CIP White Paper

Semiconductor Optical Amplifiers for WDM Applications

Contents

1. Introduction

In today's Wavelength Division Multiplexing (WDM) Metro and Access network, where bands of wavelength are transmitted over tens of kilometres, Semiconductor Optical Amplifiers (SOA) can play an important role. Possible applications for a SOA include single channel boosters in complex WDM transmitters to maintain a high signal power, pre-amplifiers in terminal equipment to improve receiver sensitivity and multi-channel amplifiers to extend reach and overcome losses in network nodes, such as add/drop multiplexers in Metro networks (as shown in Fig1).

Provided the SOA is operated in its linear regime, not only is its gain independent of the number of wavelengths being amplified, but also the gain is not effected by dynamic effects of network reconfiguration or bursty data, like in a packet network.

In order to maintain the SOA in its linear state, a careful assessment of the amplifier characteristics versus input power must be done. This white paper describes the characteristics of a Linear SOA (L-SOA) for application in either a Continuous Wave (CW) or 10Gbit/s environment and under both single and multi-channel operation. The following work relates to C band, but may also apply to other wavelengths.

2. Amplifier requirements for today networks

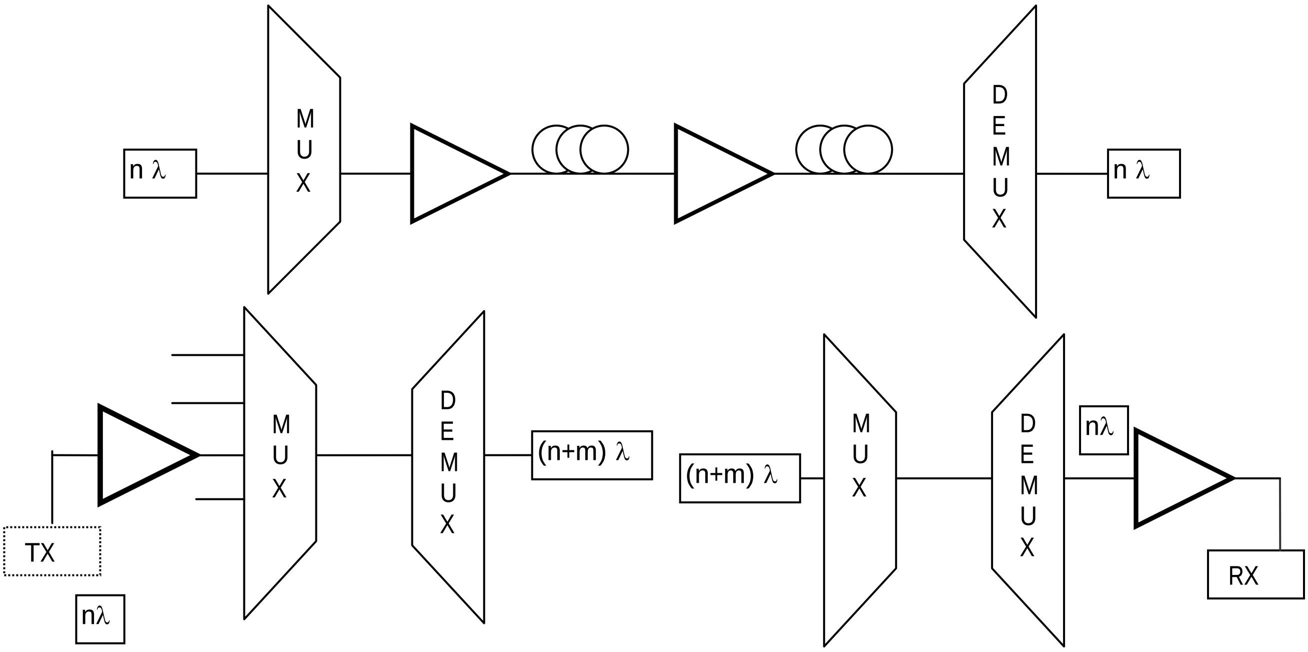

Figure 1: SOA in a WDM network as an in line amplifier, single channel booster at the transmitter (TX) and amplifier in a Receiver (RX)

