Chapter 6

Full-duplex CWDM-routed reflective PONs

This chapter presents a newly applied scheme to demonstrate full-duplex operation, allowing for increased bandwidth utilisation of the reflective access network architecture presented in preceding chapters. Full-duplex functionality is achieved by using the well-known polarisation division multiplexing (PDM) technique to increase the data throughput for each reflective PON. This is implemented in the OLT by assigning each ONU downstream data and CWs on orthogonal SOPs. Assessment of the polarisation-multiplexed OLT capability to route composite wavelengths through coarse channels of the AWG is investigated in the consideration of crosstalk between the orthogonal pairs, and contrasting full-duplex occupancy to its half-duplex counterpart.

6.1 Application of polarisation division multiplexing for full-duplex transmission

The multi-PON access network architecture [1] presented in the previous chapter, utilised a CWDM OLT and RSOA-based ONUs to serve multiple reflective PONs. In that architecture, downstream data and CWs, provided by the OLT, were time-interleaved in a single burst, demonstrating half-duplex transmission [2, 3] since the transmitter is required to alternate between two modes of transmission. This could result to restrict bandwidth utilisation efficiency in commercial application where concurrent bidirectional data transfer, such in video conferencing and web casting, is utilised [4].

To demonstrate full-duplex operation, several remodulation schemes have been proposed on the basis of reusing the downstream signal for upstream transmission [3, 5-7] by either employing subcarrier multiplexing in the electrical domain to separate downstream data and CWs on different electrical frequencies, or by directly remodulating downstream data signals with a higher ER in the RSOA to demonstrate upstream transmission. Nevertheless, the former scheme could be inadequate for implementation because of potential electrical circuitry complexity in both OLT and ONUs, and the limitation in upstream and downstream transmissions capacity due to the excessive use of the RSOA electrical bandwidth [5, 6]. In the case for the latter scheme, downstream transmission performance is limited due to signals' relatively low ER [7], while upstream transmission capacity is particularly limited due to significant Rayleigh backscattering in the OLT resulted from relatively high power in downstream utilised to compensate on the low ER, all resulting to limited fibre distances or the use of a dual feeder fibre [7].

As will be analysed further, full-duplex transmission has been established here [8] by splitting the original downstream CWs in the OLT into two orthogonal polarisations, one of which is modulated for downstream data transmission while the other is fed to the corresponding RSOA for upstream transmission. Independent transmission of burst data and unmodulated carriers

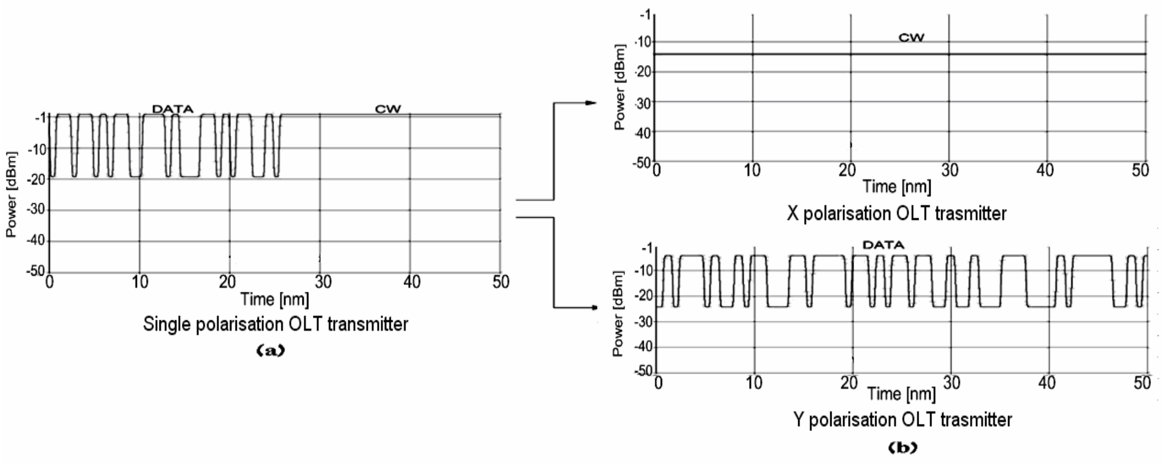


Figure 6-1 Time domain representation of burst-data and CW (a) time-interleaved (b) PDM

over the two polarisations for each ONU overcomes time-interleaving in the OLT of the available transmission time-slots, as illustrated in Figure 6-1(a), allowing for their simultaneous transmission to avoid multiplexing idle time and required guard time, as illustrated in Figure 6-1(b). Assuming the use of symmetrical broadband services such as video conferencing and online gaming [9] and Web 2.0 applications, the proposed scheme could potentially double the bandwidth utilisation for each subscriber, resulting in increased network upstream and downstream throughput.

