# Annex 200B (Informative)
# Super-PON black link implementation

## 200B.1 Example of Super-PON black link implementation

Figure 1 shows an example of Super-PON black link implementation, able to satisfy the Super-PON objectives. In this arrangement, the MUX/Amp module contains all the discrete optical components needed for Super-PON, including the MUX/DEMUX, amplifiers, and band MUX. The MUX/Amp is expected to reside inside the central office (CO). Each set of wavelengths is aggregated into a simplex fiber before connecting to the optical distribution network (ODN). Packaging of the components inside the MUX/Amp module is at the discretion of the operator. In this example implementation they are packaged into a single module to simplify deployment. Alternatively, they could be deployed as individual components.

The wavelength router and the power splitters are expected to both be a part of the outside plant, or optical distribution network. The wavelength router is expected to be a passive component that is temperature stabilized enough to operate over a sufficiently wide temperature range to be placed outside in a temperature uncontrolled environment.
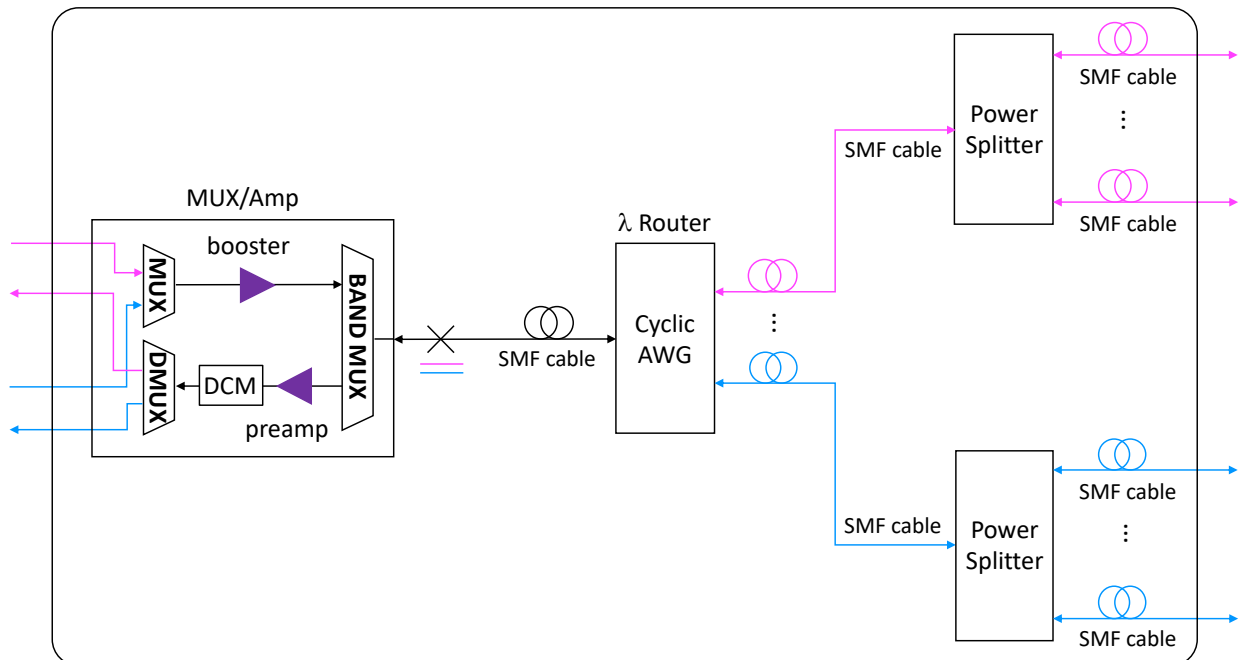


**Figure 1 - Example of Black Link Implementation**

Table 1 shows the expected loss of a 50 km Super-PON passive ODN link, which is defined to be from the MUX/Amp module to an ONU. 41 dB is the maximum link loss supported by the black link implementation described in this Annex.

