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Mobile Optical Pluggables Alliance (MOPA)

Technical paper on
Coherent lite for mobile networks

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1 Introduction

Dense Wavelength Division Multiplexing (DWDM) is used in mobile backhaul networks and for Centralized Radio Access Networks (CRAN) in scenarios where capacity requirements are high and fiber resources are scarce. The DWDM mobile optical solution blueprints currently published by MOPA all rely on Intensity-Modulated Direct-Detection (IM-DD) transceivers.

As per wavelength data rates increase, use of IM-DD becomes challenging, because the receiver sensitivity degrades inversely proportional to the symbol rate and the Chromatic Dispersion (CD) tolerance scales inversely proportional to the square of the symbol rate (approximately 80km for 10G NRZ → 15km for 25G NRZ). Inserting tunable chromatic dispersion compensation, either in the transceiver or in the link, adds significant cost and complexity, and leads to increased optical losses. More complex IM-DD modulation formats like PAM4 can partially alleviate the CD limitations but result in further degradation of the receiver sensitivity and loss budget.

Coherent transmission can be used to address the limitations of IM-DD solutions. In a coherent transceiver, the received signal is mixed with light from a Local Oscillator (LO) laser, resulting in enhanced receiver sensitivity. A coherent receiver detects not only amplitude, but also phase and polarization information, which enables advanced compensation schemes in a Digital Signal Processor (DSP), virtually removing any penalty due to CD and other link impairments.

Coherent transmission was first employed in long-haul networks, but advances in technology have successively reduced size, power dissipation, and cost of Digital Coherent Optics (DCO) transceivers. 100G DCO transceivers are now becoming available in the same form factor (QSFP28) and with similar power consumption (5W) as 100G IM-DD solutions. Multiple standards have been developed to ensure multi-vendor interoperability, e.g.

- IEEE Std. 802.3-2022 100GBASE-ZR
- ITU-T Recommendations G.709.2 / G.698.2
- CableLabs Point-to-Point Coherent Optics (P2PCO-SP-PHYv1.0-I03-200501)

Existing MOPA DWDM blueprints all rely on bidirectional transmission over a single fiber:

- 8.3.3. 15 km RU-DU, passive DWDM over a single fiber.
- 8.3.4. 15 km RU-DU, passive DWDM bus over a single fiber.
- 8.3.5. 15 km RU-DU, semi-active DWDM over a single fiber.
- 9.2.4. 15 km DRAN backhaul, passive DWDM bus over a single fiber.
- 9.2.8. 15 km CRAN backhaul, passive DWDM over a single trunk fiber.

This paper explores options for upgrading those blueprints with 100G DCO transceivers.

2 Bidirectional DWDM Trunk Links

Figure 1 Single fiber DWDM link with separated wavelengths for upstream and downstream traffic.

The aforementioned MOPA DWDM blueprints all take advantage of the fact that the receiver in an IM-DD transceiver is broadband, i.e. can receive signals on any wavelength in the C-band. As illustrated in Figure 1, this allows different wavelengths to be used for upstream and downstream traffic and means that while the trunk uses a single fiber, the transceivers are standard duplex transceivers.

As described in the introduction, a coherent receiver mixes the incoming signal with the output of a LO laser. This means the receiver will only detect signals at the same center wavelength as the LO. In most small form factor DCO transceiver implementations, a single laser is used both to generate the carrier wave for the transmitter and to act as the LO, thus forcing the transmitter and receiver to use the same DWDM channel. Such single laser DCO transceivers can therefore not be used as a direct replacement for IM-DD transceivers in any of the MOPA DWDM blueprints.

2.1 Dual Laser DCO Transceivers

The most obvious solution to address the above limitation is to add a second laser, such that the transmitter and receiver of the DCO transceiver can operate on independent channels. The drawback is that this will increase the cost of the transceiver by an estimated 30%-35%. It will also increase the power consumption by about 25% and may require a slightly larger transceiver form factor, e.g. the Type 2 form factor defined in the QSFP112 MSA rather than the original Type 1 form factor defined in the QSFP+ specification (SFF-8661).

The benefit on the other hand is that it imposes no limitations on the optical performance of the DCO transceiver relative to the use case where separate fibers are used for upstream and downstream traffic. In fact, there may be the possibility to improve both the transmit output power and the receiver sensitivity, because the optical output power of the laser does not need to be shared between the transmitter and the receiver (although operating the separate lasers at a lower output power level than the single, shared laser could help offset some of the increase in power consumption).

2.2 Single Laser DCO Transceivers with Circulator

Figure 2 Single fiber DWDM link using bidirectional DCO transceivers with optical circulator.