6.2 Network architecture design

The revised network architecture is shown in Figure 6-2, for which the OLT and ONUs are modified to accommodate orthogonal transmission and detection. In the OLT, the CW out of tunable laser TL1 is initially split in an optical coupler. The lower coupler arm is applied at a MZM for downstream data modulation, consequently linearly-vertical-polarised (Y polarisation) by a polarisation controller. The upper arm, displaying the linearly-horizontal-polarised CW (X polarisation), is connected directly to a PBC to be recombined with the orthogonal Y polarisation.

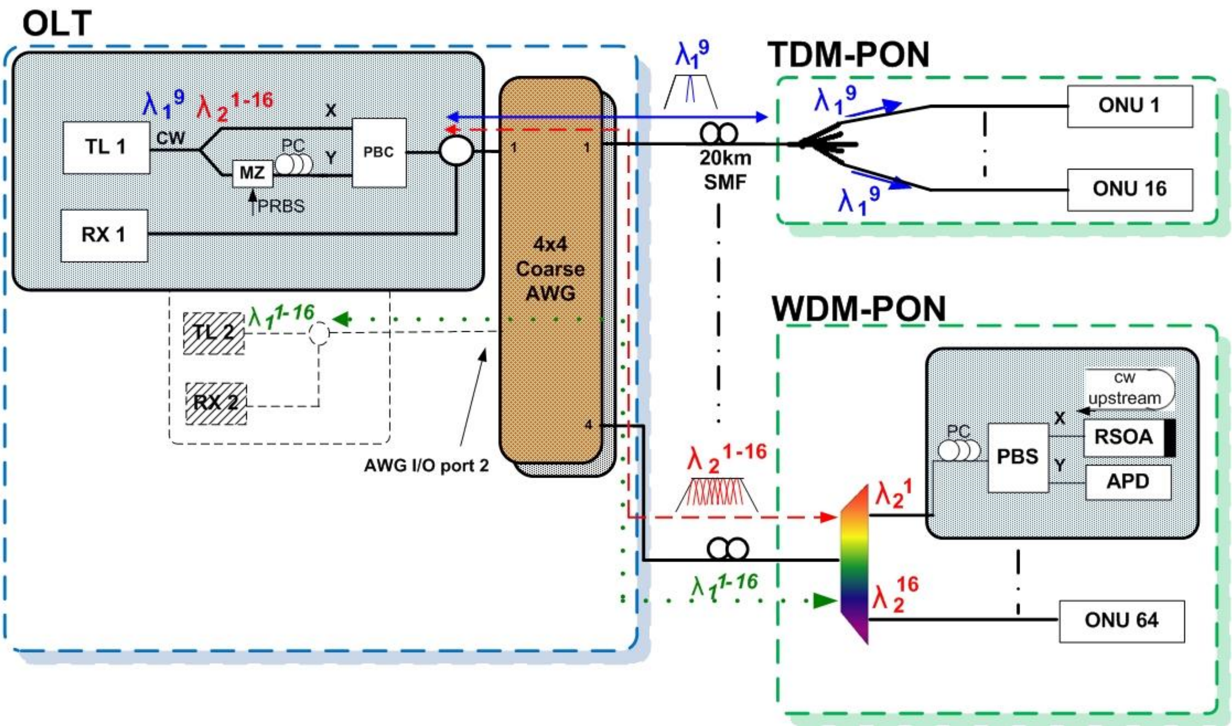


Figure 6-2 Full-duplex CWDM-routed reflective PONs network architecture

Subsequently, the two orthogonally multiplexed signals are applied at first to a circulator to allow bidirectional transmission and depending on the operating wavelength and AWG input port, routed [10] via the appropriate AWG coarse channel to the corresponding PON, following the same methodology described in earlier chapters. Once having accessed an ONU, independently of whether connected to a TDM or WDM-PON, the two orthogonal signals are applied to a polarisation controller to be aligned with the succeeding PBS's x-y coordinated outputs. After demultiplexing, the CW polarisation is injected into the RSOA for upstream transmission while the received data carrier is terminated at an APD. In contrast to the architecture employed so far [1], the RSOA in each ONU is solely used for upstream power shaping and modulation, requiring the use of an APD for downstream detection. This resulted in added ONU complexity since, unlike a typical implementation of an RSOA plus photodetector in an ONU using an optical coupler [5, 7, 11-13], traffic for the APD and RSOA is effectively divided with the configuration of a PBS and polarisation controller.

