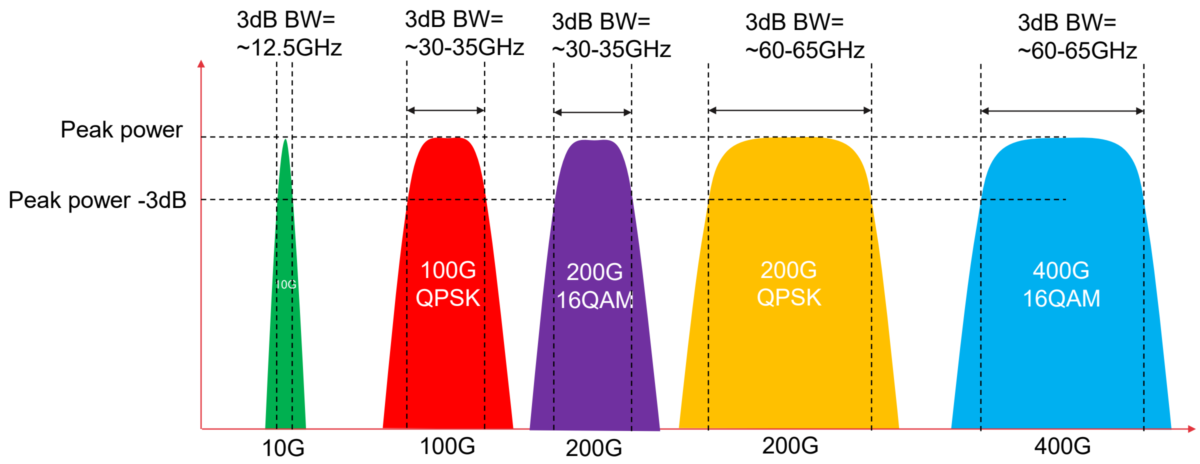
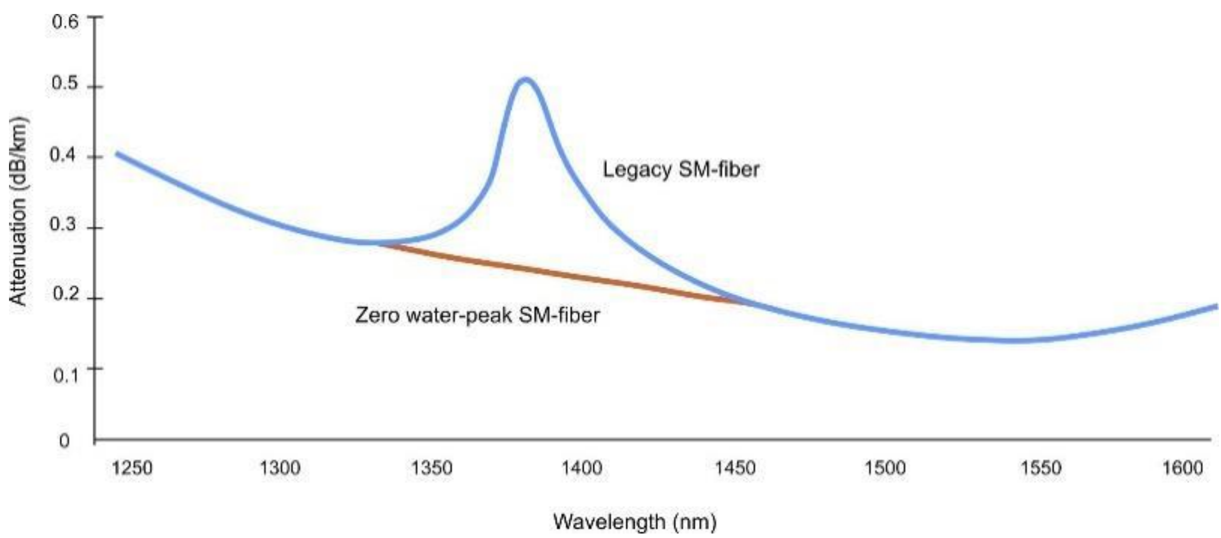
Design Guidelines

DCP-release-12.0.1 A



Signal formats



Fiber loss for SSMF G.652 fiber

Contents

1 Introduction

1.1 General

This manual contains design rules for the DCP products on a system level. The manual is divided into two main sections, one for unamplified systems and one for amplified systems. Several different transmission parameters are covered, e.g. optical power levels, dispersion, OSNR, filter penalty, non-linear penalty etc.

1.2 In commercial confidence

The manual is provided in commercial confidence and shall be treated as such.

1.3 Document Revision History

Revision	Date	Description of changes
7.0.5 A	2022-07-07	Released version for Design Guidelines manual for R7.0.5
7.0.5 B	2022-08-12	Updated table with optical power levels for unamplified systems
7.1.1 A	2022-10-19	Updated tables with 100G QSFP-DD TQD011-TUNC-SO
7.1.2 A	2023-01-11	Released version for Design Guidelines manual for R7.1.2. No update from 7.1.1.
8.0.1 A	2023-04-25	Updated tables with 400G QSFP-DD TQD013-TUNC-SO and TQD014-TUNC-SO
8.1.1 A	2023-06-29	No updates
8.1.3 A	2023-08-22	No updates
8.1.4 A	2023-10-12	No updates
8.1.5 A	2023-11-02	Added info about 200G 16QAM mode
8.1.6 A	2023-12-01	Updated transceiver tables
8.1.7 A	2024-01-04	No update
9.0.1 A	2024-01-19	No update
10.0.1 A	2024-06-28	Added PPM-DCM10-100GHZ
10.0.2 A	2024-09-05	No update
11.0.2 A	2024-12-17	Added TQ2025-TUNC-SO and TQ2028-TUNC-SO
11.1.1 A	2025-03-26	No update
11.3.1 A	2025-04-24	No update
12.0.1 A	2025-06-24	Added TQD029-TUNC-SO, H-MD-09-xxxx-yyyy-8C, H-MD-32-9140-9605

2 Design rules for unamplified systems

2.1 Optical power budget

There are mainly two transmission parameters that will determine how long distance that can be covered by an unamplified system, optical power budget and dispersion limit. These works in the same way for both CWDM and DWDM when there are no amplifiers. In DWDM it is possible to add amplifiers or dispersion compensation to extend the distance.

The optical power budget is given by the difference between the transmitter output power and the receiver sensitivity of the transceiver or transponder that is used. It is easiest to work with logarithmic scale and express power levels in dBm. 1mW = 0 dBm.

The Tx output power and Rx sensitivity for different transceivers can be found in the data sheets. Sometimes the receiver sensitivity will also depend on the dispersion and that can be expressed as a dispersion penalty.

Power budget = Tx output power – Rx sensitivity - Dispersion penalty
Power budget is expressed in dB.

SO part number	Traffic format	Min Tx power [dBm]	Overload [dBm]	Rx Sensitivity [dBm]	Dispersion penalty [dB]
SO-SFP-10GE-ER-Dxxxx	10G (ER 40km)	-1	-1	-15	2dB @ +800ps/nm
SO-TSFP-10G-ZR-DWDM-A	10G (ZR 80km)	-1	-7	-24*	3dB @ +1400ps/nm
SO-SFP-16GFC-ER-Dxxxx	16GFC (ER)	0	-2	-13	2dB @ +800ps/nm
SO-SFP28-L10E-Dxxxx-I	25G	0	-5	-18	NA
32G-IR-Dxxx-BR	32G	-3	+2	-10	NA
SO-CFP-LPC-DWDM	100G QPSK	-5	0	-30	0.5dB@40000ps/nm
SO-TQSFP-DD-4CC-ZR	400G 16QAM CFEC	-10	0	-20	NA
SO-TQSFPDD4CCZRP	400G 16QAM OFEC	-13 -10***	0	-21	NA
SO-TQSFPDD4CCZRP	300G 8QAM	-12 -11***	0	-23	NA
SO-TQSFPDD4CCZRP	200G QPSK	-10.5 -8.5***	0	-29****	NA
SO-TQSFPDD4CCZRP	100G QPSK	-6	0	-32****	NA
TQD011-TUNC-SO	100G QPSK	-5	0	-32****	NA
TQ2025-TUNC-SO	100G QPSK	-8	+3	-30	NA
TQ2028-TUNC-SO	100G QPSK	-8	+3	-30	NA
TQD013-TUNC-SO	400G 16QAM OFEC	0	+13	-21	NA
TQD014-TUNC-SO	400G 16QAM OFEC	0	+3	-23	NA
TQD029-TUNC-SO	400G QPSK	1	+15	-27	NA

* = Assume 3dB improvement with FEC
** = Per lane. 2 lanes per channel
***=Higher Tx power possible with special settings on pulse shaping, but then the signal is wider
****=Default LOS threshold -28dBm. Must be changed with smartboard if lower value is needed.