**Table 1 - Expected loss of a 50 km Super-PON access link**

| Component | Count | Typical loss [dB] | Worst case loss [dB] | Total loss [dB] |
|---|---|---|---|---|
| Fiber [km] | 50 | 0.24 | 0.24 | 12 |
| Connectors[1] | 6 | 0.2 | 0.5 | 1.5 |
| Splices[2] | 17 | 0.05 | 0.2 | 1 |
| CAWG[3] | 1 | 4 | 4 | 4 |

| | | | | |
|---|---|---|---|---|
| 1:64 Splitter[4] | 1 | 20.5 | 20.5 | 20.5 |
| Margin | 1 | 2 | 2 | 2 |
| **Total** | | | | **41** |

[1] Assumes 1 bad connector and 5 good ones per link.

[2] Assumes 10 inline splices and 7 for components/cables changes.

[3] Assumes low-loss design.

[4] Assumes premium grade optical splitters.

Note that premium grade 1:64 optical splitters and/or low-loss design CAWGs are required only at the maximum link length of 50 km. For smaller link lengths (e.g., <40 km) average components can be used to achieve the 41 dB maximum link loss, due to the reduced fiber loss.

## 200B.2 MUX/Amp

Subclause 200B.2 describes an example implementation of the MUX/Amp, with components arranged as shown in Figure 1.

### 200B.2.1 MUX/DEMUX characteristics

The MUX and DEMUX may be implemented using flat-top arrayed waveguide gratings (AWG). The MUX and DEMUX functions in the MUX/Amp do not require cyclical properties, so they should be designed to have a free spectral range (FSR) significantly wider than the defined frequencies of operation. Each AWG operates over one 16-channel wavelength band: the MUX operates over C-band 1; the DEMUX operates over L-band 1. The required specifications for the flat-top AWG based MUX/DEMUX are shown in Table 2.

**Table 2 - Specifications for the flat-top AWG based MUX/DEMUX**

| Parameter | Conditions | Min | Max |
|---|---|---|---|
| Number of channels | | 16 | |
| Number of bands | | 1 | |
| Channel spacing (MUX) [GHz][*] | | 98.8 | |
| Operational wavelength (MUX) [nm] | | 1547.715 | 1563.047 |
| Channel spacing (DEMUX) [GHz][*] | | 100.0 | |
| Operational wavelength (DEMUX) [nm] | | 1583.907 | 1599.594 |
| Clear pass band (CPB) [GHz] | Relative to nominal | -15 | +15 |
| In-channel ripple | Over CPB for all SOP | | 1.0 |
| Insertion loss (IL) [dB] | Over CPB for all SOP | | 5.5 |
| Adjacent channel crosstalk [dB] | Over CPB of adjacent channels | -23 | |
| Non-adjacent channel crosstalk [dB] | Over CPB of non-adjacent channels | -28 | |
| Total integrated crosstalk [dB] | Sum of all crosstalk | -20 | |
| Operating temperature [C] | | 0 | 40 |

[*] Channel spacing for the four wavelength bands are different because of cyclical AWG implementation constraints. This channel plan allows the use of a single cyclical AWG for the 4-band wavelength router.

### 200B.2.2 Booster optical amplifier characteristics

The downstream booster optical amplifier may be implemented using a constant gain high-power erbium-doped fiber amplifier (EDFA). EDFAs are chosen to minimize inter-channel interactions between the WDM

channels. Gain flattening is required over the 16-channel operational range to minimize the imbalance between wavelength channels after amplification. The required specifications for the constant gain EDFA based downstream booster amplifier are shown in Table 3.