The alternative to adding a separate laser for the LO is using an optical circulator, either integrated into the transceiver, or as an external component such that the same transceiver can be used for unidirectional and bidirectional applications. A circulator is lower in cost than a second laser and does not increase the power consumption. However, performance may be impaired due to discrete or distributed back-reflections and potential multi-path interference effects. The circulator will also reduce the optical loss budget due to the insertion loss in both the transmitter to common and common to receiver directions.

The remainder of this paper will summarize preliminary testing that has been performed to assess the impact of these impairments.

3 Test #1 –OpenZR+ MSA

The first set of tests used QSFP-DD (Quad Small Factor Pluggable-Double Density) modules operating in 100G OpenZR+ mode, i.e. using Dual Polarization Quadrature Phase Shift Keying (DP-QPSK) modulation at a symbol rate of 30 GBd with Open Forward Error Correction (O-FEC) code. The link consisted of two QSFP-DD-DCO modules, each connected to an optical circulator. The two circulators were connected either with simple fiber span, or with splitters before and after the fiber span to allow the introduction of controlled, discrete back-reflections.

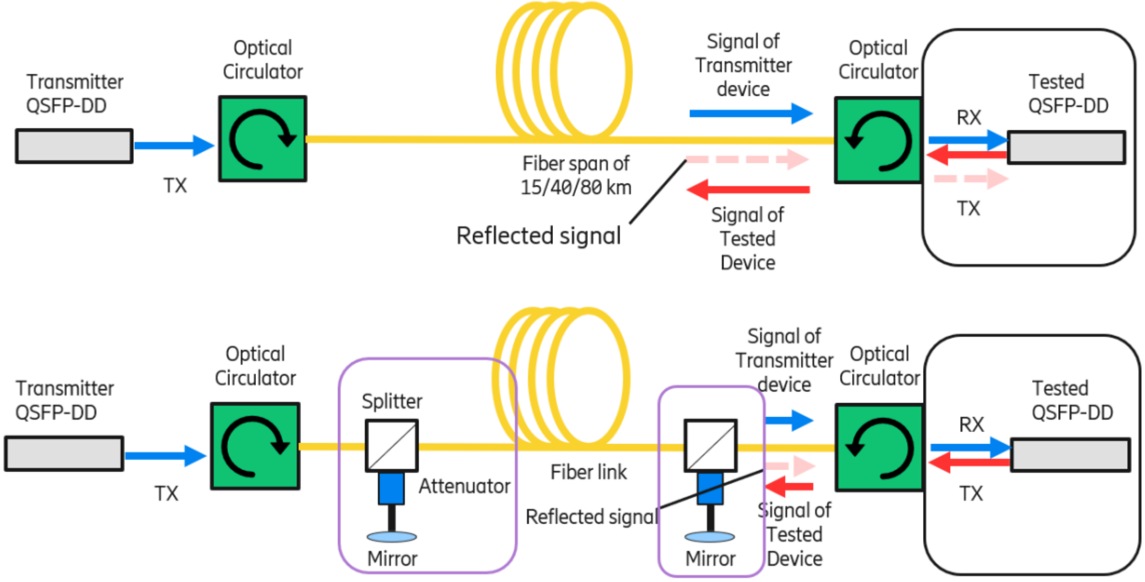

Figure 3 Test setup.

In the latter configuration the input signal of the local module under test is the combination of the transmit signal from the remote module and the reflected transmit signal from the module under test caused by distributed backscattering across the entire fiber length and discrete reflections at the splitters, one close to the local circulator and the other close to the remote circulator. The magnitude of these reflections was adjusted using Variable Optical Attenuators (VOAs).

3.1 Test Conditions

All tests were performed at a case temperature of 40°C. The optical frequency of the module was set at 191.3 THz. The media (line) interface was configured as 100G OpenZR+ with-O-FEC and the host interface was configured as CAUI-4 with KR4 FEC. The optical circulators had a directivity (crosstalk from Tx port to Rx port) of more than 50dB and a return loss of more than 45 dB.

To evaluate the contribution of the disturbing signal, two pre-FEC BER vs input power curves were measured with each link configuration: one with the local transmitter turned on, i.e., with the crosstalk from reflections present, and one with the local transmitter disabled. The receiver sensitivity was measured as the receiver input power level at which the post-FEC Loss of Alignment alarm de-asserted.