Figure 1. *Example of power budget parameters for different transceivers*

The overload value shows the maximum input power that can be tolerated on the receiver. With higher power it is possible to get bit errors and damage the receiver.

The maximum distance that can be reached will depend on the fiber properties and attenuation that is introduced by different components in the system. The attenuation of the fiber is different for different wavelengths.

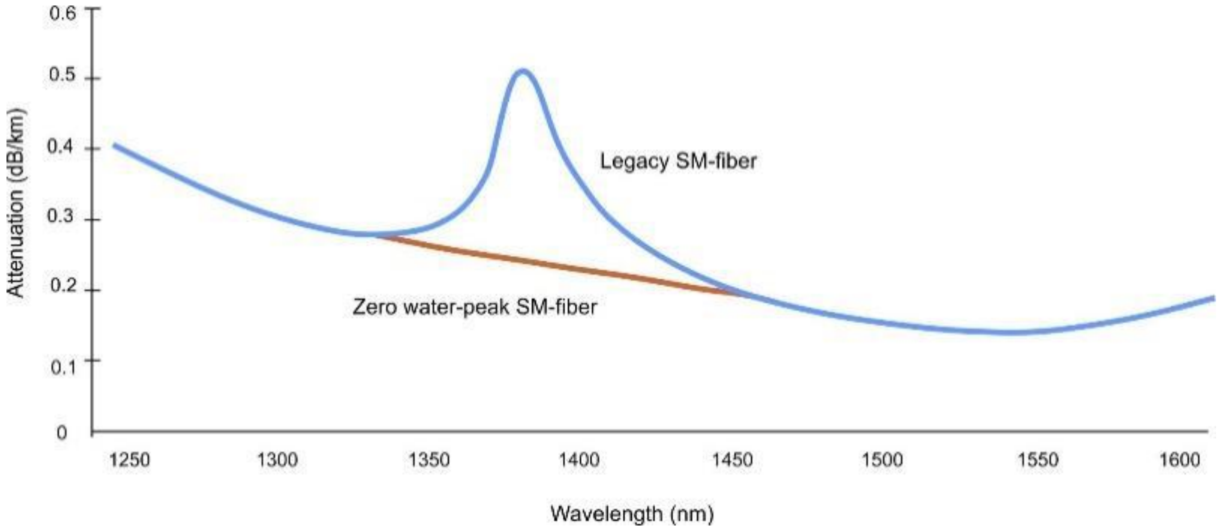


Figure 2. *Typical fiber attenuation*

All components in the system will add loss to the system. The loss for different components can be found in the data sheets. An unamplified system will work when the power level and dispersion at the receiver is within the specified range.

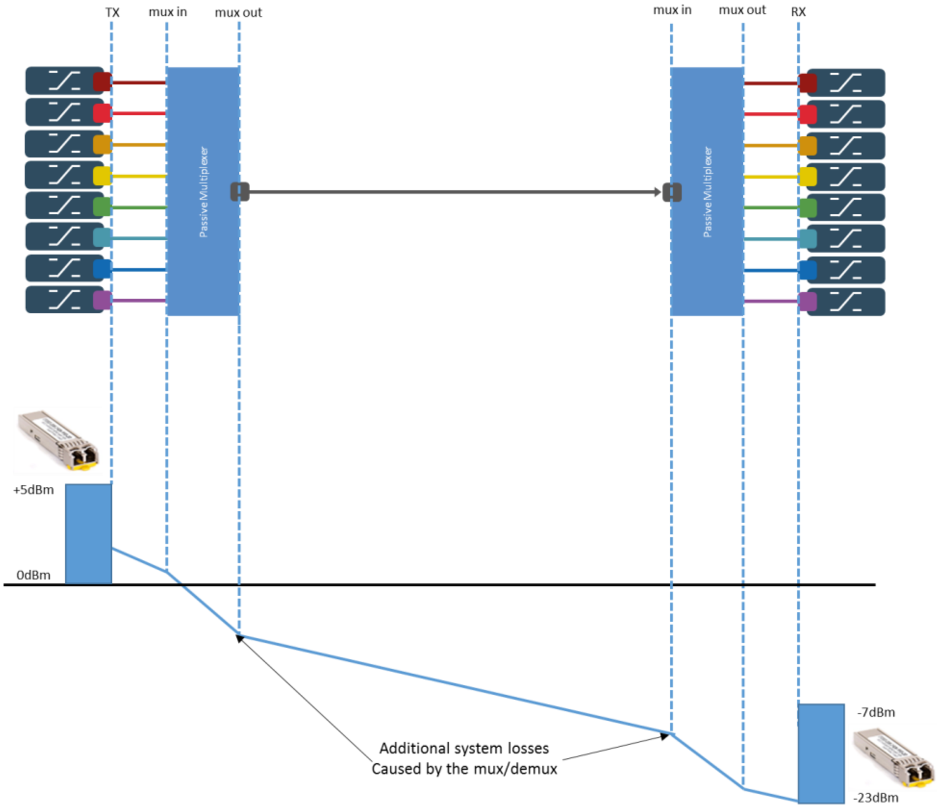


Figure 3. *Example of power calculation for unamplified system*

Product	Add loss [dB]	Drop loss [dB]	Add+drop loss [dB]	Express loss [dB]	Filter 3dB BW [GHz]	Isolation adjacent channels [dB]	Isolation non-adjacent channels [dB]
H-MD-40-921-960	5.9 (5.4)	5.9 (5.4)			80	11	21
H-MD-16-xxx-yyy	4.4 (4.0)	4.4 (4.0)	6.5 (5.9)	4.8 (4.3)	~60*	28	40
H-MD-09-xxx-yyy	3.1 (2.8)	3.1 (2.8)	4.5 (4.0)	3.5 (3.2)	~60*	28	40
H-MD-09-xxx-yyy-EM-LL	2.8 (2.5)	2.8 (2.5)	4.8 (4.3)	1.0 (0.8)	~60*	30	40
H-OADM1x4-xxx-yyy	2.5 (2.2)	2.5 (2.2)	3.5 (3.2)	1.8 (1.6)	~60*	28	40
H-OADM2x4-xxx-yyy	2.5 (2.2)	2.5 (2.2)		3.2 (2.9)	~60*	28	40
H-MD-09-xxx-yyy-4C	3.0 [3.5]	3.0 [3.5]	4.6 [5.2]	0.9 [1.0]	72.5	28	40
H-OADM1x4-xxx-yyy-4C	2.2 [2.5]	2.2 [2.5]	3.6 [4.0]	0.9 [1.0]	72.5	28	40
H-OADM2x4-xxx-yyy-4C	2.2 [2.8]	2.2 [2.8]	3.6 [4.5]	1.8 [2.0]	72.5	28	40
H-MD-09-xxxx-yyyy-8C	3.0 [3.5]	3.0 [3.5]	4.6 [5.2]	2.4 [2.7]	135	20	35
H-MD-32-9140-9605		6.0			150	9	30

( ) Values in brackets represent typical loss
[ ] Values in brackets represent loss for I-temp
*=Not specified. Should not be used for 400G

Figure 4. *Example of loss values for H-series DWDM filters*

Example of power calculation to find out actual Rx power:

Rx power = Tx power – Fiber loss – Component losses

Example of power calculation to find out maximum allowed fiber loss:

Max allowed fiber loss = Tx power – Rx power – Dispersion penalty – Component losses

2.2 Dispersion

The chromatic dispersion is different for different wavelengths and different fiber types. The shape of the dispersion curve depends on the fiber type. For standard single mode fiber specified in ITU-T G.652 the dispersion is zero around 1300nm. The dispersion parameter of the fiber is expressed in units of ps/(nm*km).