The requirements for an amplifier to be used in Metro and Access networks, will vary depending on the amplifier role within the network. Let’s consider some of the desirable features. In a transmission part of the network, the typical fibre span would be tens of kilometres, the loss of which can be overcome by a booster amplifier with a properly matched gain. Also, this installed fibre does not preserve the state of polarisation, therefore the utilisation of polarisation insensitive amplification is an important factor. The noise added to the signal by the amplifier is not a desired feature, particularly if we are in a pre-amplification application: care must be taken in the choice of amplifier design and the correct operating conditions to give the best noise figure. Amplifier non linearities which can lead to cross talk effects are not a desired feature in a network, therefore an amplifier with high saturation input power is necessary in order to keep the device in its linear regime. An elevated saturation power is also desirable for a power booster where the high output power is the primary parameter of interest. Moreover, with the increasing demand of optical bandwidth, particularly with the increasing interest to move from a Dense WDM (DWDM) to a Coarse WDM (CWDM) scenario, a colourless and wide band amplification is ideal, giving a wider choice on the wavelengths to be chosen for the transmission. In a future proof network, which can carry data rates from Mbit/s to 40Gbit/s, the use of a data rate transparent amplifier is another advantage. Finally in a dynamic channel count network[1], when some channels are dropped or added at kHz frequencies, a quick amplifier with recovery time of the order of μsec or better, is required in order to maintain constant power constant along the line.

3. The Linear SOA CW characteristics

Our CIP linear SOA is a low confinement factor device optimised for moderate gain in C band, low noise and high saturated output power. The particular device used in our testbed (SOA-L-OEC-1550 2917) offers the characteristics illustrated in Fig. 1 and 2 and in table 1 .

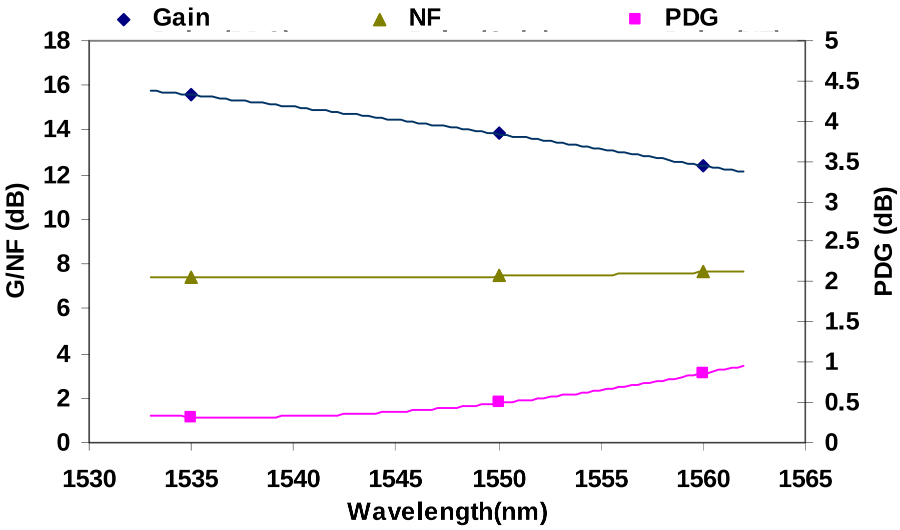

Figure 2: SOA C band CW characteristics at 20˚C

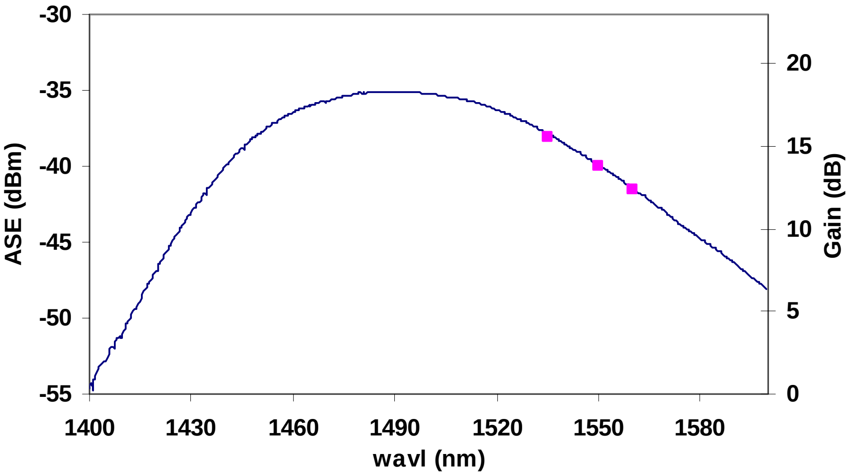

Figure 3: Amplified Spontaneous Emission (ASE) for SOA under test at 20˚C. The C band Gain is shown as well (pink squares)