3.2 Test Results

3.2.1 Sensitivity Penalty versus Optical Signal to Crosstalk Ratio (OSXR)

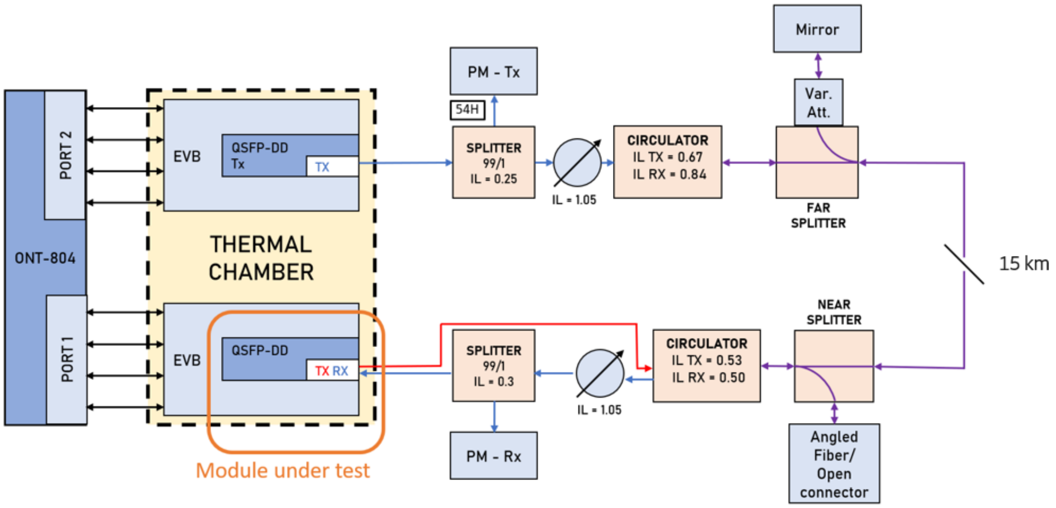

Figure 4 Test setup for measuring sensitivity penalty versus OSXR.

Using the setup shown in Figure 4, pre-FEC BER vs receiver input power curves were measured with different optical signal to crosstalk ratio (OSXR). This ratio was adjusted by controlling the VOA placed close to the remote module and measured with a power tap at the receiver input. The OSXR was calculated by comparing (a) the power measured with the local transmitter disabled and the remote transmitter enabled and (b) the power measured with the local transmitter enabled and the remote transmitter disabled. The return losses for the discrete reflections were fixed at more than 50dB for the far splitter and at 20dB (corresponding to an open connector) for the near splitter. The input power to the receiver of the local module was adjusted using a VOA to determine the receiver sensitivity as a function of OSXR.

Table 1 and Figure 5 below show the measured sensitivity penalty versus OSXR:

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Fiber Link Length [km]	Near Return Loss [dB]	Far Return Loss [dB]	OSXR [dB]	Sensitivity Penalty [dB]
15	20*	>50	11	2.5
			10	3.5
			9	5.0
			8	7.5
			7	>15.0

Table 1 Sensitivity penalty vs OSXR results

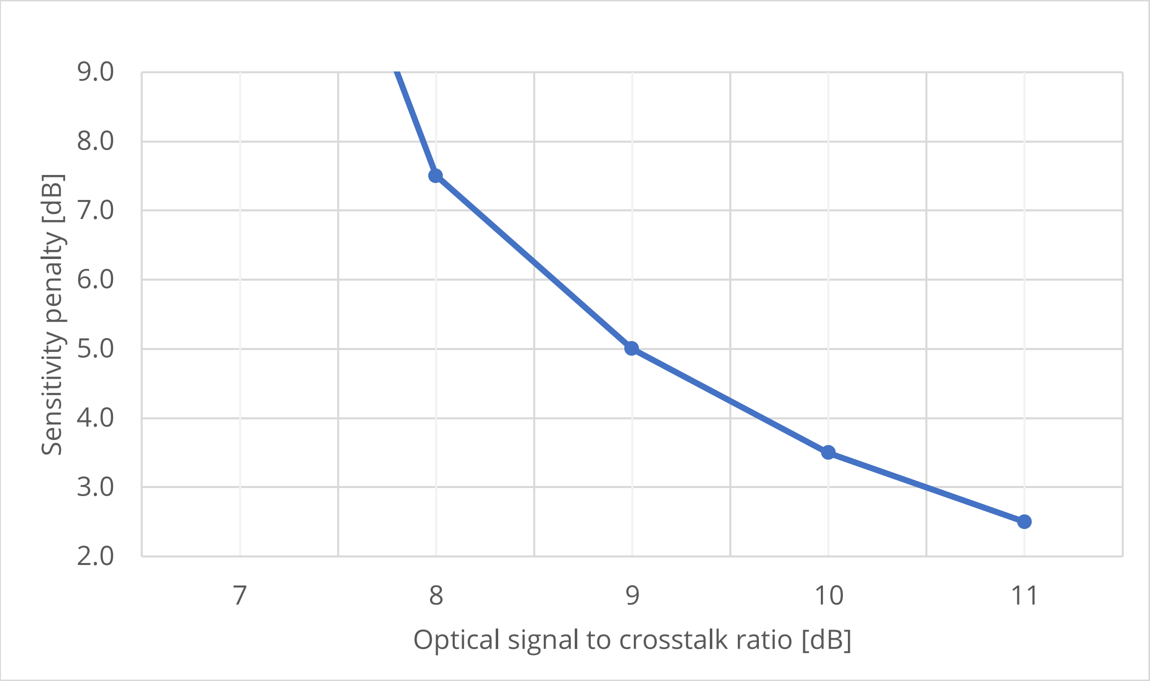

Figure 5 Sensitivity penalty vs OSXR graph

Subsequent sections explore the impact of various sources of reflections.