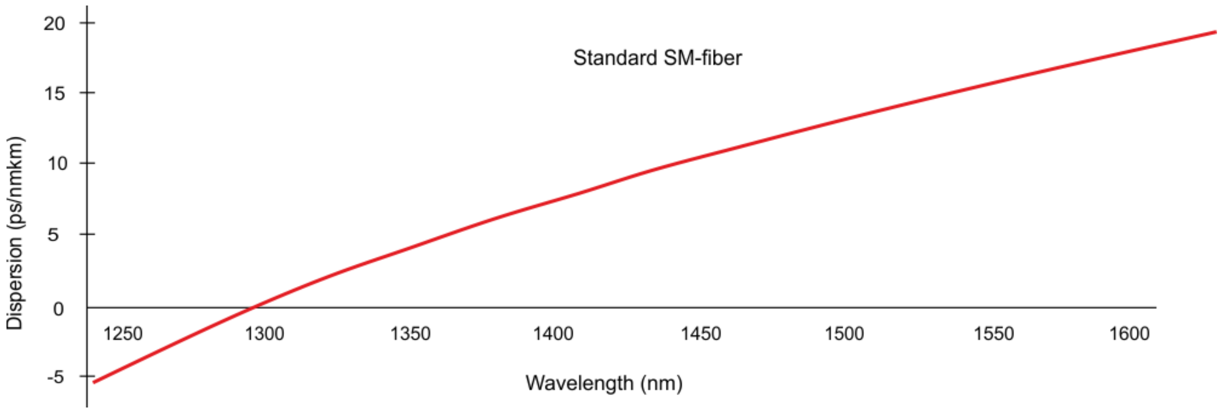


Figure 5. *Typical dispersion curve for standard G.652 fiber.*

Due to chromatic dispersion different wavelengths will travel at different speed and this will have a broadening effect of the signals in the time domain after transmission. The broadening will cause dispersion penalty that will degrade the transmission performance. All transceivers have a minimum and maximum dispersion limit that can be tolerated before the system gets too many bit errors.

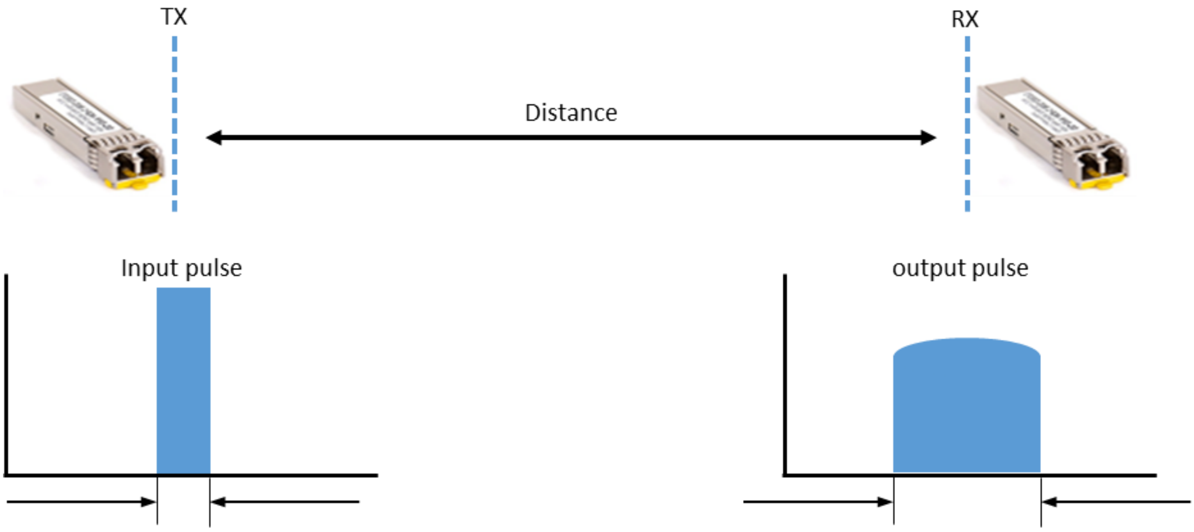


Figure 6. *Pulse broadening due to chromatic dispersion.*

The minimum and maximum dispersion limits for each transceiver can be found in the data sheets.

3 Design rules for amplified systems

3.1 Input power range

The recommended input power range is different for amplified systems compared to unamplified systems. The reason for this is that the transmission performance for amplified systems will be affected by many other parameters than just the receiver sensitivity. When the signal is mixed with noise it is necessary to have higher input power to get same bit error rate. For amplified systems there are also dynamic effects that can create some variation in input power. For this reason it is also good to have some safety margin on both minimum and maximum allowed input power.

For 10G the receiver sensitivity is around -23dBm and the overload around -7dBm. For an amplified system it is recommended to be in the range -10 to -20dBm.

SO part number	Traffic format	Min Tx power [dBm]	Overload [dBm]	Rx Input power range [dBm]
SO-SFP-10GE-ER-Dxxxx	**10G (ER)**	**-1**	**-1**	**-1 to -12**
SO-TSFP-10G-ZR-DWDM-A	**10G (ZR)**	**-1**	**-7**	**-10 to -20**
SO-TSFP-10G-ZR-DWDM-A	**10G w GFEC (ZR)**	**-1**	**-7**	**-10 to -20**
SO-TSFP-10G-ZR-DWDM-A	**10G w EFEC (ZR)**	**-1**	**-7**	**-10 to -20**
SO-SFP-16GFC-ER-Dxxxx	**16GFC (ER)**	**0**	**-2**	**-1 to -10**
SO-SFP28-L10E-Dxxxx-I	**25G**	**0**	**-5**	**-10 to -15**
32G-IR-Dxxx-BR	**32G**	**-3**	**+2**	**-2 to -10**
SO-QSFP-40G-Dxxxx	**40G PAM4**	**-1**	**+4**	**-7 to +4**
SO-QSFP28-Dxx	**100G PAM4**	**-11***	**+6**	**+6 to -2**
SO-QSFP28-Dxx-A	**100G PAM4**	**-7**	**+5**	**-3 to +4.5**

*Per lane. 2 lanes per channel

Figure 7. *Recommended input power range for non-coherent signals in amplified networks.*

For signals with very high OSNR it could be possible to run with lower input power that is closer to the receiver sensitivity. Check data sheets to find required OSNR to do this.

SO part number	Traffic format	Min Tx power [dBm]	Rx Input power range [dBm]
SO-CFP-LPC-DWDM	**100G QPSK**	**-5**	**-18**
SO-TQSFP-DD-4CC-ZR	**400G 16QAM CFEC**	**-10**	**-12 (0dB penalty) -14 (0.5dB penalty) -16 (1dB penalty)**
SO-TQSFPDD4CCZRP	**400G 16QAM OFEC**	**-13 -10***	**-12 (0dB penalty) -14 (0.5dB penalty) -16 (1dB penalty)**
SO-TQSFPDD4CCZRP	**300G 8QAM**	**-12 -11***	**-15 (0dB penalty) -17 (0.5dB penalty) -19 (1dB penalty)**
SO-TQSFPDD4CCZRP	**200G QPSK**	**-10.5 -8.5***	**-18 (0dB penalty) -20 (0.5dB penalty) -22 (1dB penalty)**
SO-TQSFPDD4CCZRP	**100G QPSK**	**-6**	**-20 (0dB penalty) -23 (0.5dB penalty) -25 (1dB penalty)**
TQD011-TUNC-SO	**100G QPSK**	**-5**	**-20 (0dB penalty) -23 (0.5dB penalty) -25 (1dB penalty)**
TQ2025-TUNC-SO (QSFP28)	**100G QPSK**	**-8**	**-18 (0dB penalty) -22 (1dB penalty)**
TQ2028-TUNC-SO (QSFP28)	**100G QPSK**	**-8**	**-18 (0dB penalty) -22 (1dB penalty)**
TQD013-TUNC-SO	**400G 16QAM OFEC**	**0**	**-12 (0dB penalty) -14 (0.5dB penalty) -16 (1dB penalty)**
TQD014-TUNC-SO	**400G 16QAM OFEC**	**0**	**-12 (0dB penalty)**
TQD029-TUNC-SO	**400G QPSK**	**1**	**-12 (0dB penalty) -22 (1dB penaty)**

*Higher Tx power possible with special settings on pulse shaping, but then the signal is wider

Figure 8. *Recommended input power range for coherent signals in amplified networks.*

The penalty for input power for coherent signals is OSNR penalty.

3.2 Dispersion

This section is divided into two parts, one for chromatic dispersion and one for polarization mode dispersion.

3.2.1 Chromatic dispersion

For amplified systems the power budget between transmitter and receiver can be extended with amplifiers. In this case the system could be limited by the dispersion tolerance. It will then be necessary to do dispersion compensation. This could be done in different ways, e.g. use passive or active dispersion compensating modules or electrical dispersion compensation.