**Table 3 – Specifications for the constant gain EDFA based downstream booster amplifier**

| Parameter | Conditions | Min | Max |
|---|---|---|---|
| Operating wavelength range [nm] | | 1547.715 | 1563.047 |
| Single channel input power [dBm] | | -8 | -5 |
| Number of channels | | 1 | 16 |
| Small signal gain [dB] | Over all SOP | 21 | |
| Gain ripple [dB] | 16-channel input, over all input powers | | 2 |
| Saturation power [dBm] | | 26.5 | |
| Noise figure [dB] | | | 12 |
| Operating temperature [C] | | 0 | 40 |

**200B.2.3 Band MUX characteristics**

The band MUX is responsible for combining the multiplexed downstream and upstream signals into a bidirectional signal for transmission over a single fiber ODN. Since the wavelengths for a next-generation system are already defined (i.e., L-band 2 and C-band 2), the band-mux also has expansion ports to allow the next generation system to be inserted without the need to interrupt service. The band MUX may be implemented using a thin-film filter (TFF) with three stages. Additional stages can be inserted for monitoring, if desired. The required specifications for the TFF based band MUX are shown in Table 4.

**Table 4 – Specifications for the TFF based band MUX**

| Parameter | Conditions | Min | Max |
|---|---|---|---|
| Number of ports | (not including common) | 4 | |
| Channel wavelengths | L-band 1<br>L-band 2<br>C-band 1<br>C-band 2 | 1583.907<br>1565.602<br>1547.715<br>1530.233 | 1599.594<br>1581.109<br>1563.047<br>1545.393 |
| Insertion loss [dB] | | | 1 |
| In-band ripple [dB] | | | 1 |
| Channel uniformity [dB] | | | 1 |
| Adjacent channel crosstalk [dB] | | -40 | |
| non-adjacent channel crosstalk [dB] | | -40 | |
| Operating temperature [C] | | 0 | 40 |

**200B.2.4 Preamp characteristics**

The upstream optical preamplifier may be implemented using a gain-clamped EDFA. Similar to the downstream power amplifier, EDFAs are preferred to minimize the interaction between the WDM channels. The time period of upstream bursts are long enough to cause gain fluctuations in a standard EDFA. Gain clamping is therefore required to avoid gain variations for the burst-mode upstream signals. There are multiple methods for optical gain clamping; the exact implementation is not prescribed. The required specifications for the gain-clamped EDFA based upstream preamplifier are shown in Table 5.

**Table 5 – Specifications for the gain-clamped EDFA based upstream preamplifier**

| Parameter | Conditions | Min | Max |
|---|---|---|---|
| Operating wavelength range [nm] | | 1583.907 | 1599.594 |
| Single channel input power [dBm] | Continuous power | -38 | -18 |
| Number of channels | | 1 | 16 |
| Small signal gain [dB] | Over all SOP | 25 | |
| Gain ripple [dB] | 16-channel input, over all input powers | | 2 |
| Saturation power [dBm] | For all 16 channels | 10 | |
| Noise figure [dB] | | | 5.5 |
| Burst length [us] | | 0.2 | 125 |
| Burst mode settling time [ns] | | | TBD |
| Burst-mode gain excursion [dB] | | | 0.5 |
| Operating temperature | | 0 | 40 |

The input power into the upstream preamplifier is expected to be very low. Therefore, the noise figure (NF) and gain are critical parameters. The required output power is low, thus simplifying the gain clamping implementation.

### 200B.2.5 DCM characteristics

The dispersion compensation module (DCM) may be implemented using any technology. Known solutions include:

- Fiber Bragg Grating (FBG) DCMs; and
- Negative Dispersion Fiber DCMs.

FBG DCMs are channelized and able to cover the full C- and L-bands. They have a fixed insertion loss and a fixed latency. The latency of FBG DCMs is very small (i.e., <0.025 μs). This means the optical line terminal's (OLT) calculation of the length from the ranging will be unaffected by the DCM. FBG DCMs are likely to be channelized. Therefore, it is important to make sure the amplitude and phase ripple are minimal between ±15 GHz of the nominal channel frequency

Fiber-based DCM are not channelized and their insertion loss and latency is dependent on the length of the fiber used to build them. To compensate for 50 km of standard single-mode fiber, around 10 km of dispersion compensating fiber (DCF) is required. This results in around 25 μs of latency. Because a DCM is only required for the upstream (US) direction, there will be imbalance in the latency, with greater latency in the upstream direction. PON protocols are tolerant of latency asymmetry so this is expected to not be a problem, even if this will lead to an overestimation of the link length by the OLT of ~5 km. Other time sensitive protocol may break (e.g., time transport protocol) may break when using this type of DCM.