Item	Value	Unit
Gain (G)	13.8	dB
Noise Figure (NF)	7.4	dB
Polarisation Dependent Gain (PDG)	0.5	dB
Saturated Output Power (Psat)	16.7	dBm

Table 1: SOA CW characteristics at 1550nm at 20˚C

If we observe the close relationship between Gain and ASE profile, shown in figure 2, this device will offer 18dB gain in the S band[2]. The NF is low in the C band, but expected to be higher at shorter wavelengths. The device PDG is below 1dB across the C band and finally the Saturation Output Power is quite high, even at shorter wavelengths. From figure 5, we can see that the SOA is in its linear regime, at 1550nm, for input powers up to approximately 0dBm, with a correspondent output power of +13dBm.

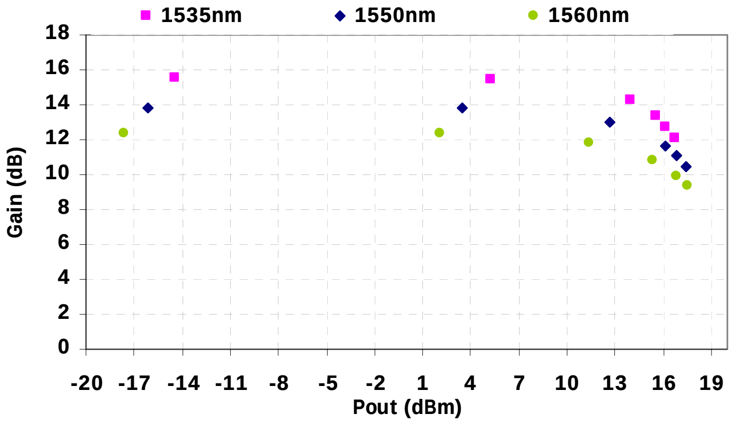

Figure 4: SOA Gain curves versus output power for 1535, 1550 and 1560nm at 20˚C

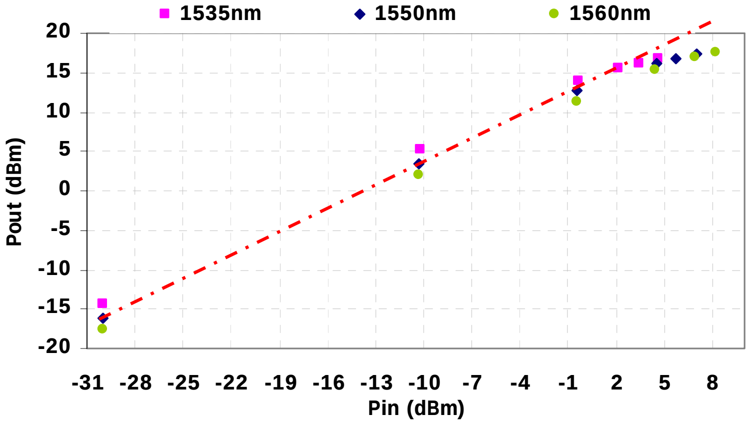

Figure 5: Linearity of SOA output power versus input power in C band at 20˚C

The above device characteristics meet the requirements we discussed in the above section 2. In particular, if this SOA is utilised as a power booster, it could compensate for the loss of 60km of SMF-28 (when considering a loss of 0.2dB/km). Also, due the broad optical bandwidth, the device can amplify not only the DWDM (DWDM), 50 or 100GHz spaced, channels, but also 20nm spaced, CWDM channels (as shown in Fig. 6).

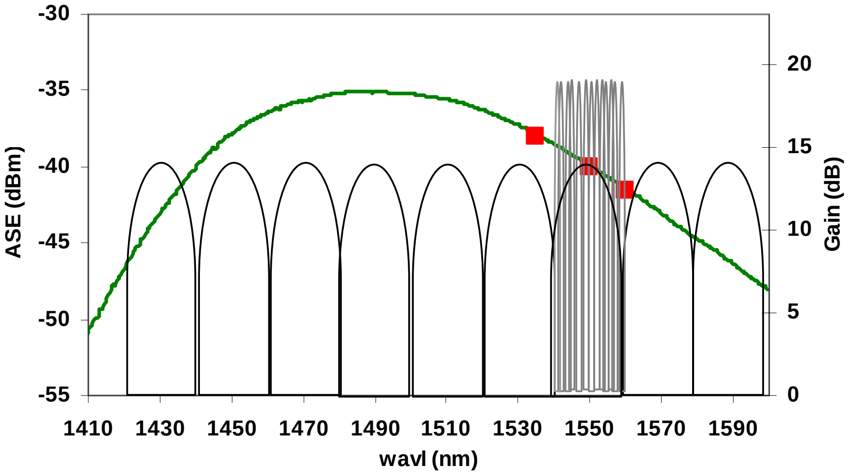

Figure 6: the SOA gain (red markers) and ASE profile (green line) compared with DWDM and CWDM wavelength grid