3.2.2 Distributed Backscattering

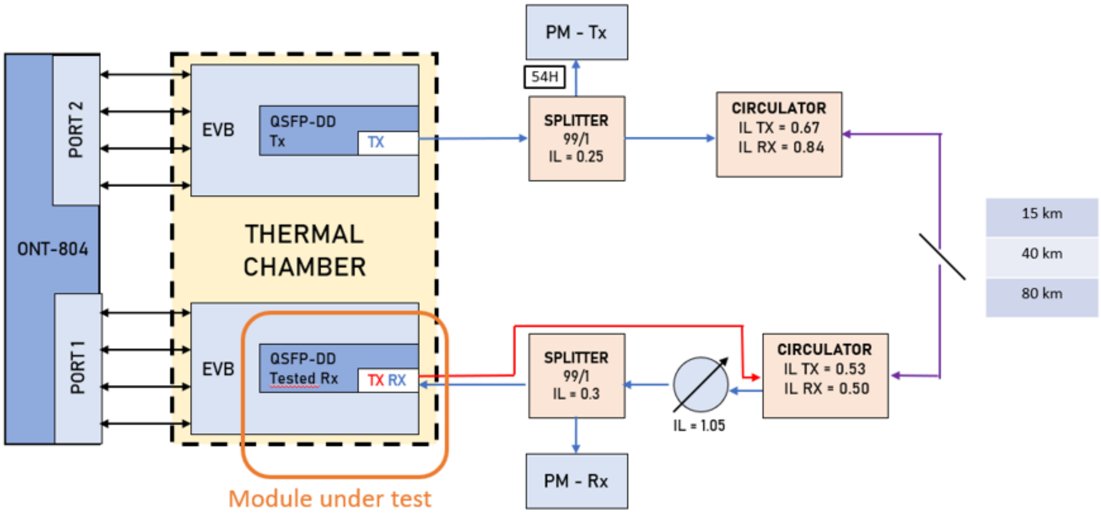

Figure 6 Test setup for measuring sensitivity penalty due to distributed backscattering.

In the setup shown in Figure 6 the discrete reflections were removed in order to isolate the effects of the fiber Rayleigh backscattering. Table 2 below shows the sensitivity penalty for different fiber link lengths.

Fiber link length [km]	Sensitivity Penalty [dB]
15	0
40	0.5
80	0.5

Table 2 Sensitivity penalty vs distributed backscattering due to different fiber link lengths.

The results show that the contribution of this type of reflections is small.

3.2.3 Discrete Reflections

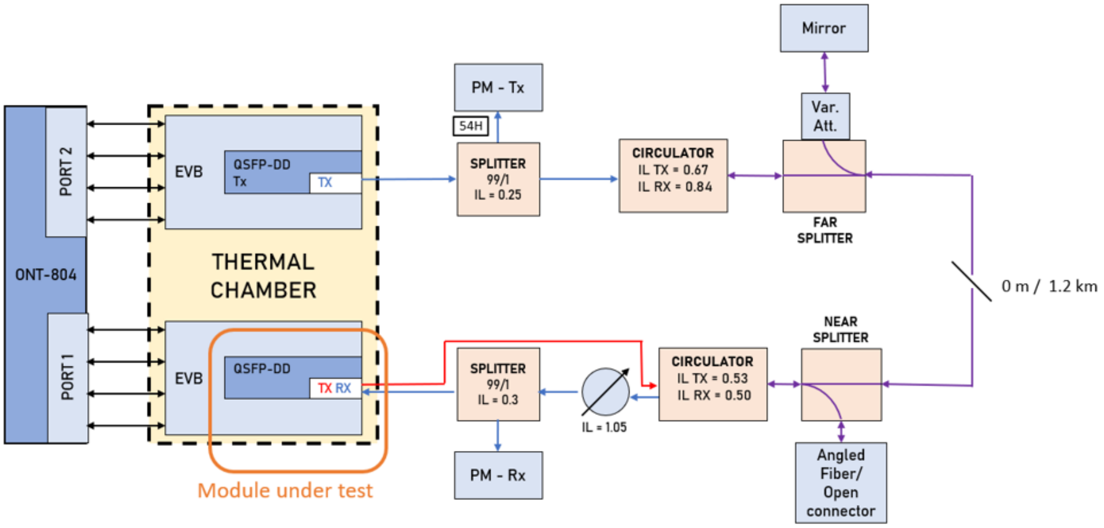

Figure 7 Test setup for measuring sensitivity penalty due to discrete reflections.