3.2.1.1 Tunable Dispersion Compensation Module, TDCM

For cases where the dispersion compensation has to be very accurate it is necessary to use tuneable dispersion compensation modules, TDCMs. Smartoptics DCP-M series has integrated TDCM and can be used for signals that have a small dispersion tolerance, e.g. 100G PAM4 or 32G. The TDCM can do dispersion compensation corresponding to 80km SSMF G.652 fiber. Addional passive dispersion compensation modules, DCMs, could also be included to increase the maximum compensation by one DCP-M.

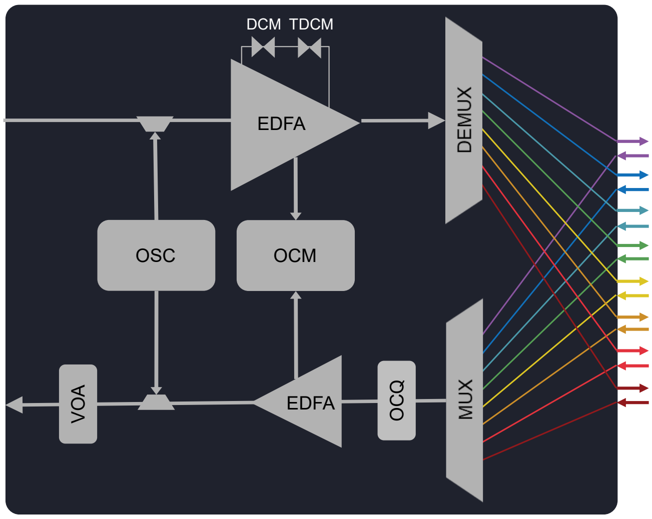


Figure 9. *DCP-M40-PAM4-ER+.*

3.2.1.2 Passive Dispersion Compensation Modules

For passive dispersion compensation it is possible to use modules based on fiber or fiber gratings. Smartoptics use modules based on fiber gratings. Those can be divided into two categories, channelized and continuous.

The channelized DCMs have pre-defined channel plans and channel widths. Three channelized DCMs are available as passive plugin modules in DCP-F.

- PPM-DCM10-100GHz
- PPM-DCM20-100GHZ
- PPM-DCM40-100GHZ
- PPM-DCM80-100GHz

These units have dispersion map that matches SSMF G.652 fiber. DCM20 will compensate for 20km of G.652 fiber for example.

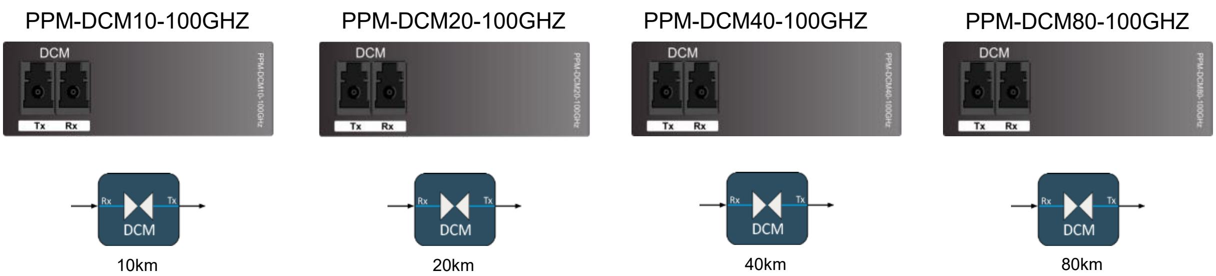


Figure 10. *DCMs in PPM form factor*

	PPM-DCM10-100GHZ	PPM-DCM20-100GHZ	PPM-DCM40-100GHZ	PPM-DCM80-100GHZ
Operating range	191.3-196.3 THz	191.3-196.3 THz	191.3-196.3 THz	191.3-196.3 THz
Compensation length	10 km	20 km	40 km	80 km
Channel spacing	100 GHz	100 GHz	100 GHz	100 GHz
Operation bandwidth	72 GHz	72 GHz	72 GHz	72 GHz
Dispersion at 196.3 THz	-156 ps/nm	-310 ps/nm	-619 ps/nm	-1238 ps/nm
Dispersion at 191.3 THz	-175 ps/nm	-356 ps/nm	-711 ps/nm	-1423 ps/nm
Insertion loss	4.5 dB	3 dB	3 dB	3 dB

Figure 11. *Optical parameters for PPM DCMs*

The continuous DCMs have no limitation on channel plan or bandwidth so they can be used also in networks with high baud rate signals like 400G. The continuous DCMs are external units with their own rack mounting. Two modules can be mounted in same 1RU rack mount.

Figure 12. *Mounting bracket with two continuous DCM modules*

SO part number	Short Description	Dispersion at 1545nm	Insertion loss [dB]
DCM-MB-2-19	1RU, 2-slot, 19" DCM Mounting brackets		
DCM-20	20km dispersion comp module (DCM)	-330	3.7
DCM-40	40km dispersion comp module (DCM)	-660	3.7
DCM-60	60km dispersion comp module (DCM)	-991	3.7
DCM-80	80km dispersion comp module (DCM)	-1321	3.7
DCM-100	100km dispersion comp module (DCM)	-1651	3.7
DCM-120	120km dispersion comp module (DCM)	-1981	3.7

Figure 13. *Optical parameters for continuous DCMs*

3.2.2 Dispersion tolerance for amplified systems

For standard non-coherent transceivers there are specified limits for both minimum and maximum dispersion. The values at each limit are usually associated with some penalty.

- For unamplified systems the penalty is on the receiver sensitivity.
- For amplified systems the penalty is on the OSNR tolerance.

The penalty is exponential and grows quite rapid close to the limits. In order to reduce the OSNR penalty it is recommended to narrow down the allowed dispersion range for amplified systems.

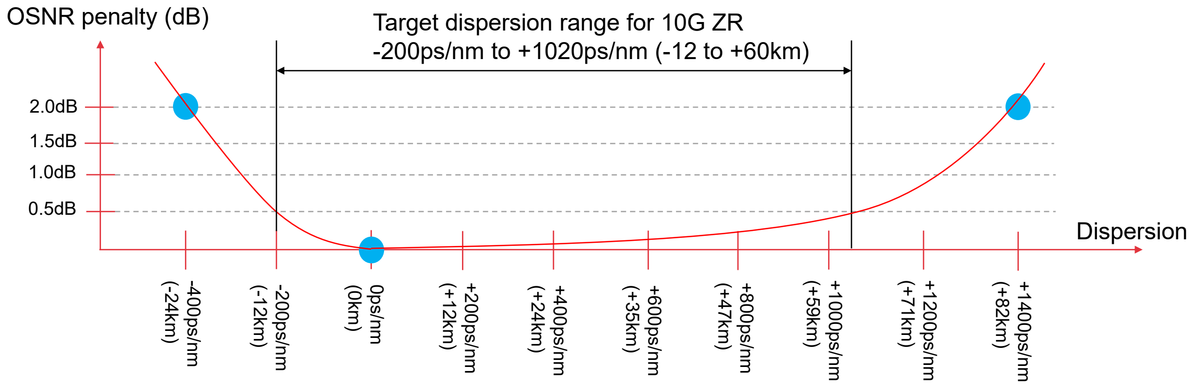


Figure 14. *Recommended dispersion range for 10G signals.*

	Traffic format	Chromatic Dispersion range unamplified [ps/nm]	Chromatic Dispersion range amplified [ps/nm]	PMD limit [ps]
SO-SFP-10GE-ER-Dxxxx	10G (ER 40km)	0 to +800	0 to +800	10
SO-TSFP-10G-ZR-DWDM-A	10G (ZR 80km)	-300 to +1400	-200 to +1020	10
SO-TSFP-10G-ZR-DWDM-A	10G w GFEC (ZR)	-300 to +1400	-200 to +1020	10
SO-TSFP-10G-ZR-DWDM-A	10G w EFEC (ZR)	-300 to +1400	-200 to +1020	10
SO-SFP-16GFC-ER-Dxxxx	16GFC (ER)	0 to +800	-200 to +600	6.25
SO-SFP28-L10E-Dxxxx-I	25G	-200 to +200	-200 to +200	4
32G-IR-Dxxx-BR	32G	-170 to +170	-170 to +170	3.125
SO-QSFP28-Dxx	100G PAM4	-100 to +100	-100 to +100	2
SO-QSFP28-Dxx-A	100G PAM4	-40 to +40	-40 to +40	2

Figure 15. *Dispersion range for non-coherent signals in amplified systems.*

Coherent signals have electrical dispersion compensation that is done in the Digital Signal Processor, DSP. This compensation is enough for most metro and regional systems. It means that additional dispersion compensation is not needed.