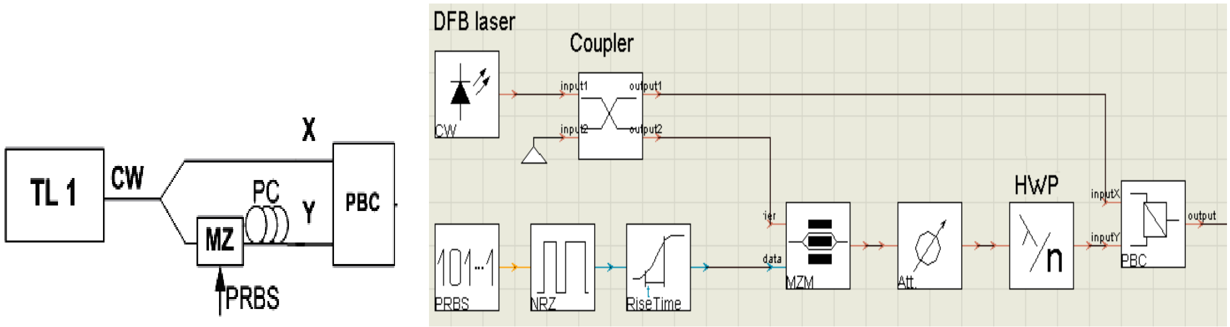
In upstream, each reflected modulated wave is routed through exactly the same path followed in downstream, and subsequently terminated in turn to a single receiver RX1 in the OLT.

6.3 Modified network model

The physical layer OLT and ONU models in VPI were modified to provide bidirectional orthogonal transmission and detection by employing standard VPI network elements. Particular attention was paid in multiplexing and demultiplexing the burst data and CW polarisations in order to avoid leakage of power from the former to the latter that could result in degrading the performance of the upstream transmission.

6.3.1 Optical line terminal

The OLT block diagram, shown in Figure 6-3(a) is displayed in conjunction with its corresponding VPI model, shown in Figure 6-3(b). In the model, TL1 is realised by a DFB laser module, the output of which is applied at the MZM through the lower arm of a 1:97 coupler, denoted in the figure by output2. The upper coupler arm, indicated by output1, is connected directly to inputX of the PBC to provide orthogonal CWs in order to demonstrate upstream transmission in the ONUs. A PRBS module in conjunction with an NRZ module, used as an electrical converter and a RiseTime module to readjust the NRZ signal rise-time are employed to establish downstream data transmission while avoiding excess frequency deviation in the MZM. Following modulation of the laser CWs, the MZM output is subsequently applied to a fixed attenuator to model loss in the MZM, not included in the standard VPI module, followed by a half-wave plate (HWP) utilised to linearly-vertical polarise the modulated CWs at



(a) (b)