4. 10 Gbit/s 8 channel SOA characteristics

A simplified schematic of the WDM test rig is shown in Figure 7. Eight lasers in the C band, 100GHz spaced, (as indicated in table 2 and Fig. 8) go through a Multiplexer. They are modulated by a CIP Electro Absorption Modulator (40G-SR-EAM-1550)and then fed to the SOA under test. The 8 channels are then demultiplexed. The attenuator at the receiver input gives the Sensitivity value. Its output is filtered (via a

1nm bandwidth filter) and then detected by a Lightwave converter for Bit Error Rate (BER) and Q evaluation. A detailed setup is described in Annex 1.

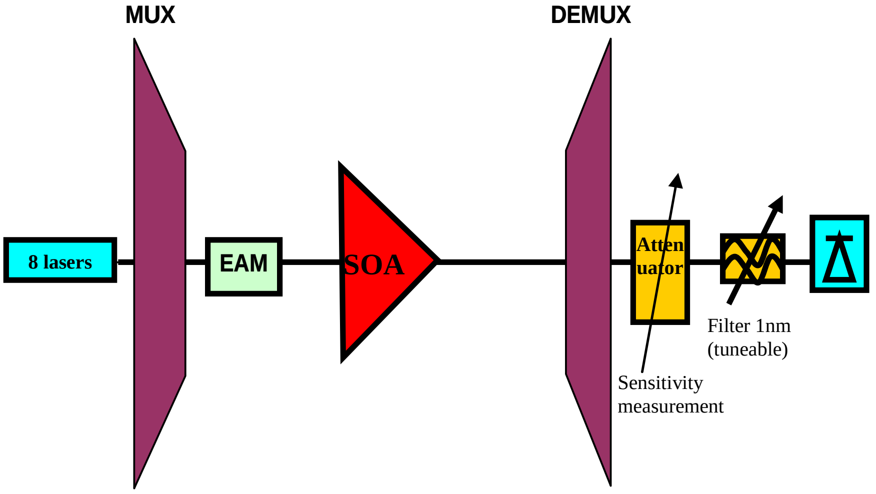

Figure 7: WDM test rig (simplified)

Channel #	Wavelength (nm)
1	1551.001
2	1551.835
3	1552.595
4	1553.479
5	1554.294
6	1554.995
7	1555.788
8	1556.641

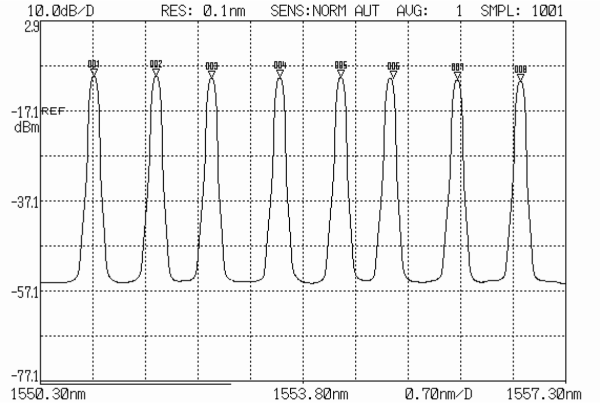

Figure 8, Table 2: 8 channels used in the WDM experiment

The system performance at 10Gbit/s was assessed in terms of BER, Sensitivity and Q factor 8, 4, 2 and 1 channels to enable the study of the effects of crosstalk, including Four Wave Mixing (FWM) and cross gain modulation (XGM). The details of the testing conditions are listed in Table 3.