Measurements were performed with several combinations of return losses at the near and far ends, and with or without the presence of a short fiber link of 1.2km. The results are shown in Table 3 and Figure 8 below.

Direct Fiber Link			**1.2 km Fiber Link**		
Near Return Loss [dB]	**Far Return Loss [dB]**	**Sensitivity Penalty [dB]**	**Near Return Loss [dB]**	**Far Return Loss [dB]**	**Sensitivity Penalty [dB]**
20*	10	7	20*	10	5.5
>50	10	4	>50	10	3,5
20*	14	2.5	20*	14	3
>50	14	1.5	>50	14	1
20*	24	1.5	20*	24	1.5
>50	24	0.5	>50	24	0.5
20*	36	1.5	20*	36	1.5
>50	36	0.5	>50	36	0.5
20*	46	2	20*	46	1.5
>50	46	0.5	>50	46	0.5

Table 3 Sensitivity penalty for different combinations of near end and far end return losses, with or without a short fiber link of 1.2km.

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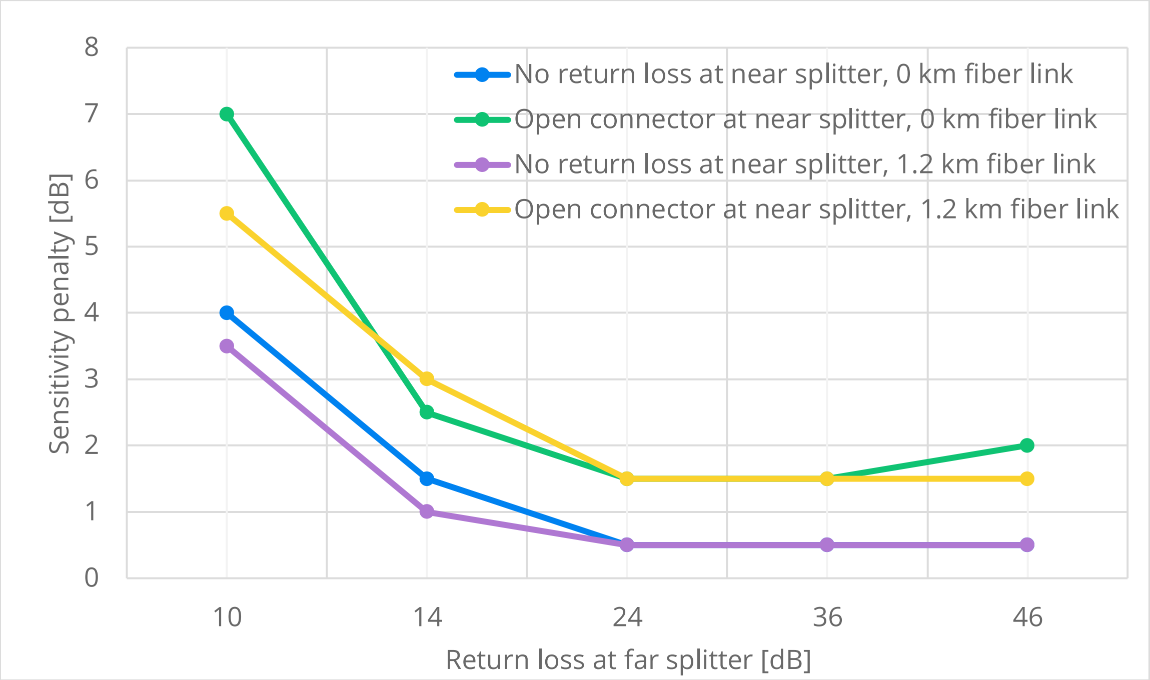

Figure 8 Sensitivity penalty for different combinations of near end and far end return losses, with or without a short fiber link of 1.2 km.

As expected, with decreasing return loss at the far splitter the penalty increases in all configurations, since the OSXR is decreasing. For the same reason, the configurations with an open connector at the near splitter always have higher penalties. The worst configuration is found with 1.2 km fiber link, 10dB of return loss at the far splitter and an open connector at the near splitter.