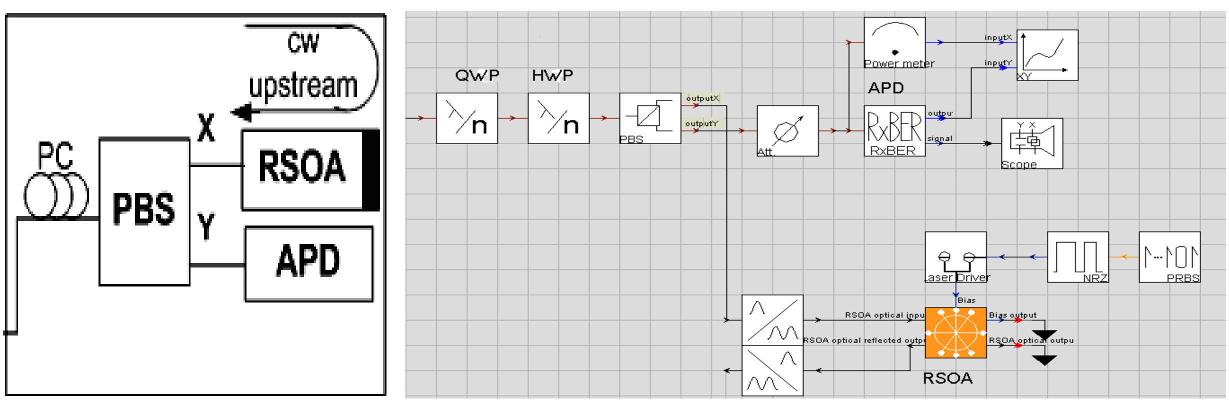
Figure 6-3 Orthogonally-multiplexed OLT modelling

the PBC inputY to display orthogonallity with respect to the unmodulated CWs at the upper coupler arm.

6.3.2 Optical network unit

The ONU VPI model, shown in Figure 6-4(b) is displayed again in conjunction with its associated block diagram, shown in Figure 6-4(a). The polarisation controller block is realised by a 45° tilted, quarter-wave plate (QWP) module employed to convert a circular-polarised signal arriving from the SSMF downstream to a linear-polarisation, and a HWP module utilised to align the two orthogonally multiplexed signals with the subsequent PBS x-y coordinated outputs. Moving across the diagram, the PBS outputY is applied to an optical attenuator, utilised to obtain BER performance characteristics, subsequently connected to an RxBER module comprising an APD and BER measurement unit for downstream detection. The optical power meter, XY-plot module and scope are employed also to obtain BER performance characteristics and to display eye diagrams respectively.

To demonstrate upstream modulation, the PBS outputX is sequentially injected into the RSOA through its optical input port and reflected via the RSOA optical reflected output port. The PRBS module, providing upstream data, is applied via an NRZ module to a laser driver module for modulating the RSOA reflected CW via its bias input electrode.



(a) (b)

Figure 6-4 Full-duplex ONU modelling

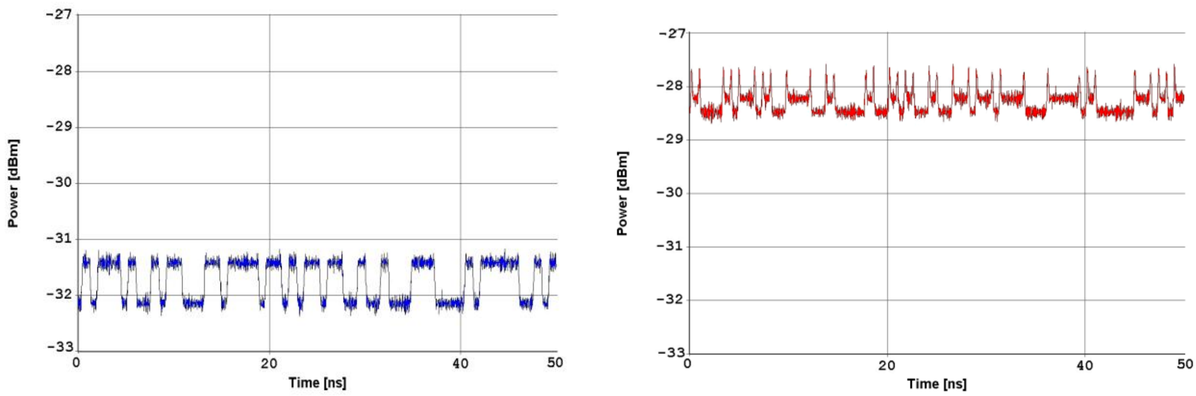
6.4 Full-duplex transmission simulation results

Full-duplex network modelling and performance evaluation were carried out to explore the potential of the polarisation-multiplexed OLT to provide concurrent downstream and upstream wavelengths and significantly study the effect of the coarse AWG Gaussian response [14] and passband shifting [10] in the power distribution and orthogonality of the multiplexed signals. This was carried out by simulating an access network comprising a WDM-PON terminated to the CWDM OLT since WDM ONUs, as clearly demonstrated in previous chapters, exhibit the most significant degradation in the form of the longest wavelength transmission over the AWG passbands, with up to 1.8 nm PDW shift and 3 dB PDL reported figures [1].