SO part number	Traffic format	Dispersion range [ps/nm]	PMD limit [ps]
SO-CFP-LPC-DWDM	100G QPSK	40000	25
SO-TQSFP-DD-4CC-ZR	400G 16QAM CFEC	2400	20
SO-TQSFPDD4CCZRP	400G 16QAM OFEC	13000	30
SO-TQSFPDD4CCZRP	300G 8QAM	26000	30
SO-TQSFPDD4CCZRP	200G QPSK	50000	30
SO-TQSFPDD4CCZRP	100G QPSK	80000	40
TQD011-TUNC-SO	100G QPSK	8600	40
TQ2025-TUNC-SO	100G QPSK	2400*	10
TQ2028-TUNC-SO	100G QPSK	2400*	10
TQD013-TUNC-SO	400G 16QAM OFEC	13000	30
TQD014-TUNC-SO	400G 16QAM OFEC	12000	20
TQD029-TUNC-SO	400G QPSK	58000	

*Entended mode with 6000 possible with 0.2W extra power

Figure 16. *Dispersion range for coherent signals in amplified systems.*

3.2.3 Polarization mode dispersion

Light will travel with different speed in different polarization states if the refractive index of the fiber core is not 100% symmetric. The core could be affected by manufacturing asymmetries or dynamic changes due to tension of temperature. Differential group delay, DGD, is the measured time difference for light in two different polarizations at a certain point in time.

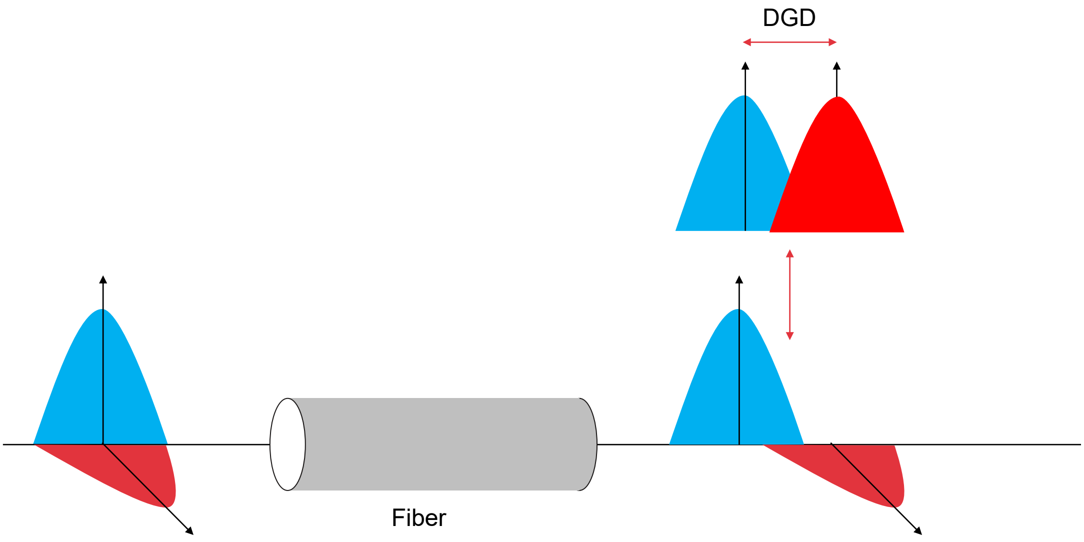


Figure 17. *Differential Group Delay*

The DGD values will vary over time and it is necessary to measure multiple values and apply a statistical approach. Polarization Mode Dispersion, PMD, is defined as the average

value of all DGD values. PMD must be measured over a long time period or over many wavelengths to get good statistics. The total PMD can be calculated as the square root of the sum of squares for all components:
PMD_tot = sqrt (PMD1^2 + PMD2^2 + ….)

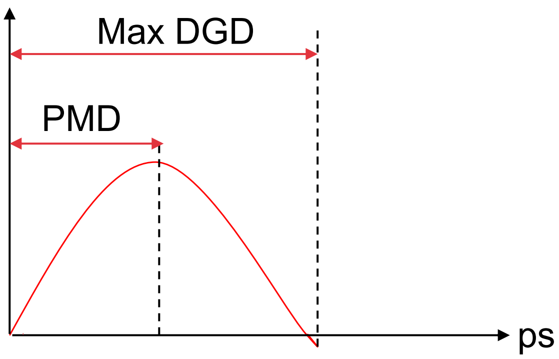
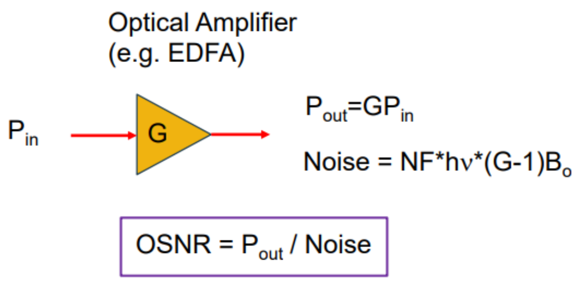


Figure 18. *PMD is the average of the DGD values.*

For PMD it is not possible with passive compensation since the DGD values varies over time. It is also very expensive to use tuneable PMD compensators so it is recommended to regenerate the signal before the PMD limit is reached.

3.3 OSNR limitations

Amplifiers will add noise to the system and the relation between signal and noise is called Optical Signal to Noise Ratio, OSNR. OSNR is defined as the ratio between signal and noise in 0.1nm spectral window.



OSNR = ratio of signal power to optical noise

P_{out} = signal power of a DWDM channel of interest

Noise = amplified spontaneous emission noise power in both optical polarizations

G = amplifier gain

NF = amplifier noise figure

$h\nu$ = photon energy at wavelength of interest (e.g. 1550 nm)

B_o = optical bandwidth for noise measurement (typically 0.1 nm)

Figure 19. *OSNR in amplifier.*

When G is big it is possible to simplify the formula to be OSNR = Pin / ($NF*h\nu*B_o$)

Then it is also possible to derive a simple formula for the OSNR for one amplifier in logarithmic scale:

OSNR = 58 + Pin – NF, where Pin is the input power in dBm and NF is the noise figure in dB.

For multiple amplifiers it is possible to calculate the OSNR for multiple amplifiers in linear scale.

$$\frac{1}{OSNR} = \frac{1}{OSNR1} + \frac{1}{OSNR2}$$

3.3.1 TX OSNR

Many coherent signals have an integrated amplifier on the transmit side and that amplifier will generate noise. It is possible to define a TX OSNR value. This value can be different at the signal wavelength and at other wavelengths. The value at the transmitted wavelength is called TX OSNR inband. The value at other wavelengths is called TX OSNR outband.

For standard filter based solution it is the TX OSNR inband that is important.
For colorless solutions with couplers both the TX OSNR inband and outband will be added.

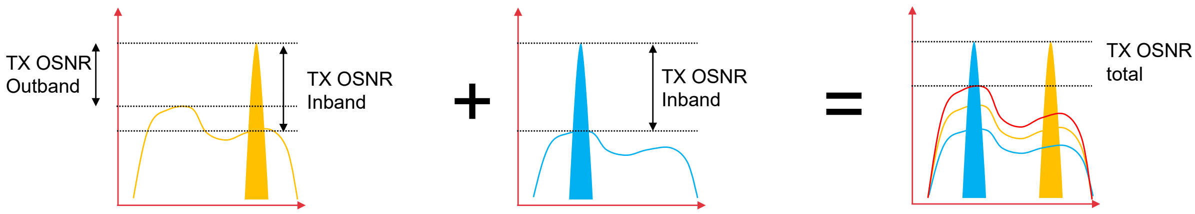


Figure 20. *Example of aggregated TX OSNR for two coherent signals that are combined in a coupler.*

SO part number	Traffic format	TX OSNR (inband) [dB]	TX OSNR (outband) [dB]
SO-CFP-LPC-DWDM	100G QPSK	40	
SO-TQSFP-DD-4CC-ZR	400G 16QAM CFEC	42	42
SO-TQSFPDD4CCZRP	400G 16QAM OFEC	42	42
SO-TQSFPDD4CCZRP	300G 8QAM	42	42
SO-TQSFPDD4CCZRP	200G QPSK	42	42
SO-TQSFPDD4CCZRP	100G QPSK	42	42
TQD011-TUNC-SO	100G QPSK	42	42
TQ2025-TUNC-SO	100G QPSK	40	35
TQ2028-TUNC-SO	100G QPSK	40	35
TQD013-TUNC-SO	400G 16QAM OFEC	38	42
TQD014-TUNC-SO	400G 16QAM OFEC	43	40
TQD029-TUNC-SO	400G QPSK	37	TBD

Figure 21. *TX OSNR for coherent transceivers.*

3.3.2 OSNR tolerance

The OSNR tolerance is one of the most important parameters for the transmission performance in amplified networks. It is the OSNR value that is required for a certain condition to get Bit Error Rate, BER=1e-12.