3.2.4 Combined Distributed Backscattering and Discrete Reflections

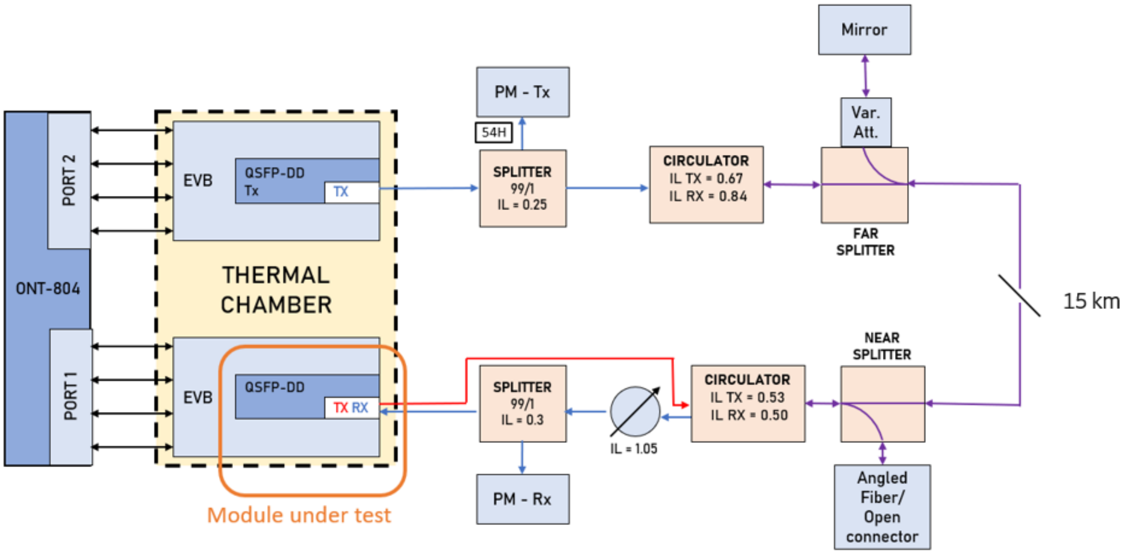

Figure 9 Test setup for measuring sensitivity penalty due to combined distributed backscattering and discrete reflections.

The setup in Figure 9 combines the presence of a longer fiber with that of discrete reflections. The results are shown in Table 4 below.

Fiber Link Length [km]	Near Return Loss [dB]	Far Return Loss [dB]	OSXR [dB]	Sensitivity Penalty [dB]
15	20*	20*	11.0	3
		10	9.5	4
		8	9.0	5
		7	8.5	6
		6	8.0	7

Table 4 Sensitivity penalty for combined distributed backscattering and discrete reflections.

With a longer fiber length, for instance 40 km, the receiver input power was too low to tolerate the presence of the open connector at the near splitter.

3.2.5 Discrete Reflection Distribution

In order to study the impact of the distribution of discrete reflections between the near end and the far end, the OSXR was maintained constant while the total return loss was distributed in different ways and the sensitivity penalty for each configuration was measured. The results are shown in Table 5 below:

Fiber link length [km]	OSXR [dB]	Near Return Loss [dB]	Far Return Loss [dB]	Sensitivity Penalty [dB]
15	9	16	24	4.5
		17	23	5.0
		18	22	5.5
		20	20	5.0
		34	6	5.0

Table 5 Sensitivity penalty for different return loss distributions resulting in the same OSXR.

This test showed no significant impact of the return loss distribution between the two splitters.

3.2.6 Discrete Reflection Distance

In this test, the OSXR was maintained constant while different fiber lengths were inserted between the two splitters and the sensitivity penalty for each configuration was measured. The results are shown in Table 6 below:

Far Return Loss [dB]	Near Return Loss [dB]	OSXR [dB]	Fiber link length [km]	Sensitivity Penalty [dB]
20*	20*	9	0	5.0
			5	5.0
			10	5.0
			15	4.5
			20	5.0

Table 6 Sensitivity penalty for different fiber link lengths between discrete reflections.

This test showed no significant impact of the distance between the two splitters.

4 Test #2 – IEEE Std. 802.3 100GBASE-ZR

The second set of tests used transceivers operating in IEEE Std. 802.3 100GBASE-ZR mode, i.e. using Dual Polarization Differential Quadrature Phase Shift Keying (DP-DQPSK) modulation at a symbol rate of 28GBd with Staircase Forward Error Correction (SC-FEC) code.

4.1 Test Conditions

The optical frequency of the modules was set at 191.7 THz. The media (line) interface was configured as 100GBASE-ZR with SC-FEC and the host interface was configured as CAUI-4 with KR4 FEC. A simplified test set-up was used that combined the signal of the remote transmitter with the attenuated signal of the local transmitter and fed this into the local receiver.