In particular, a DFB laser at +1 dBm was applied at a commercially-available 1:97 optical coupler [15] to accommodate the network wavelength-specific losses, in the range of 13 dB to 19.5 dB, and to allow sufficient CW downstream power while avoiding to saturate the RSOA's -29 dBm input power figure. At the lower coupler arm, each CW at approximately 0 dBm was modulated by a 1.25 Gbit/s, 2^7-1 long PRBS to comply with the limited RSOA electrical frequency response at 900 MHz, in contrast to the upper coupler arm CWs at -13 dBm due to the 1:97 splitting ratio. Following multiplexing at the PBC, the orthogonal signals of each wavelength were applied to a circulator and via the AWG downstream I/O port 4 coupled to a 20 km of SSMF. At the network distribution point, a 1×16 demultiplexer communicated the optical signals to the designated ONUs of the WDM-PON. In each ONU, the reflected modulated wavelengths at an optical power ranging from -3 dBm to 0 dBm due to the RSOA TE gain of 29 dB, to eradicate polarisation-dependent gain (PDG), were in turn modulated by another random sequence with the same length and rate to demonstrate upstream transmission at ER of 12 dB.

The AWG induced PDW shift and associated PDL could potentially degrade the degree of orthogonality of any multiplexed signals if they are not aligned with the device TE and TM modes [16]. In the architecture the AWG is located in the OLT and as a result the two SOPs are already aligned with the device input transmission modes, preserving their degree of orthogonality (see appendix B for orthgonality-error extensive investigation). After transmission via the SSMF, the multiplexed signals reaching the distribution point display random but mutually orthogonal SOPs [16]. Subsequently, the demultiplexing device in the distribution point has been shown [16] not to impose a significant effect on the degree of orthogonality as a result of its typical 0.5 dB PDL [17].

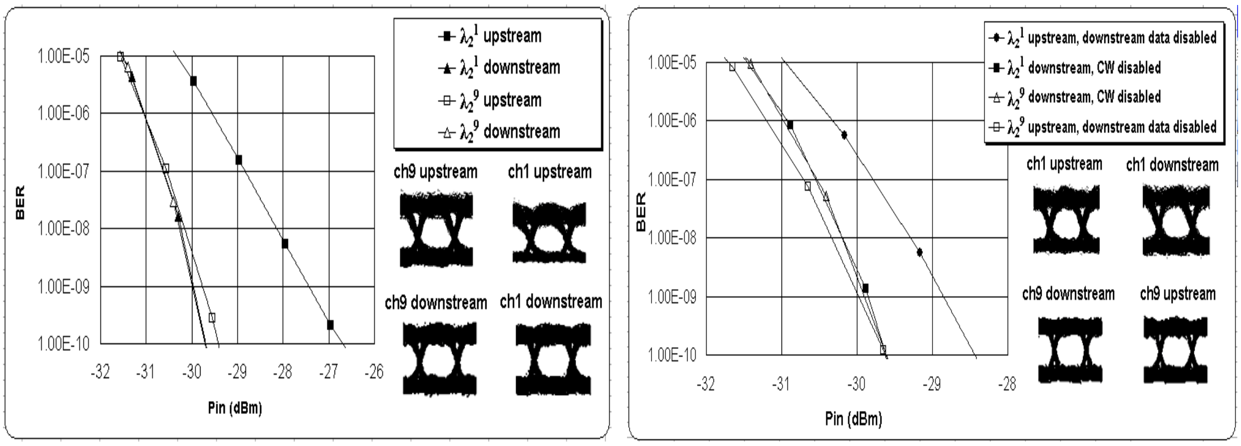
In defining error-free detection downstream and optimal modulation in the RSOA, the crosstalk characteristics between the transmitted data and CW for the AWG most and least severely degraded wavelengths at λ_2^1=1553.33 nm and λ_2^9=1550.12 nm respectively were monitored with the objective to maintain low interference among the two forms of transmission to allow minimum leakage of burst-data in the RSOA injected wave. As shown in Figure 6-5, an insignificant crosstalk figure of no more than 1 dB in power leakage is observed compared to the measured ER of 12 dB of each reflected modulated wavelength. In addition, a 3 dB power difference can be also observed between the received CW signals due to the AWG Gaussian response.