### 200B.3 λ Router (CAWG)

The cyclical wavelength router is best implemented using a cyclical AWG. AWGs are naturally cyclical and their repetition frequency is referred to as the free spectral range (FSR). For the Super-PON wavelength router, the FSR for the CAWG should be approximately 2200 GHz wide, the width of each wavelength band including all the unused channels. The response is defined only for the channels in the four wavelength-bands used in Super-PON. However, the cyclical nature of the AWG will actually repeat for many more cycles. It is possible to use those additional cycles for applications not defined in this standard, such as OTDR.

In addition, this device is intended to be deployed in the outside plant as part of the ODN. Therefore, the device should be able to operate over an extended temperature range. Multiple athermalization methods exist for AWGs and a specific athermalization method is not prescribed.

The required specifications for the cyclical AWG based wavelength router are shown in Table 6.

**Table 6 – Specifications for the CAWG based wavelength router**

| Parameter | Conditions | Min | Max |
|---|---|---|---|
| Number of channels | | 16 | |
| Number of bands | | 4 | |
| Channel spacing (MUX) [GHz] | L-band 1<br>L-band 2<br>C-band 1<br>C-band 2 | 97.7<br>98.8<br>100.0<br>101.2 | |
| Operational wavelength (MUX) [nm][*] | L-band 1<br>L-band 2<br>C-band 1<br>C-band 2 | 1583.907<br>1565.602<br>1547.715<br>1530.233 | 1599.594<br>1581.109<br>1563.047<br>1545.393 |
| Clear pass band (CPB) [GHz] | Relative to nominal | -15 | +15 |
| In-channel ripple | Over CPB for all SOP | | 1.0 |
| Insertion loss (IL) [dB] | Over CPB for all SOP | | 4.0[**] |
| Adjacent channel crosstalk [dB] | Over CPB of adjacent channels | -23 | |
| Non-adjacent channel crosstalk [dB] | Over CPB of non-adjacent channels | -28 | |
| Total integrated crosstalk [dB] | Sum of all crosstalk | -20 | |
| Temperature range | | -40 | 65 |
| [*] The full channel plan is shown in table 200-4<br>[**] The low-loss implementation of the CAWG is only required for deployments using 64-port splitters up to 50 km. In this implementation a Mach-Zehnder interferometer precedes the AWG, which reduces the loss of the AWG device. A standard AWG design can be used for lower loss ODNs, such as ODNs with less than 40 km of fiber plant or ODNs using 32-port or lower count splitters. | | | |

## 200B.4 Power splitter

The power splitters for Super-PON are as those used in other PON standards. In order to minimize the link loss, premium low-loss splitters are required for links approaching 50-km using a 64-port splitter to keep the total link loss below 41 dB. The required insertion loss of 20.5 dB for a 64-port splitter is not exotic and can be achieved by most splitter manufacturers by selecting the lower loss units from a batch.

For links shorter than 40 km, the loss through the fiber is 2.8 dB lower. This allows the use of a standard 21 dB loss 64-port splitter.