4.2 Test Results

Figure 10 shows the measured receiver sensitivity as a function of the reflected power.

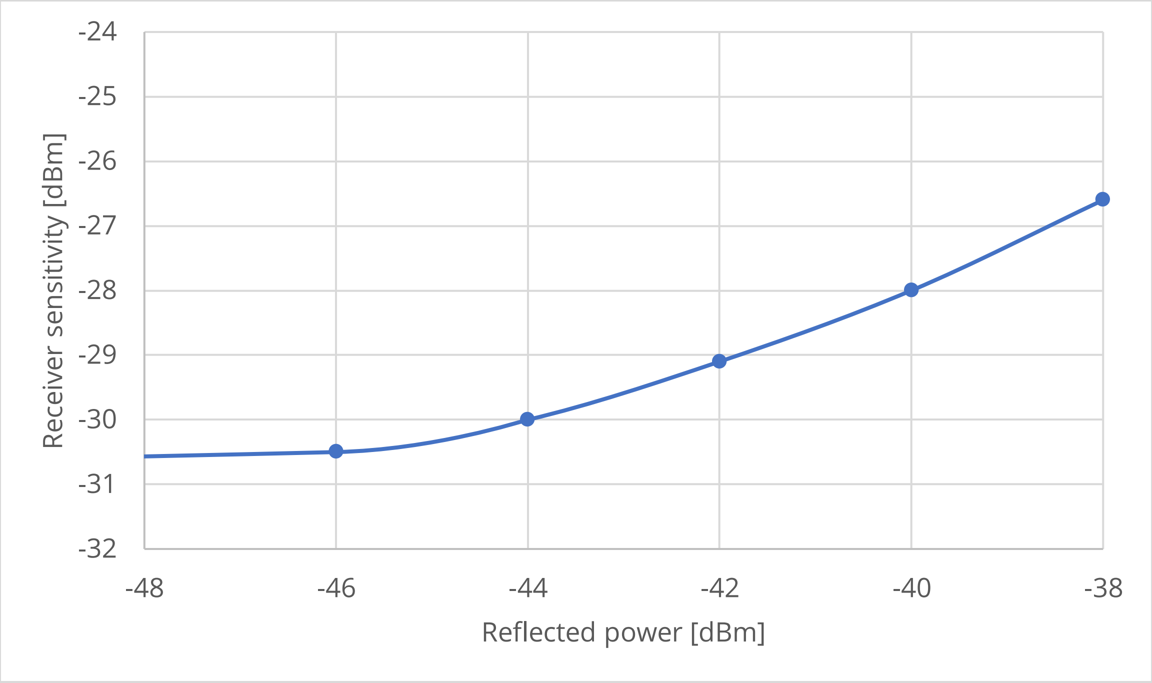

Figure 10 Receiver sensitivity vs reflected power.

Figure 11 plots the sensitivity penalty as a function of the optical signal to crosstalk ratio for the 100GBASE-ZR mode and compares the results to those obtained for the 100G OpenZR+ mode in §3.2.1.