(a) **(b)**

Figure 6-5 Injected CW at RSOA optical input (a) λ_2^1=1553.33 nm (b) λ_2^9=1550.12 nm

To evaluate the full-duplex network performance with respect to its half-duplex counterpart, BER responses were drawn to account for the most and least severely degraded wavelengths servicing WDM-PON. Confirmed by Figure 6-6(a), 10^{-9} BERs were achieved by all upstream ONUs at the expense of a maximum 2.5 dB power penalty between λ_2^1 and λ_2^9 due to the induced PDM crosstalk and AWG response. In downstream, Figure 6-6(a) displays no penalty among the wavelengths due to a high measured crosstalk isolation of 26 dB. To make evident the capability of the network to allow full-duplex operation with insignificant limitation due to crosstalk, BER responses under half-duplex transmission were also drawn with either the downstream data or CW disabled for the duration of the upstream and downstream transmissions respectively. Confirmed by Figure 6-6(b), similar BER figures were achieved by all ONUs at the expense of 1.2 dB power penalty between λ_2^1 and λ_2^9 due to the AWG response. Contrasting the half-duplex network performance to its full-duplex operation it is concluded that an approximate 1.3 dB increase in power penalty is induced the most severely degraded wavelengths in the later, allowing for effective simultaneous transmission of data by means of overcoming sharing of the available transmission time-slots.



(a) **(b)**

Figure 6-6 BER for (a) full-duplex bi-directional (b) half-duplex upstream and downstream transmissions

6.5 Power budget analysis

The network is designed in terms of power budgeting with respect to individual elements losses throughout the optical path and their polarisation dependency, with the aim to provide sufficient power for both data-carrying polarisation and CWs. This is achieved while, as frequently mentioned, avoiding to saturate the RSOAs in destination ONUs to allow error-free transmission of all wavelengths of the WDM-PON. Power budget analysis figures for the most severely degraded ONU at maximum PDW shift are summarised in Table 6-1.

According to Table 6-1 the highest network link loss of 29 dB was measured for the longest wavelength between the DFB laser in the OLT and the APD in the ONU, caused mainly by the coarse AWG due to its Gaussian response and associated PDL.

Table 6-1 Downstream power budget

Parameter	Value
DFB minimum launched power	1 dBm
Optical coupler loss	0.5 dB
MZM insertion loss	7.5 dB
Optical circulator	1 dB
Coarse AWG loss @ longest wavelength	10.5 dB
20 km SSMF loss	4 dB
Distribution point losses	5.5 dB
APD sensitivity @ 10^{-9} BER	-30 dBm

Table 6-2 summarises the upstream data transmission power budget including the loss of downstream CWs that directly influence the RSOA reflected power modulated CWs upstream, required to overcome upstream network losses. The downstream path associated with the longest wavelength transmission between the DFB laser in the OLT and the RSOA in the ONU exhibits as expected the highest link loss, reaching a figure of up to 33.5 dB, caused mainly by the optical coupler employed to reduce the CW power to avoid the risk of the central wavelength driving the RSOA into saturation at a power level greater than -28 dBm. The relatively high loss is subsequently compensated by the RSOA gain allowing for sufficient reflected power for error-free transmission upstream. The upstream path power budget exhibits the highest link loss of 21 dB, measured for the longest wavelength between the RSOA and APD in the OLT, including the losses of distribution point multiplexer, 20 km SSMF, coarse AWG and optical circulator. The 8 dB loss of the coarse AWG shown in Table 6-2 for the downstream path includes no PDL since the CWs downstream X polarisation is preserved in the OLT, as opposed to upstream for which the signal SOP at the output of the fibre is random, resulting in a potential extra loss of 3 dB PDL to be included in the power budget.