## 200B.5 Link budget analysis

### 200B.5.1 Downstream for a 50-km link

Figure 2 shows the downstream link components and expected losses/gains for each component. The expected minimum power for different locations in the ODN is shown at the bottom of the figure. For simplicity, all connector, splice and link aging losses are lumped together right before the receiver (ONU).
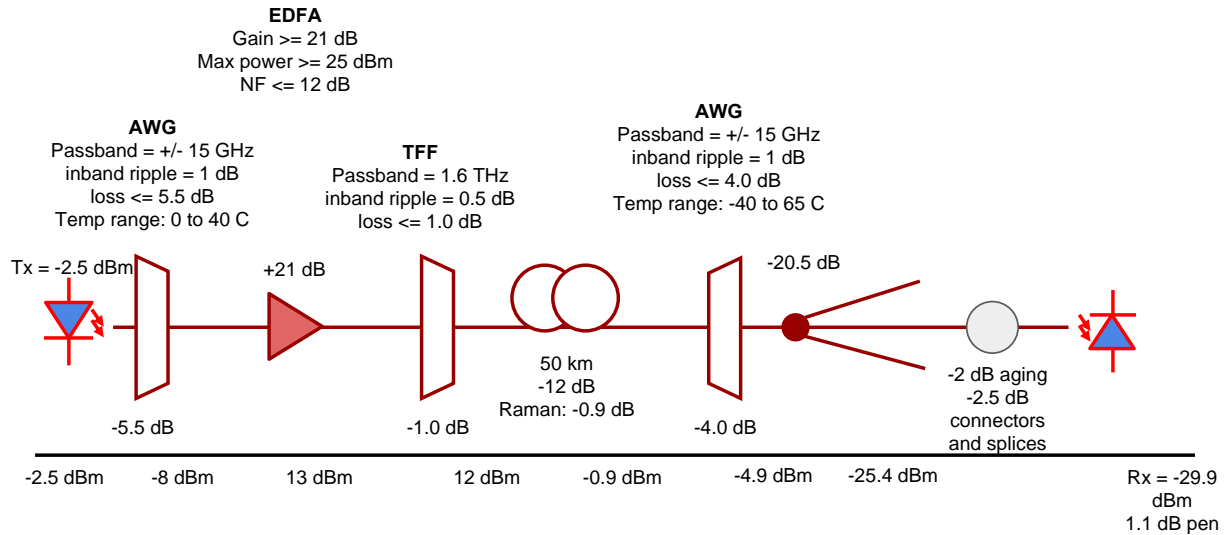
**EDFA**
Gain >= 21 dB
Max power >= 25 dBm
NF <= 12 dB

**AWG**
Passband = +/- 15 GHz
inband ripple = 1 dB
loss <= 5.5 dB
Temp range: 0 to 40 C

**TFF**
Passband = 1.6 THz
inband ripple = 0.5 dB
loss <= 1.0 dB

**AWG**
Passband = +/- 15 GHz
inband ripple = 1 dB
loss <= 4.0 dB
Temp range: -40 to 65 C

Tx = -2.5 dBm          +21 dB                                                -20.5 dB

50 km
-12 dB
Raman: -0.9 dB

-2 dB aging
-2.5 dB
connectors
and splices

-5.5 dB              -1.0 dB                    -4.0 dB

| -2.5 dBm | -8 dBm | 13 dBm | 12 dBm | -0.9 dBm | -4.9 dBm | -25.4 dBm | Rx = -29.9 dBm 1.1 dB pen |

**Figure 2 - Downstream link budget**

## 200B.5.2 Upstream for a 50-km link

Figure 3 shows the upstream link components and expected losses/gains for each component. The expected minimum power for different locations in the ODN is shown at the bottom of the figure. For simplicity, all connector, splice and link aging losses are lumped together right before the transmitter (ONU).
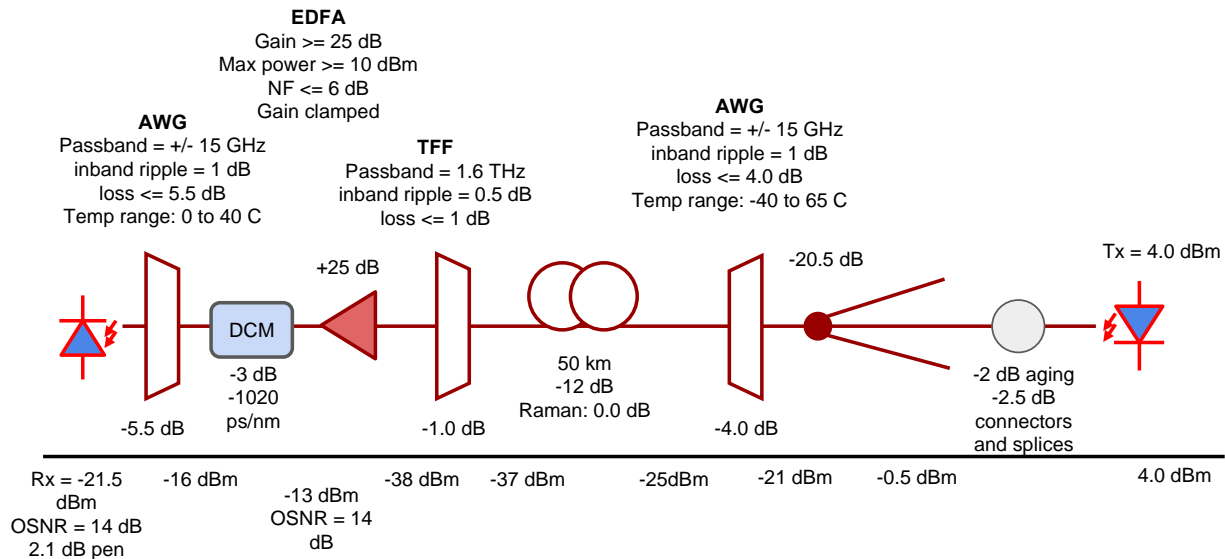
**EDFA**
Gain >= 25 dB
Max power >= 10 dBm
NF <= 6 dB
Gain clamped