For non-coherent signals it is possible to tolerate more noise for lower bit rates, i.e. lower OSNR values can be accepted. It is possible to improve the OSNR tolerance by adding Forward Error Correction, FEC, coding.

The OSNR tolerance will depend on the input power level and dispersion level. In order to improve the OSNR tolerance it is recommended to relax the allowed input power range and dispersion range compared to unamplified systems.

SO part number	Traffic format	Rx Input power range [dBm]	OSNR limit [dB]	Dispersion range [ps/nm]
SO-SFP-10GE-ER-Dxxxx	10G (ER)	-1 to -12	26	-200 to +800
SO-TSFP-10G-ZR-DWDM-A	10G (ZR)	-10 to -20	26	-200 to +1020
SO-TSFP-10G-ZR-DWDM-A	10G w GFEC (ZR)	-10 to -20	17	-200 to +1020
SO-TSFP-10G-ZR-DWDM-A	10G w EFEC (ZR)	-10 to -20	15	-200 to +1020
SO-SFP-16GFC-ER-Dxxxx	16GFC (ER)	-1 to -10	29	0 to +600
SO-SFP28-L10E-Dxxxx-I	25G	-10 to -15	33	-200 to +200
32G-IR-Dxxx-BR	32G	-2 to -10 -2 to -4	33 29	-170 to +170 -170 to +170
SO-QSFP28-Dxx	100G PAM4	+6 to -2*	31	-100 to +100
SO-QSFP28-Dxx-A	100G PAM4	+4.5 to -3	33.5	-40 to +40

*Per lane. 2 lanes per channel

Figure 22. *OSNR tolerance for non-coherent transceivers.*

For coherent signals the OSNR tolerance will be determined by the FEC in the DSP, the modulation format, the bit rate and the baud rate.

SO part number	Traffic format	Min Tx power [dBm]	Rx Input power range [dBm]	TX OSNR (inband) [dB]	TX OSNR (outband) [dB]	OSNR limit [dB]
SO-CFP-LPC-DWDM	100G QPSK	-5	-18	40		14
SO-TQSFP-DD-4CC-ZR	400G 16QAM CFEC	-10	-12 (0dB penalty) -14 (0.5dB penalty) -16 (1dB penalty)	42	42	26
SO-TQSFPDD4CCZRP	400G 16QAM OFEC	-13 -10*	-12 (0dB penalty) -14 (0.5dB penalty) -16 (1dB penalty)	42	42	23.4
SO-TQSFPDD4CCZRP	300G 8QAM	-12 -11*	-15 (0dB penalty) -17 (0.5dB penalty) -19 (1dB penalty)	42	42	20.3
SO-TQSFPDD4CCZRP	200G QPSK	-10.5 -8.5*	-18 (0dB penalty) -20 (0.5dB penalty) -22 (1dB penalty)	42	42	15.0
SO-TQSFPDD4CCZRP	100G QPSK	-6	-20 (0dB penalty) -23 (0.5dB penalty) -25 (1dB penalty)	42	42	11.8
TQD011-TUNC-SO	100G QPSK	-5	-20 (0dB penalty) -23 (0.5dB penalty) -25 (1dB penalty)	34	30	15.5
TQ2025-TUNC-SO TQ2028-TUNC-SO	100G QPSK	-8	-18 (0dB penalty) -22 (1dB penalty)	40	35	16.5
TQD013-TUNC-SO	400G 16QAM OFEC	0	-12 (0dB penalty) -14 (0.5dB penalty) -16 (1dB penalty)	38	42	23.4
TQD014-TUNC-SO	400G 16QAM OFEC	0	-12 (0dB penalty)	43	40	23.5
TQD029-TUNC-SO	400G QPSK	1	-12 (0dB penalty) -22 (1dB penaty)	37		17.9

*Higher Tx power possible with special settings on pulse shaping, but then the signal is wider

Figure 23. *OSNR tolerance for coherent transceivers.*

3.4 Non-linear penalty

Light with high intensity can cause local changes in the refractive index in the fiber (Kerr effect). Changes in refractive index will affect the phase of the signal and together with dispersion also the amplitude can be affected.

There are non-linear effects related to both single channel transmission (e.g. SPM=Self Phase Modulation) and multi-channel transmission (e.g. XPM=Cross Phase Modulation)

The degradation of transmission performance can be expressed in terms of OSNR penalty. This means that the OSNR has to be increased to reach same BER (Bit Error Rate) compared to transmission where the non-linear effect is not active.

The non-linear OSNR penalty will depend on the launch power in the fiber, the fiber type, the channel spacing and the type of signal formats that are transported.

Signals with amplitude modulation (e.g. 10G or 100G PAM4) will cause more penalty for coherent signals than other coherent signals that are phase modulated.

The penalty can be reduced by lowering launch power or by introducing guard channels.

3.4.1 Guard channels

Guard channels are unused channels that are introduced to reduce the interaction between neighbor channels. Normally it is not required to have guard channels for a group of signals of same signal type. It is often required to have guard channels when non-coherent and coherent signals are mixed.

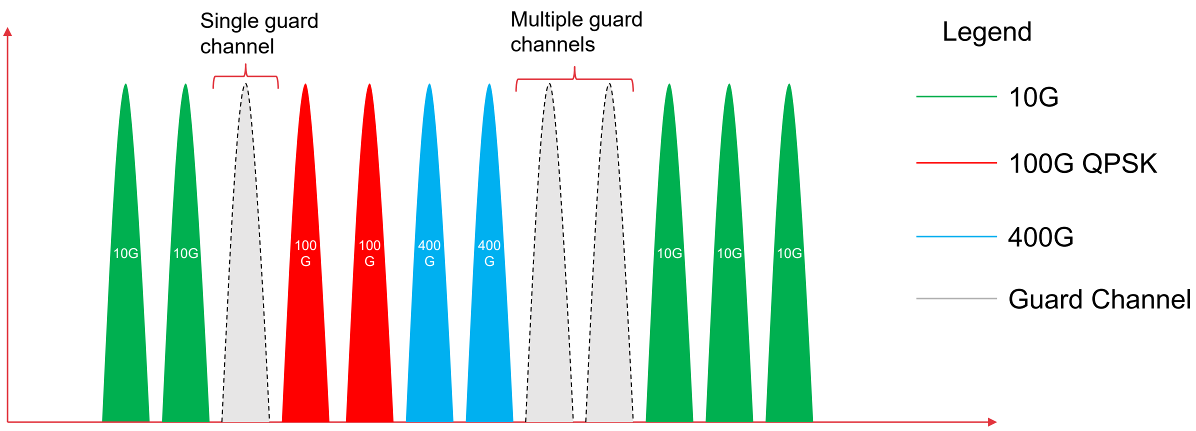


Figure 24. *Example of mixed signal types and guard channels.*

3.4.2 Maximum launch power into fiber

The non-linear effects increase with increased launch power into the fiber. There is a maximum launch power that can be affected for each signal type. The maximum launch power will also depend on fiber type, channel spacing and number of spans.

SO part number	Traffic format	Single span, Max launch power (dBm)	Multiple spans**, Max launch power (dBm)
SO-CFP-LPC-DWDM	100G QPSK	+11*	4*
SO-TQSFP-DD-4CC-ZR	400G 16QAM CFEC	+7*	3.5*
SO-TQSFPDD4CCZRP	400G 16QAM OFEC	+7*	3.5*
SO-TQSFPDD4CCZRP	300G 8QAM	+7*	3.5*
SO-TQSFPDD4CCZRP	200G QPSK	+7*	3.5*
TQD013-TUNC-SO	200G 16QAM	+7*	3.5*
SO-TQSFPDD4CCZRP	100G QPSK	+11*	4*

*OSNR penalty and guard channels may be required
**Span not contributing to penalty if <2km or launch power <-5dBm/ch

Figure 25. *Maximum launch power for different signal types.*

3.4.3 Non-linear penalty for 100G QPSK

For 100G QPSK it is possible to calculate the OSNR penalty with GNPy tool. The table below shows calculated values for different scenarios.