Table 6-2 Upstream power budget

Parameter	**Value**
DFB minimum launched power	1 dBm
Optical coupler loss	15 dB
Optical circulator	1 dB
Coarse AWG loss @ longest wavelength	8 dB
20 km SSMF loss	4 dB
Distribution point losses	5.5 dB
RSOA gain	30 dB
Network losses upstream	21.5 dB
APD sensitivity @ 10^{-9} BER	-27.5 dBm

6.6 10 Gigabit transmission modelling

Given that the RSOA in the full-duplex network architecture is not utilised for detection and as a result downstream transmission is not restricted to the device's limited 900 MHz electrical bandwidth, data rates can be potentially increased using a higher bandwidth photodetector [18] in the ONU. In addition, since the fibre length in the network spans up to approximately 20 km, chromatic and polarisation mode dispersions at 10 Gbit/s are unlikely to limit considerably the downstream transmission performance, allowing for increased bandwidth in the network. Upstream data rates would have to remain to 1.25 Gbit/s since the RSOA is still used for modulation.

To assess the network capability to allow full-duplex operation with insignificant limitation due to crosstalk between the CW and burst-data at 10 Gbit/s rates, BER responses under full and half-duplex operation were drawn for the least and most severely degraded ONUs of a WDM-PON, when either the CW is enabled or disabled for the duration of the downstream transmission. Confirmed by Figure 6-7, similar BER figures were achieved by all ONUs with measured BER of 10^{-9} at -28.4 dBm, suggesting that downstream performance has not been reduced due to fibre dispersion and crosstalk, and as a result a bidirectional transmission at 10 Gbit/s would be feasible when 10 Gbit/s RSOAs become commercially-available.

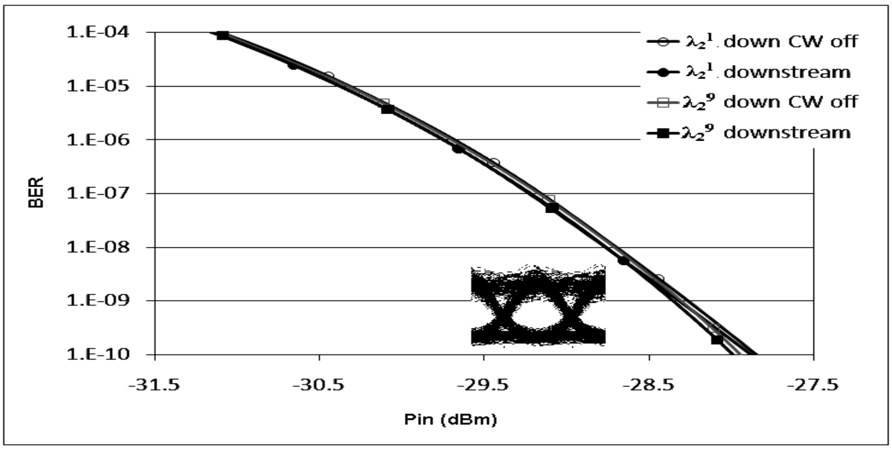


Figure 6-7 Measured BER for upstream and downstream transmission at 10 Gbit/s

6.7 Summary

This chapter demonstrated the application of orthogonally-multiplexed OLT and reflective ONUs to achieve full-duplex operation of the CWDM access network presented in preceding chapters [1]. Simulation results for the transmission of the multiplexed CW and data signals through the 7 nm-wide passband windows of the AWG, have confirmed error-free transmission for all ONUs of a WDM-PON in the presence of a worst-case 3 dB PDL, allowing for more bandwidth availability to each ONU due to the independent transmission of the CWs and burst-data.

Further investigations verified no more than 1 dB power leakage of the data-carrying polarisation onto the CWs, imposing no limitation in the network transmission efficiency when compared to a measured 12 dB ER of upstream modulated signals in the RSOA. Contrasting between half and full-duplex operations has demonstrated a moderate 1.3 dB penalty superimposed at the later that still allows for 10^{-9} BER transmission at 1.25 Gbit/s. As a result, by assuming the use of symmetrical broadband services such as video conferencing, online gaming [9] and Web 2.0 applications, the scheme has verified its potential to double the bandwidth utilisation for each subscriber, allowing for increased bidirectional network throughput.

Finally, it was demonstrated that fibre dispersion and crosstalk between the two polarisations would not limit a potential 10 Gbit/s network bidirectional transmission when RSOA devices at 10 Gbit/s operating speeds become commercially-available.

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