Parameter	Value
SOA Bias Current	500mA
SOA Temperature	20˚C
EAM Reverse DC Voltage	2.7V
EAM RF drive	2.9V$_{pk2pk}$
RF pattern	2^{31}-1, NRZ, PRBS
EAM Input Power (Pin)	+13dBm
EAM Extinction Ratio (XR)	10.8dB at 1553nm

Table 3: Operating conditions for SOA and EAM

Results in terms of Sensitivity and Q, when the channel 4 was detected, are shown in figure 9: in the first plot the data are represented as a function of per channel input power into the SOA (Pin/ch), while the second graph has the total Input power into the SOA in the x axis (PinTOT). The performances for the different channel count cases coincide up to Pin/ch=-6dBm. Therefore no significant crosstalk effects are visible for a 20dB input power swing, from -26dBm to -6dBm Pin/ch. Also, in this Pin/ch interval, the

Sensitivity and Q variation is quite small, giving the flexibility of varying the SOA input power without compromising the overall system performance.

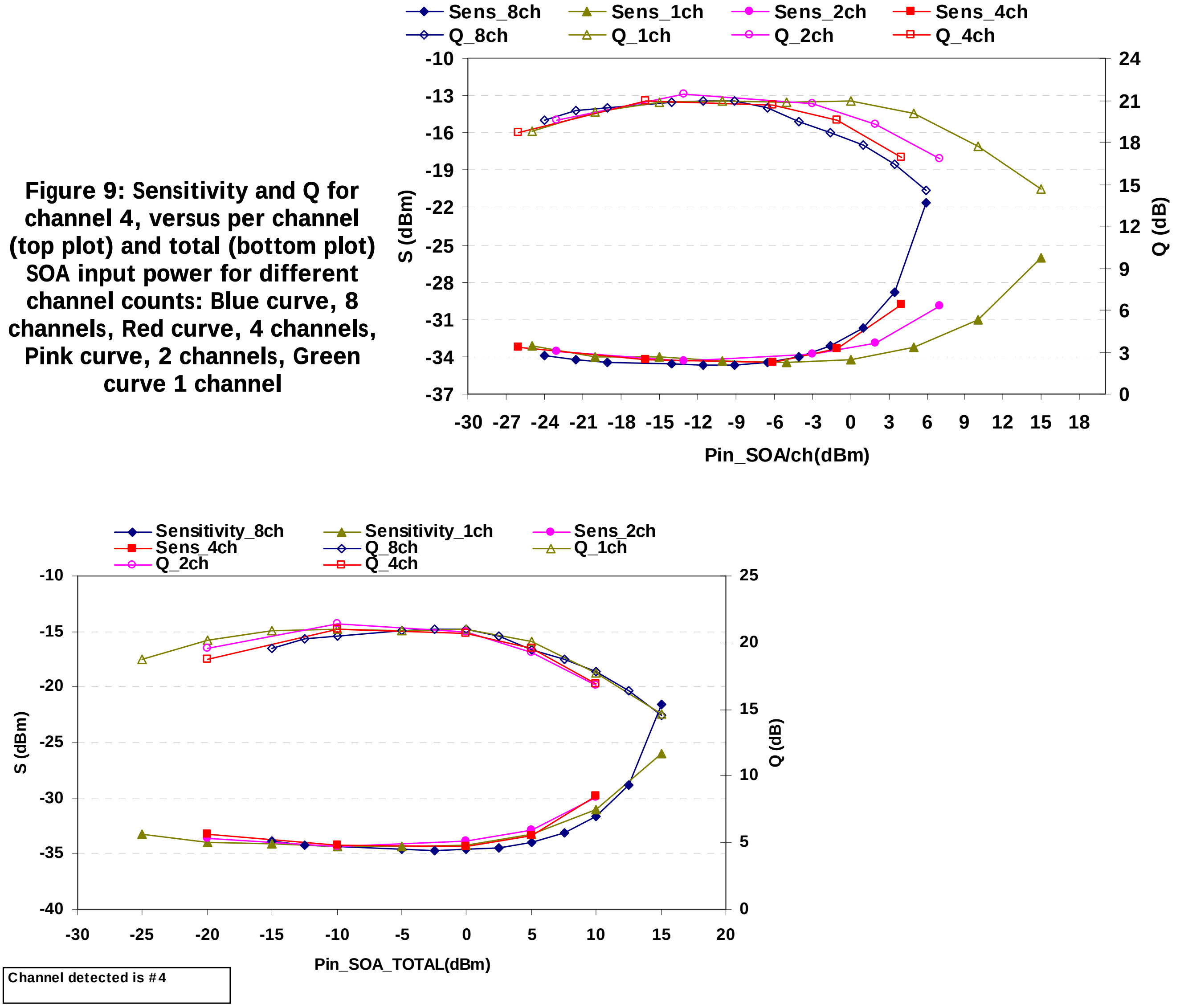

Figure 9: Sensitivity and Q for channel 4, versus per channel (top plot) and total (bottom plot) SOA input power for different channel counts: Blue curve, 8 channels, Red curve, 4 channels, Pink curve, 2 channels, Green curve 1 channel