Fiber spans	Launch power (dBm/ch)	Channel spacing (GHz)	Guard channels	GNPy OSNR penalty(dB)
1	11	100	0	3.15
1	9	100	0	1.52
1	7	100	0	0.66
1	4	100	0	0.24
2	4	100	0	0.44
3	3.5	100	0	0.43
5	3.5	100	0	0.71
10	3.5	100	0	1.56
15	3.5	100	0	1.85
20	3.5	100	0	2.14

Figure 26. *Non-linear penalty table for 100G QPSK on G.652 fiber*

The launch power in the table is average over multiple spans.

3.4.4 Non-linear penalty for 10G + 100G QPSK

For mixed cases with 10G + 100G QPSK it is not possible to calculate the OSNR penalty with GNPy tool. Contact Smartoptics for designs with mixed 10G and 100G.

3.4.5 Non-linear penalty for 200G and 400G 16QAM

For 400G 16QAM it is possible to calculate the OSNR penalty with GNPy tool. The table below shows calculated values for different scenarios.

Fiber spans	Launch power (dBm/ch)	Channel spacing (GHz)	Guard channels	GNPy OSNR penalty(dB)
1	7	100	0	2.03
1	4	100	0	0.55
1	0	100	0	0.06
2	4	100	0	0.82
2	0	100	0	0.14
3	3.5	100	0	0.8
3	0	100	0	0.20
5	3.5	100	0	1.21
5	0	100	0	0.29
10	3.5	100	0	1.48

Figure 27. *Non-linear penalty table for mixed 400G 16QAM on G.652 fiber*

The launch power in the table is average over multiple spans.

3.4.6 Non-linear penalty for mix 10G + 200/400G 16QAM

For mixed cases with 10G + 200/400G 16QAM it is not possible to calculate the OSNR penalty with GNPy tool. Contact Smartoptics for designs with mixed 10G and 200/400G.

3.5 Filter penalty

Different signal formats have different bandwidth and it is important to assure that filters, ROADMs, DCMs and other components have the required bandwidth for the signal to pass through.

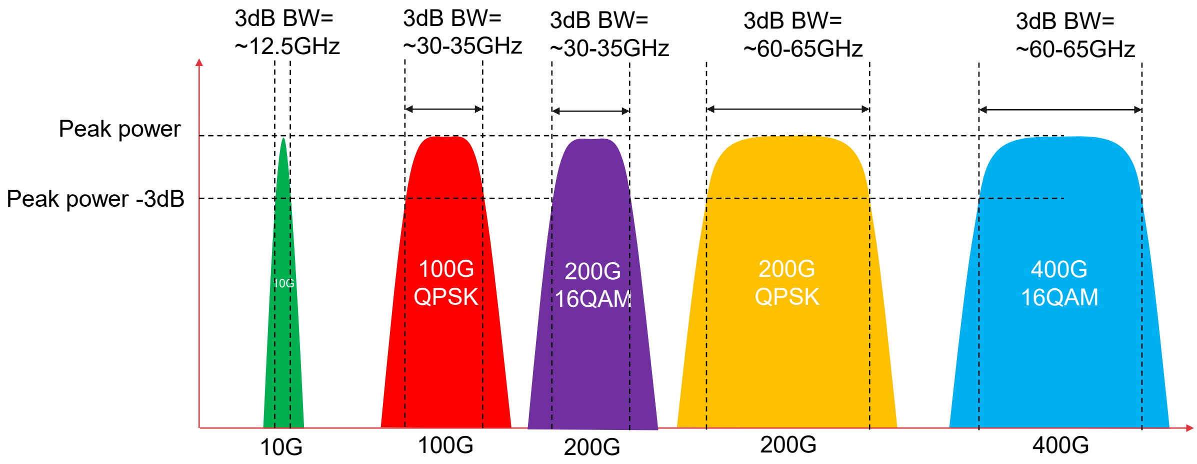


Figure 28. *Example of 3dB bandwidths for different signal formats*

The signal bandwidth will depend on bit rate, modulation format, baud rate and FEC. For low-speed signals like 10G it is not a problem to pass through filters since the signals are very narrow. However, for 400G signals with high baud rate it could be difficult to pass through DWDM filters that are not specified with for wide signals.

The filter shape is different for ROADMs, AWGs and thin film filters. If multiple filters are passed the cascaded bandwidth will smaller. The cascaded filter bandwidth will depend on the filter shape.

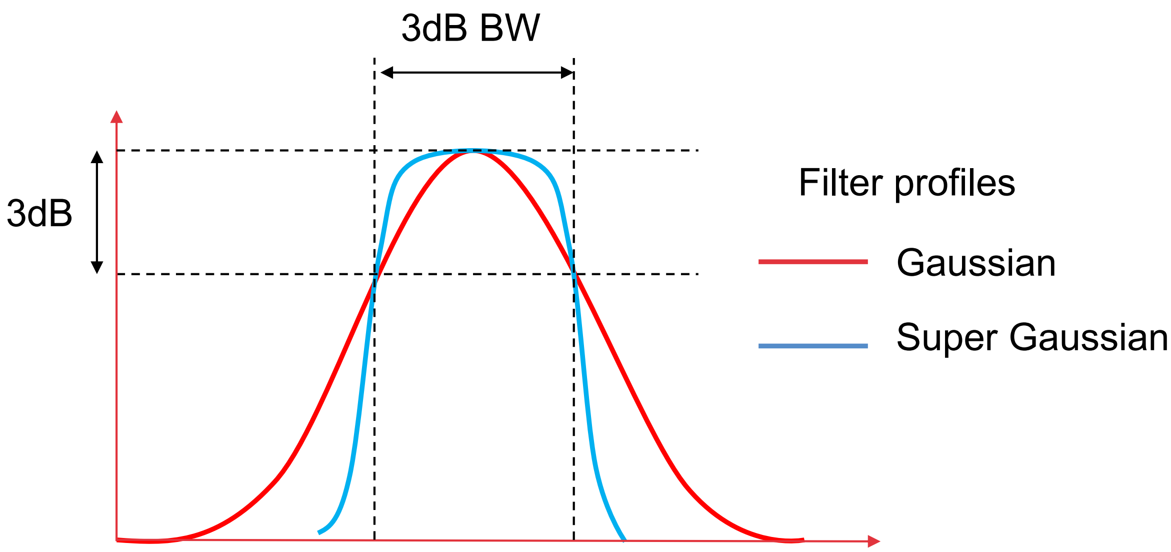


Figure 29. *Example of different filter shapes.*

The filter shape and filter bandwidth will affect how much OSNR penalty a signal will get.

Product	Filter 3dB BW [GHz]	Comment
H-MD-40-921-960	80	Could be used for high baud rate signals
H-MD-16-xxx-yyy	~60	Filter BW not specified. Should not be used for high baud rate signals
H-MD-09-xxx-yyy	~60	Filter BW not specified. Should not be used for high baud rate signals
H-MD-09-xxx-yyy-EM-LL	~60	Filter BW not specified. Should not be used for high baud rate signals
H-OADM1x4-xxx-yyy	~60	Filter BW not specified. Should not be used for high baud rate signals
H-OADM2x4-xxx-yyy	~60	Filter BW not specified. Should not be used for high baud rate signals
H-MD-09-xxx-yyy-EM-4C	72.5	Could be used for signals with baudrate 60-65Gbaud
H-OADM1x4-xxx-yyy-4C	72.5	Could be used for signals with baudrate 60-65Gbaud
H-OADM2x4-xxx-yyy-4C	72.5	Could be used for signals with baudrate 60-65Gbaud
H-MD-09-xxxx-yyyy-8C	135	Could be used for signals with baudrate 120-125Gbaud
H-MD-32-9140-9605	150	Could be used for signals with baudrate 120-125Gbaud

Figure 30. *3dB bandwidth for different H-series DWDM filters.*

Filter penalty for high baud rate signals around 60-65Gbaud:

- 2 x 40ch AWG with 80GHz 3dB BW =>0.5dB penalty
- 4 x 40ch AWG with 80GHz 3dB BW =>1.5dB penalty

Filter penalty can also come from channelized dispersion compensation. The bandwidth for channelized DCMs in PPM form factor is 75GHz so those can also create penalty for high baud rate signals. The bandwidth of tunable dispersion compensation modules will depend on how much the unit will compensate. More dispersion compensation will mean a smaller bandwidth. Small bandwidth can affect both PAM4 signals and coherent signals with high baud rate.