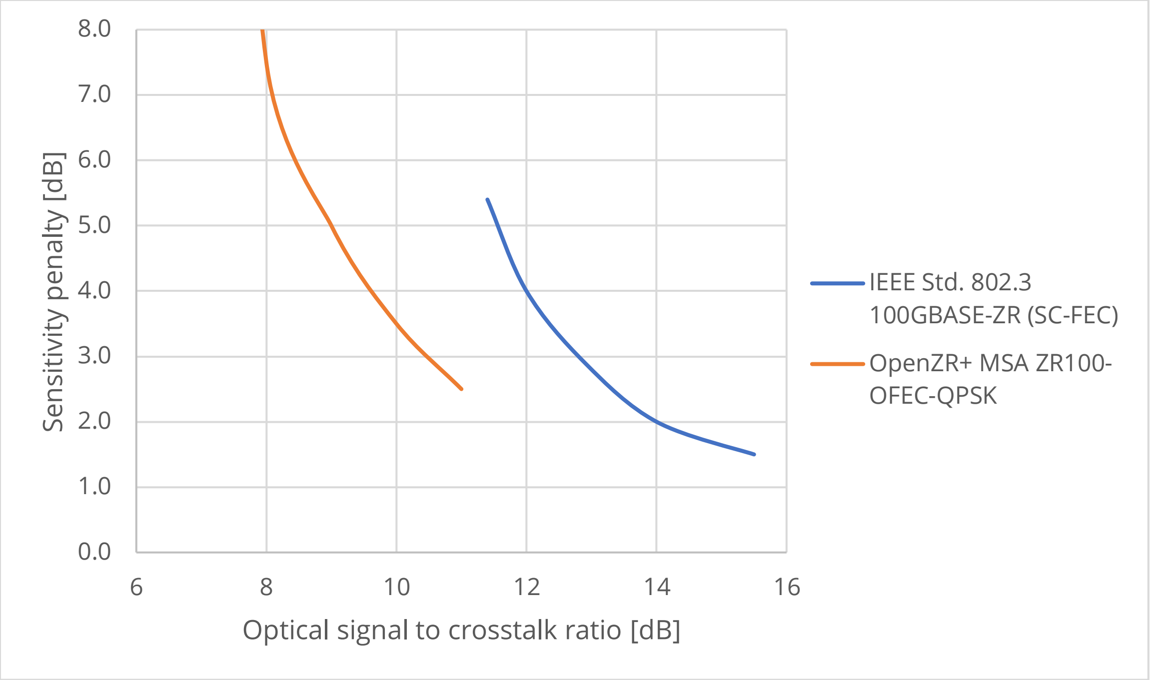

Figure 11 Comparison of sensitivity penalty vs OSXR for two operating modes.

Clearly, the 100GBASE-ZR mode appears to be less tolerant to reflections, likely due to the lower threshold of SC-FEC relative to O-FEC. On the other hand, the SC-FEC decoder requires significantly less power than the O-FEC decoder.

5 Application to Existing MOPA Blueprints

If one were to introduce bidirectional single laser DCO transceivers with a circulator into any of the below MOPA blueprints, the block diagram would look like Figure 2.

- 8.3.3. 15 km RU-DU, passive DWDM over a single fiber.
- 8.3.5. 15 km RU-DU, semi-active DWDM over a single fiber.
- 9.2.8. 15 km CRAN backhaul, passive DWDM over a single trunk fiber.

All of these blueprints assume a worst-case insertion loss of the Mux and Demux of 5.5 dB and a worst-case fiber loss of 6.8 dB. Adding 1.2 dB insertion loss for each of the circulators would bring the total link loss to 20.2dB.

Both IEEE Std. 802.3 100GBASE-ZR and OpenZR+ MSA ZR100-OFEC-QPSK specify a minimum transmit power of -8 dBm. With this transmit power, the 20.2 dB link loss would bring the receiver input power to within less than 2 dB of the receiver sensitivity specified in IEEE Std. 802.3 100GBASE-ZR, leaving little margin for power penalties due to reflections.

	Unit	Tx/Rx A	Circ.		Mux		Fiber		De-mux		Circ.	Tx/Rx B
Insertion loss	dB		1.2		5.5		6.8		5.5		1.2	
Return loss	dB				30.0				30.0		30.0	
Directivity	dB		45.0									
Signal power A -> B	dBm	-8.0	→	-9.2	→	-14.7	→	-21.5	→	-27.0	→	-28.2
			↓		↓				↓		↓	
		-53.0	←		↓				↓		↓	
		-40.4	←	-39.2	←				↓		↓	
		-65.0	←	-63.8	←	-58.3	←	-51.5	←		↓	
		-76.0	←	-74.8	←	-69.3	←	-62.5	←	-57.0	←	
Total crosstalk power B -> A	dBm	-40.2										
Signal power B -> A	dBm	-28.2	←	-27.0	←	-21.5	←	-14.7	←	-9.2	←	-8.0

Table 7 Calculation of optical signal and crosstalk power levels for the link shown in Figure 2 with insertion loss values from MOPA blueprints 8.3.3, 8.3.5, and 9.2.8.

Moreover, even with a relatively high return loss assumption for the Mux and Demux of 30dB, the optical signal to crosstalk ratio (OSXR) is less than 12 dB, which based on Figure 11 could result in power penalties anywhere from 2 dB to 6 dB depending on the modulation format and forward error correction code.

The main contributor to the crosstalk is reflections at the Mux/De-mux. While the actual Mux/De-mux components typically have much better return loss than 30 dB, reflections at the connector interfaces could cause problems. Reducing those reflections to ensure a return loss well above 30 dB may require the use of angled physical contact (APC) connectors.

On the other hand, dual laser DCO transceivers aligned with either IEEE Std. 802.3 100GBASE-ZR or OpenZR+ MSA ZR100-OFEC-QPSK could be dropped into any of the MOPA DWDM blueprints (assuming the incremental cost and power consumption are acceptable) and would be able to close those links with margin.

6 Conclusion

This paper presents some initial test results on the use of optical circulators to enable bidirectional transmission with single laser DCO transceivers. These results indicate that such a solution can be considered for existing MOPA DWDM blueprints. However, further analysis is required to determine a reasonable trade-off between requirements for various components and modify the blueprints accordingly. On the other hand, dual laser DCO transceivers remove any impairments due to reflections but lead to additional cost and power consumption that need to be considered by system vendors.