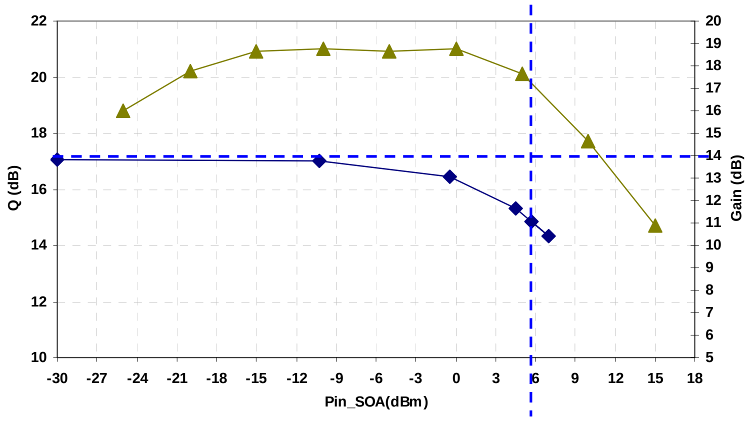

Figure 10: Single channel Q performance and CW SOA gain versus SOA input power

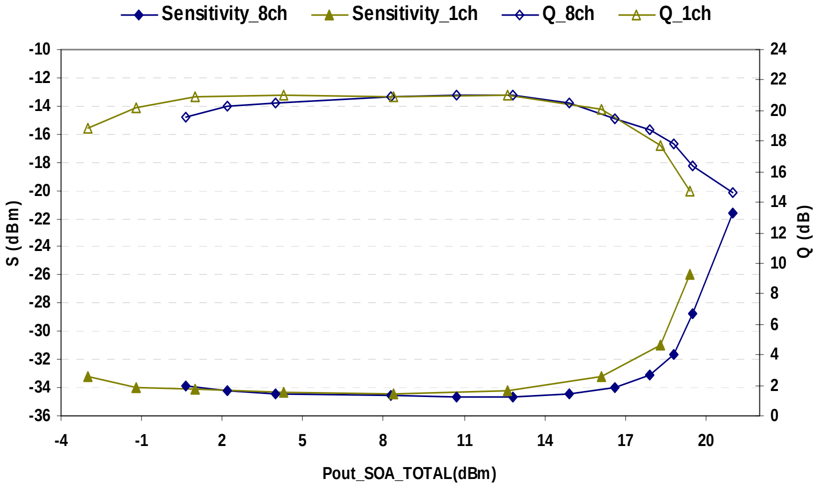

Figure 11: Sensitivity and Q versus total SOA Output power for different channel counts. Blue curve, 8 channels, Green curve 1 channel

In the single channel case, for low input power (when Pin<<3dB saturation point), as shown in fig. 10, 11 and 12, the system Q increases in direct proportion to the signal power, and hence Optical Signal to Noise Ratio, OSNR, (black line in figure 12). As the power increases, the contribution from the SOA to the overall OSNR becomes insignificant and the Q factor doesn't follow the increase in SOA input power(red line of fig. 12). Beyond 1dB into saturation (Pin=0dBm)the distortions from the SOA non linearities overcame the benefit of an increased OSNR given by a higher SOA output power (green line in fig. 12). The strong patterning effect is visible in the eye diagrams of figure 13: for SOA Pin=15dBm (corresponding to a total output power of ~20dBm), the eye is almost close, dominated by edge overshoots, indicating deep SOA saturation, but the system was still error free. The best eye diagram, that corresponds to the best Q performances, is obtained for a SOA Pin=0dBm (giving a total SOA output power equal to 13dBm): the "0" eye level of the eye benefits from a high OSNR, while the "1" level of the eye is still not degraded by the SOA saturation, even if a slight overshoot is present.

