.48
23	1303.445	230.000	166	4.29E-03	-26.54
24	1304.012	229.900	165	4.24E-03	-26.59
25	1304.58	229.800	161	4.17E-03	-26.66
26	1305.148	229.700	160	4.10E-03	-26.73
27	1305.716	229.600	157	4.01E-03	-26.83
28	1306.285	229.500	151	3.90E-03	-26.95
29	1306.855	229.400	144	3.75E-03	-27.12
30	1307.425	229.300	138	3.56E-03	-27.35
31	1307.995	229.200	128	3.27E-03	-27.71
32	1308.566	229.100	112	2.87E-03	-28.28
33	1309.137	229.000	88	2.19E-03	-29.46

* # of FWM tones with $\eta > 0.1$

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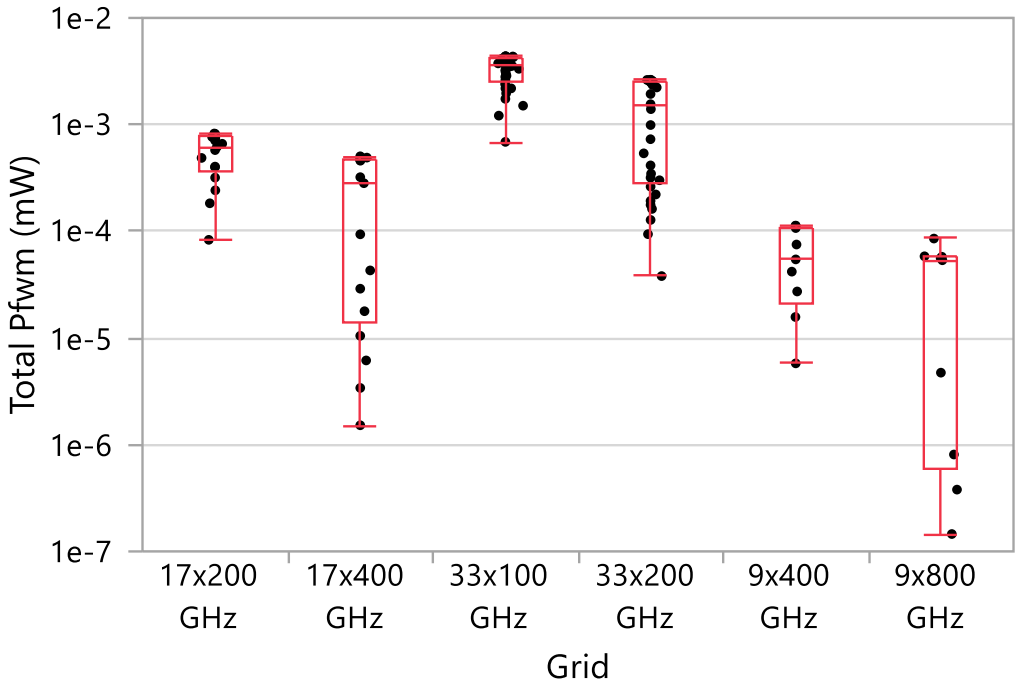
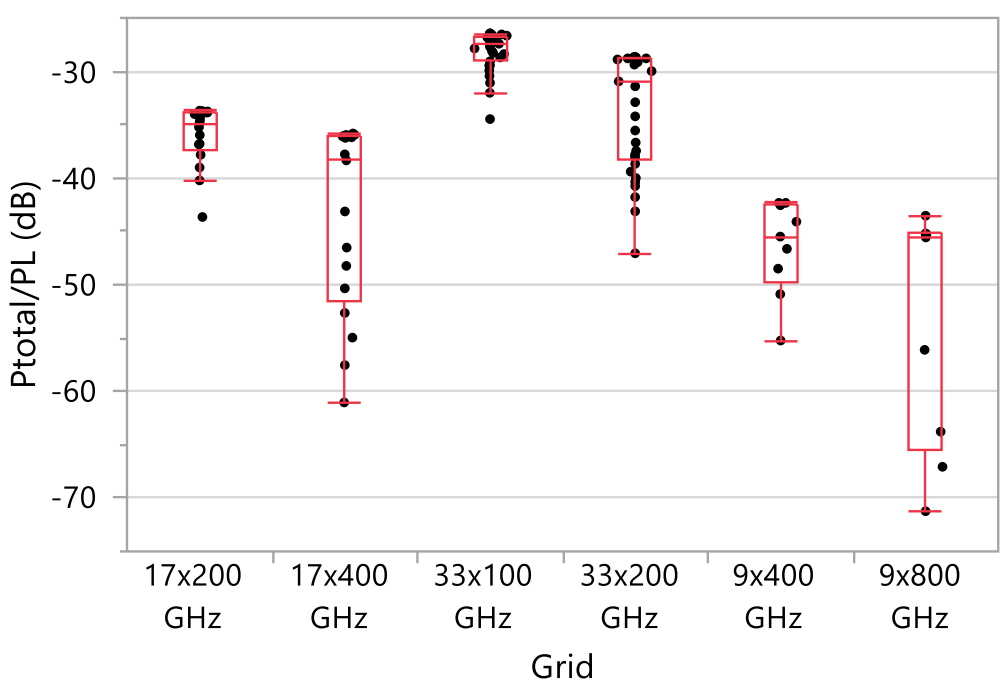
Total FWM Power for P=3dBm, L=500m