**AWG**
Passband = +/- 15 GHz
inband ripple = 1 dB
loss <= 5.5 dB
Temp range: 0 to 40 C

**TFF**
Passband = 1.6 THz
inband ripple = 0.5 dB
loss <= 1 dB

**AWG**
Passband = +/- 15 GHz
inband ripple = 1 dB
loss <= 4.0 dB
Temp range: -40 to 65 C

Tx = 4.0 dBm

+25 dB                                                    -20.5 dB

DCM
-3 dB
-1020
ps/nm

50 km
-12 dB
Raman: 0.0 dB

-2 dB aging
-2.5 dB
connectors
and splices

-5.5 dB                  -1.0 dB                    -4.0 dB

| Rx = -21.5 dBm OSNR = 14 dB 2.1 dB pen | -16 dBm | -13 dBm OSNR = 14 dB | -38 dBm | -37 dBm | -25dBm | -21 dBm | -0.5 dBm | 4.0 dBm |

**Figure 3 – Upstream link budget**

## 200B.5.3 Raman Effect Penalty

The Stimulated Raman Scattering (SRS) transfers power from shorter wavelength channels to the longer wavelength channels. The total power transferred is proportional to the product of all the powers at all the wavelengths. In the Super-PON system, the downstream signal power is substantially higher than the upstream signal power in the AWG feeder fiber, the only location where combined powers are sufficient

for substantial Raman interaction. The percentage of power transferred from the upstream signals is determined by the power in the downstream signals.

Using L-band wavelengths for upstream, the Raman effect transfers power to the upstream signals. This is illustrated by the negative Raman penalty in Figure 4. This calculation assumed the use of 16 channels for both US and DS. The channel with the highest Raman penalty is shown. A negative penalty means that power is transferred into the channel via SRS, thus receiving gain.
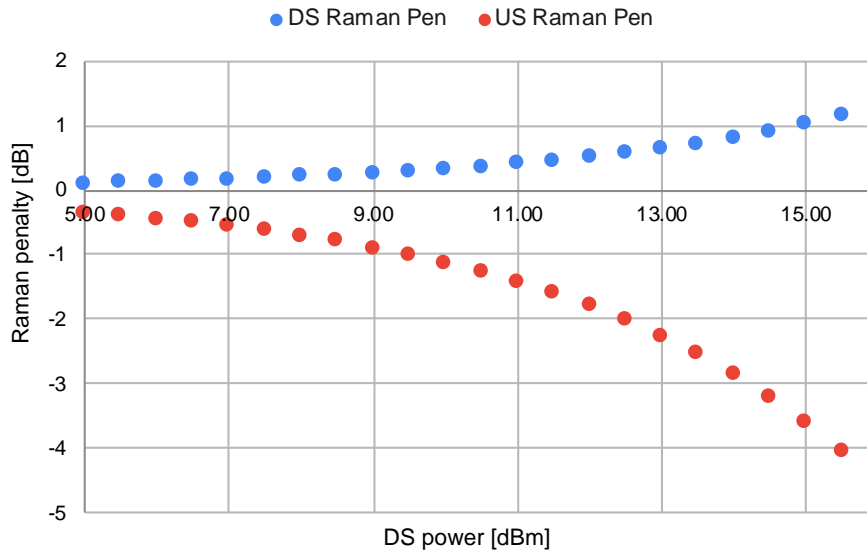