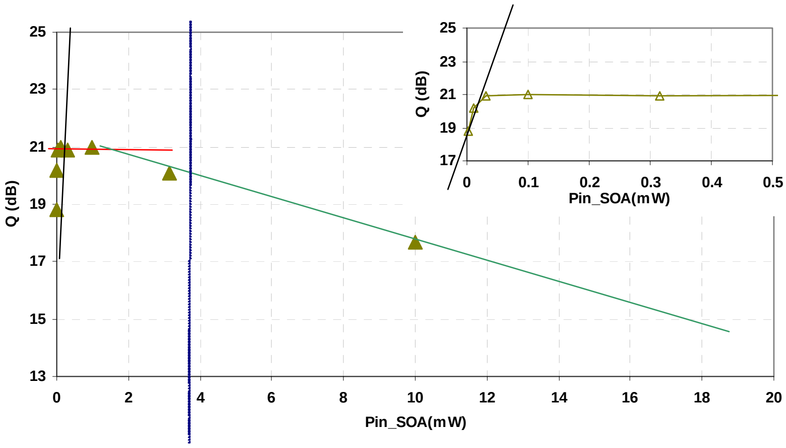

Figure 12: 1 channel Q versus SOA input power (in mWatt). Three regions are also indicated highlighting the difference dependency of the Q factor from the SOA. The blue line indicated the SOA saturated input power.

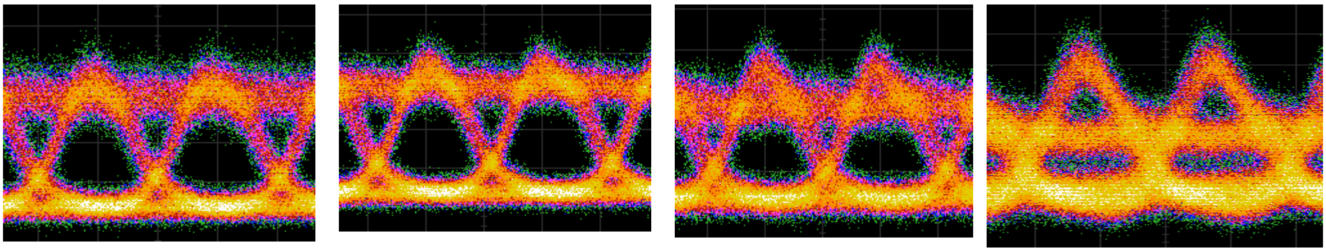

Figure 13: From left to right, eye diagrams for 1 channel transmission for SOA per channel input power of -25, 0, 5 and 15dBm

When more than one channel is launched, the situation is somewhat similar to the 1 channel case: for low per channel input power to the SOA, the system performances follow the OSNR, and, in fact, the 1, 2, 4 and 8 channel curves overlay (see top plot of fig. 9); when the SOA starts to saturate, the cross gain modulation induced distortions make the various channel count curves diverge with increased Q penalty for higher channel count, as it is also visible in Figure 14. While the eye diagrams (see fig. 15)of the single and 8 channel cases are very similar for low input power, like when Pin/ch is approximately -10dBm, the patterning effects are evident when the SOA Pin/ch=6dBm (total SOA Pin=15dBm for 8 channel and Pout=21dBm), thus when the SOA is heavily saturated. The effects of FWM are clearly visible in the SOA output spectra for 8 channel launched with a total SOA Pin=15dBm (shown in fig. 16) where many sidebands are generated, of which the worst is 30dB weaker than the signal. Even in this condition, the system was still error free.

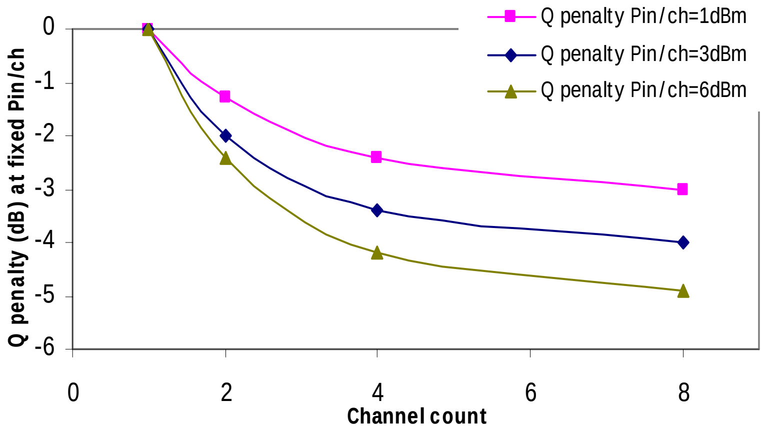

Figure 14: Q penalty for fixed SOA per channel input power (equal to 1, 3 and 6dBm) versus the number of channel launched