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Estimating BER penalty for PAM4

K. Inoue, K. Nakanishi, K. Oda and H. Toba, "Crosstalk and Power Penalty Due to Fiber Four-Wave Mixing in Multichannel Transmissions, J. Lightwave Technol., Vol. 12, No. 8, 1994.

The PAM4 electric field at the RX is written as: $E = B_s\sqrt{P_s}e^{j\theta_s} + \sum_{p,q,r} B_p B_q B_r \sqrt{P_{pqr}} e^{j\theta_{pqr}}$

where $B_i^2 = \left[1, \frac{1}{3}(2+R), \frac{1}{3}(1+2R), R\right]$ are the PAM4 levels and $\langle B_i^2 \rangle = \frac{1}{2}(1+R)$ is the average

The received electrical signal is then: $S = K|E|^2 + n_{th}$ where K is the responsivity and n_{th} is the RX thermal noise $K = \frac{\eta e}{h\upsilon}$

$S \approx B_s^2 P_s + n_F + n_{th}$ where $n_F = 2B_s\sqrt{P_s}\sum_{p,q,r} B_p B_q B_r \sqrt{P_{pqr}} \cos|\theta_s - \theta_F|$ is the noise due to FWM

In the Gaussian approximation, $\sigma_F^2 = \langle n_F^2 \rangle - \langle n_F \rangle^2$ giving $\sigma_F^2 = 2B_s^2 P_s \frac{1}{8}(1+R)^3 \sum_{p,q,r} P_{pqr}$

The total noise on the mth PAM4 level is: $\sigma_m^2 = \sigma_F^2 + N_{th}$

The Q-factor of the (m,n) sub-eye is: $Q_{m,n} = \frac{\langle S_m \rangle - \langle S_n \rangle}{\sqrt{\sigma_m^2} + \sqrt{\sigma_n^2}}$

And the sub-eye error rate is:

$BER_{m,n} = \frac{1}{2} erfc\left(Q_{m,n}/\sqrt{2}\right)$

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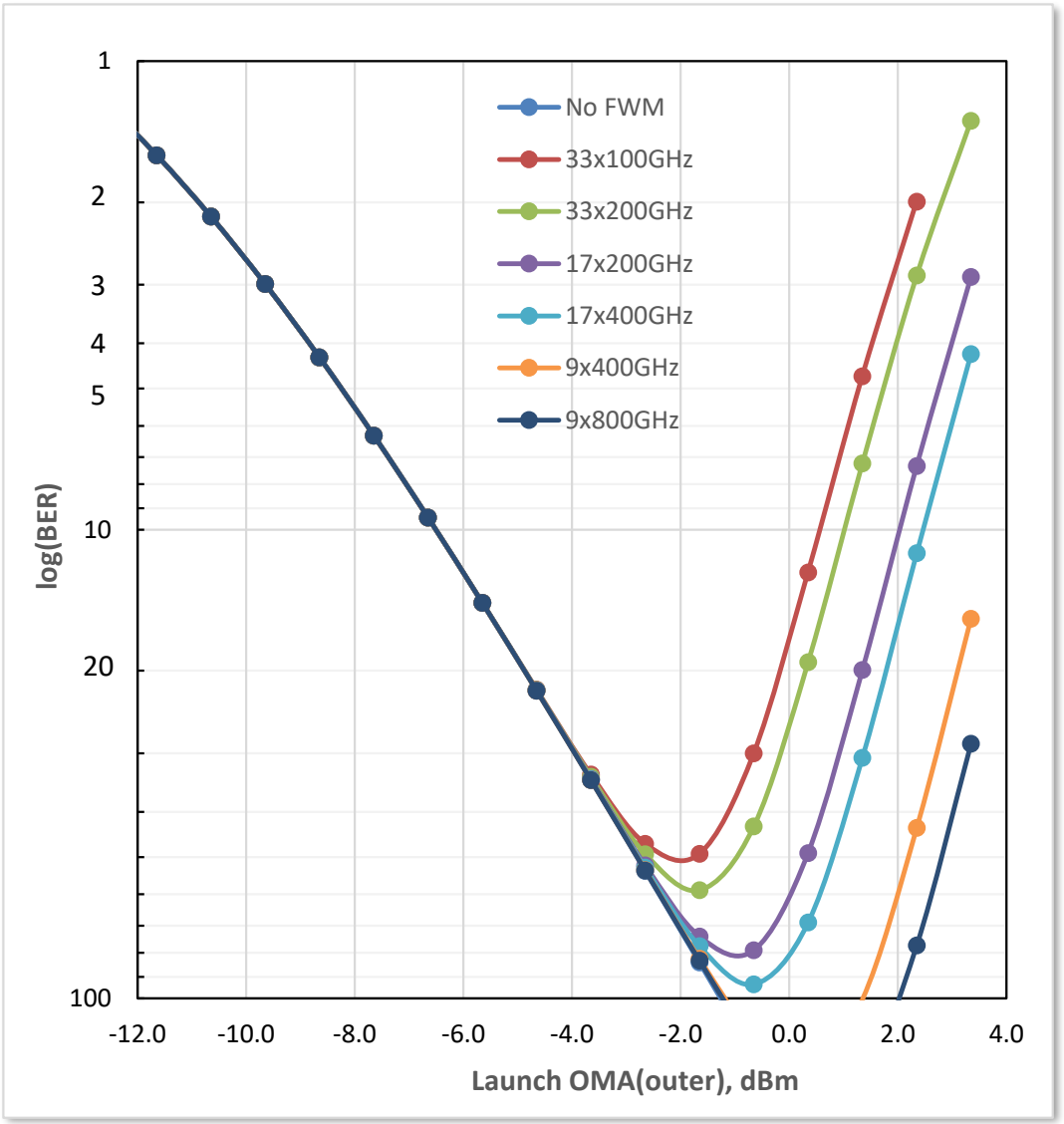
Estimated penalty for PAM4 signals

- PAM4 optical signal with ER = 5 dB
- Fiber length = 500m, loss = 0.3 dB/km
- No additional losses (worst case FWM)
- N_{th} chosen to give BER~4.8E-4 at ~ -9 dBm, similar to commercial 53 GBaud PIN RX.
- Only BER of upper (3,2) sub-eye is calculated – BER of middle and bottom sub-eyes are lower.

- The curves show the simulated (3,2) BER for the cases of No FWM, and for the worst channel FWM simulated for each proposed grid.
- At the proposed peak launch power of 2 mW (OMA_{outer} = 1.35 dBm) the 32-channel grids have rapidly increasing BER above 10^{-7}. The other grids are below the threshold of concern.
- It's recommended that the launch OMA for the 32x100GHz and 32x200GHz grids be limited to less than 0 dBm to avoid possible FWM penalties.



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

- For assumed +3 dBm (peak) launch and 500m span, the phase-matched P_{FWM}/P_L = -43.5 dB (non-degenerate) and -49.4 dB (partially degenerate) for a single FWM tone
  - As grid spacing shrinks, the phase-matching bandwidth increases, generating more near-phase-matched (NPM) tones at each channel. As channel count increases, more near-phase-matched tones are generated in each target channel.
  - The 32-channel grid plans have the potential to produce > 100 near-phase matched tones in a single channel, resulting in significant worst case BER degradation for launch OMA > 0 dBm.
- These simulations assume perfect alignment of the lasers to the grid.
  - For real systems there will random frequency offsets, leading to FWM beat tones being outside the receiver bandwidth, especially for large grid spacing.
  - The probability of occurrence of in-band FWM tones can be simulated with Monte-Carlo methods.
- These simulations assume the same zero dispersion frequency along the entire fiber span, co-polarization and CW signals with no chirp.
  - PMD scrambles the relative polarizations of each signal on longer spans, reducing the average (but not peak) efficiency of FWM generation. Not a major effect for short (< 500m) fibers.
  - 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 sophisticated system simulations and Monte-Carlo analyses are advisable.

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