**Figure 4 - Raman penalty**

This Raman gain cannot be relied upon for two reasons:

- the gain in power will only be a fraction if fewer wavelengths are used; and
- gain from a modulated pump will also result in additional noise.

Therefore, the Raman gain/penalty is assumed to be zero when calculating the required upstream powers for upstream operation.

The Raman effect between the 16 downstream channels causes the longer wavelength channels to steal power from the shorter wavelength channels. However, this effect is weaker due to the close pump-stokes separation. Again, because the upstream powers are so much lower in power, the power transferred to the upstream wavelengths is very small compared to the power transferred among the downstream channels. The predicted downstream penalty can be handled by increasing the gain and maximum power of the downstream EDFA in the MUX/Amp module. In the downstream link budget, the expected Raman power penalty is added to the loss of the fiber.

Figure 5 shows the required power levels as a function of the link budget, assuming a 2.1 dB transmission penalty for the upstream and 1.1 dB transmission penalty for the downstream. A 41-dB link budget requires an upstream launch power level of 4.0 dBm at 10Gb/s.
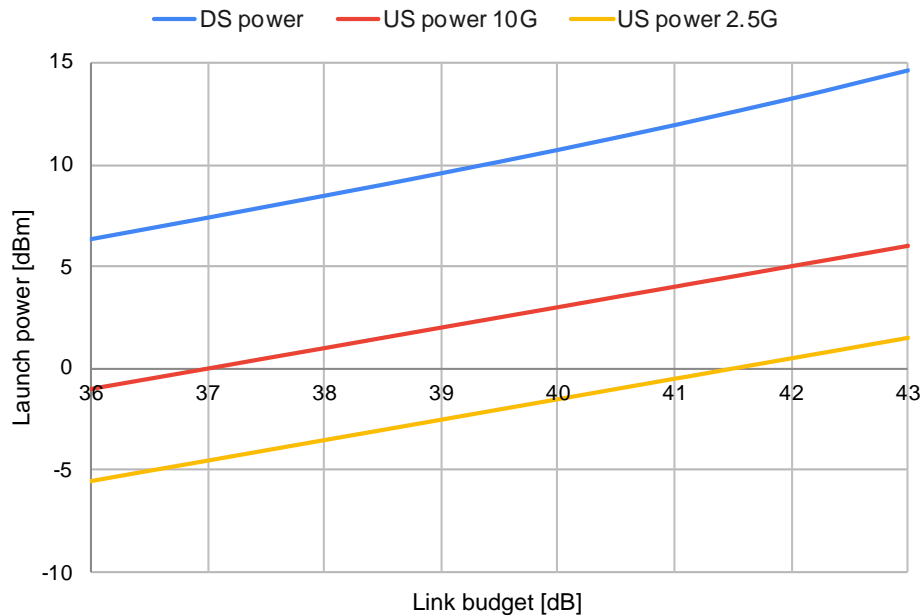
**Figure 5 - ONU power levels**

All Raman penalties are calculated assuming the power on all downstream channels is 2-dB higher than the minimum required downstream power. This is to account for some channel imbalance in the downstream channels without causing an excessively large Raman penalty on the lowest power channel(s). Note that the typical allowed variation in OLT output power is 4 dB. Allowing for 2-dB higher power for the Raman calculation assumes (and requires) an operator to perform some closed-loop balancing of channel powers for each ODN unless a tighter than usual spread in OLT transmitter power can be guaranteed by the OLT optical module.