TDCM 100 GHz
TDCM tuned @ 0 km

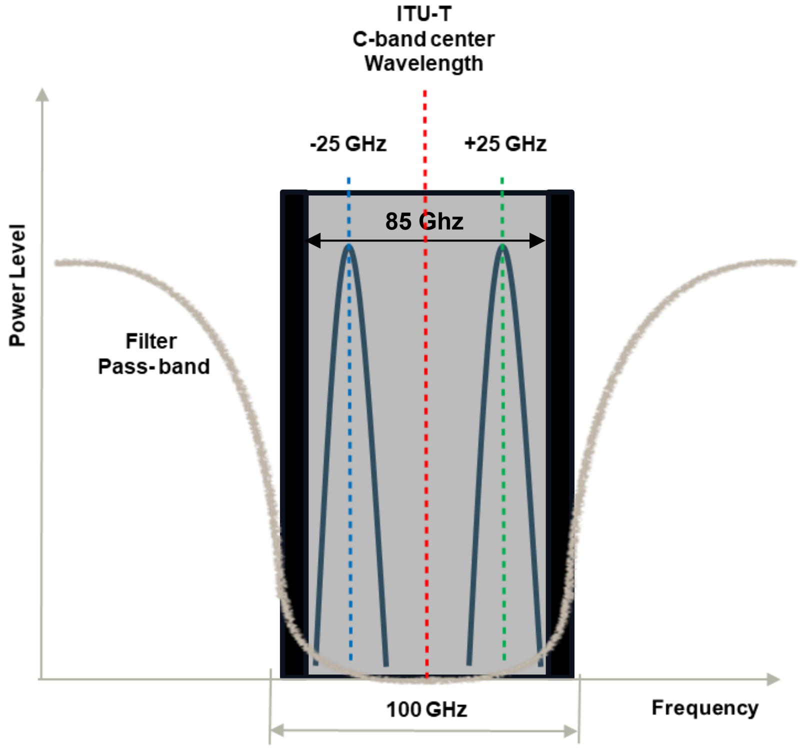


Figure 31. *3dB bandwidth for TDCM tuned to 0km.*

For TDCMs with very small compensation it is possible to get PAM4 and high baud rate signals to pass without penalty. When the compensation is around 40km the bandwidth is around 75GHz and then penalty is starting to kick in.

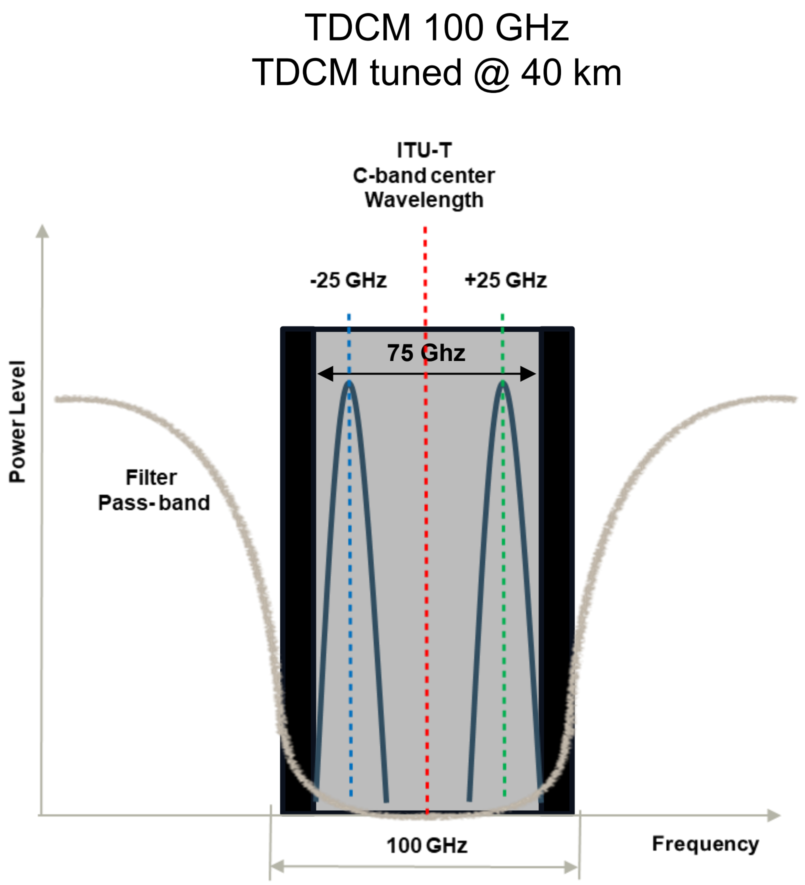


Figure 32. *3dB bandwidth for TDCM tuned to 40km.*

When the TDCM is tuned to more than 40km it is not recommended to use PAM4 with two carriers in same 100GHz frequency slot or high baud rate signals with baud rates over 60Gbaud.

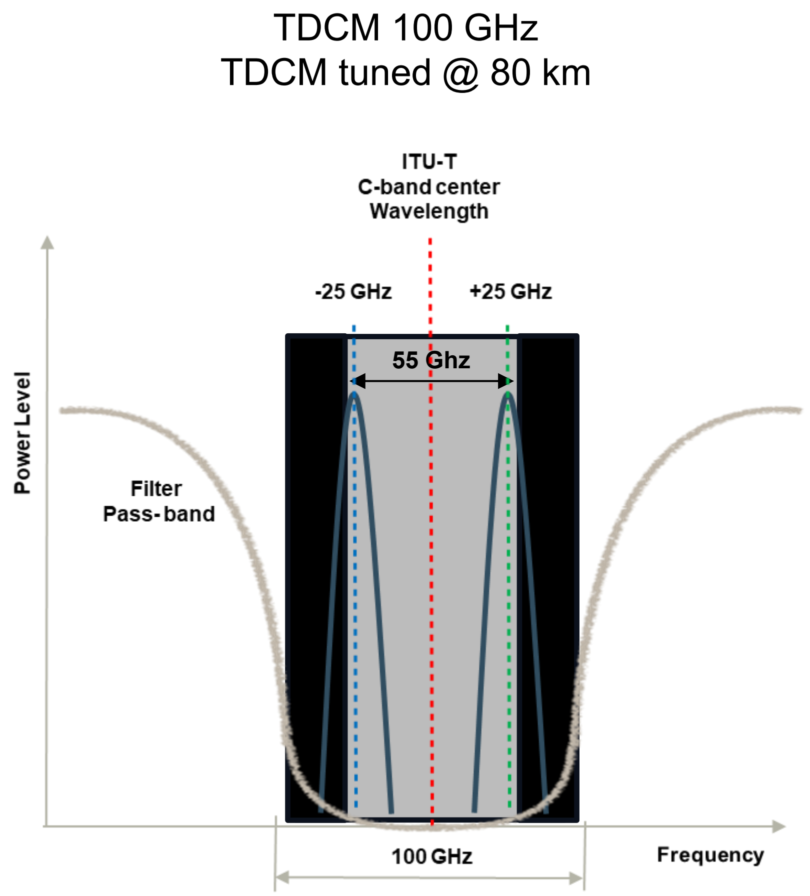


Figure 33. *3dB bandwidth for TDCM tuned to 80km.*

4 System specific design rules

4.1 DCP-M design rules

Since all components are integrated in DCP-M it is possible to pre-calculate the maximum attenuation and distance that can be covered.

DCP-M Model	Loss budget (dB)	Dispersion budget (km)	Supported Formats
DCP-M40-PAM4-ER	**0-14 dB**	**0-40 km**	**PAM4, Coherent & NRZ**
DCP-M40-PAM4-ER+	**0-14 dB**	**20-60 km**	**PAM4, Coherent & NRZ**
DCP-M40-PAM4-ZR *	**0-18 dB**	**0-80 km**	**PAM4, Coherent & NRZ**
DCP-M40-C-ZR+ **	**0-29 dB**	**0-140 km**	**Coherent & NRZ**
DCP-M8-PAM4	**0-20 dB**	**0-80km**	**PAM4**

* Number of PAM4 signals limited to 20 channels
** Distance depending on modulation format

Figure 34. *Distance and attenuation limits for DCP-M.*

The distance and attenuation for all DCP-M40-PAM4 options above are valid for PAM4. Same units may be used without PAM4 and then the distance and attenuation could be different depending on the signal format. See DCP-M manual for different operational modes and traffic options.