**200B.5.4 Dispersion compensation**

The required operational dispersion range selected for Super-PON was based on the following needs:

- Desire to enable both DML and EML solutions,
- Need to minimize the total penalty from transmission for all transmitter types.

DMLs typically have a high positive chirp, which is very difficult to avoid. This causes a large transmission penalty if there is substantial positive residual chromatic dispersion (CD) in the link. DML transmitters need CD compensation to operate in a 50-km link.

For EML transmitters, the chirp is typically determined by the bias point of the modulator. A low bias results in higher transmission powers, positive chirp, and lower extinction ratio (ER). A high bias results in lower transmission powers, low or even negative chirp, and higher ER. The requirement of 4-dBm output power is relatively high for EML transmitters, so it likely requires a moderately low modulator bias point, resulting in a positive chirp.

The performance of typical DML and EML solutions for different residual chromatic dispersion is shown in Figure 6. Both solutions are positively chirped so perform better with negative residual dispersion. The higher chirp factor of the DML transmitter results in a lower tolerance in both the positive and negative residual dispersion bounds for a 1-dB penalty. These results suggest that a residual dispersion between -600 ps/nm and +50 ps/nm allows both the EML and DML transmitters to operate within 1-dB penalty.
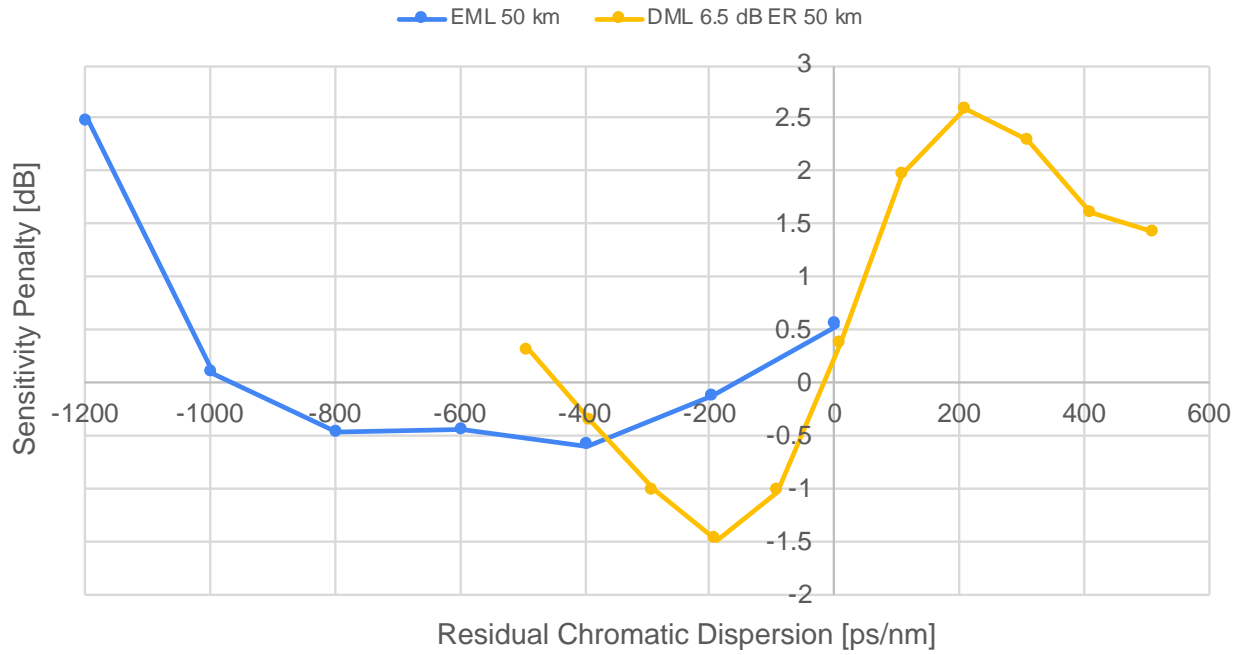
**Figure 6 – Chromatic dispersion penalty for DML and EML transmitters**