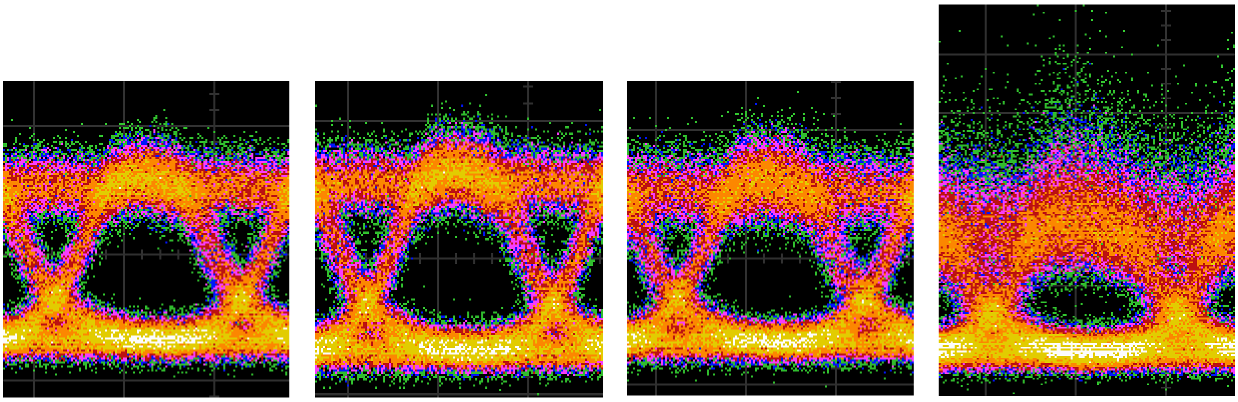

Figure 15: eye diagram for 1 and 8 channels. From left to right: 1 channel, Pin=-10dBm, 8 channel Pin=0dBm (or Pin/ch=-9dBm), 8 channel and Pin=5dBm, 8 channel Pin=15dBm (or Pin/ch=6dBm)

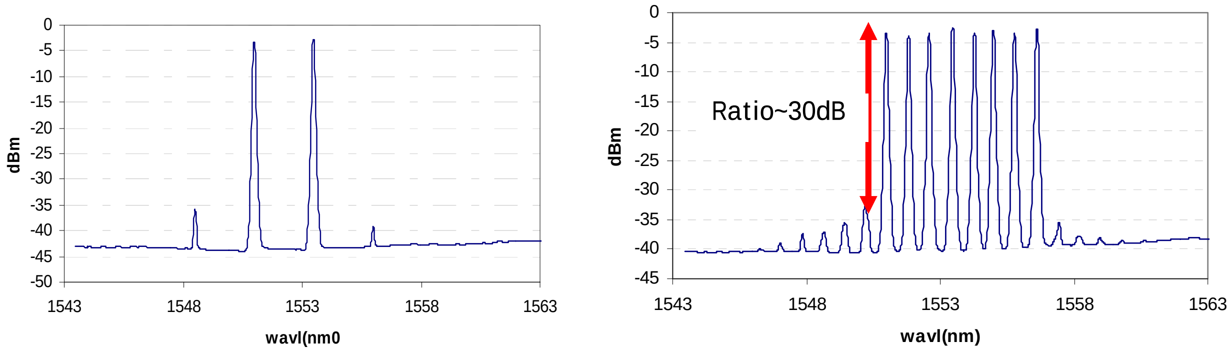

Figure 16: SOA Output Spectrum for 2 channel for a total SOA input power equal to 10dBm, 2 channels, (left) 15dBm (right), 8 channels

Finally, the system performances for the 8 channel case were assessed when different channel was detected at the receiver (as shown in fig. 17). The performances are very similar when the SOA total Pin=-15, 0dBm, thus where the crosstalk effects are not compromising the system performances. When SOA Pin=10dBm, the Q and Sensitivity values are slightly worse for the short wavelength channel. As it is also shown in the spectrum of figure 16 (8 channel launched for a total SOA Pin=15dBm), there is presence of sidebands due to FWM, particularly at shorter wavelengths (where the SOA saturates at lower input power). What seem a low level of crosstalk (30dB down from the signal) can produce power penalties due to coherent beat noise. As it is well know , FWM depends on the channel spacing. Different Q and Sensitivity values were measured, at high SOA input power, when less than 8 channel were launched in the system, depending on the channel spacing and position: for the 2 channel case (with channel 1 and 4 on), the worst case scenario was found to be when channel 1 was detected; but even in this case the system was still error free.

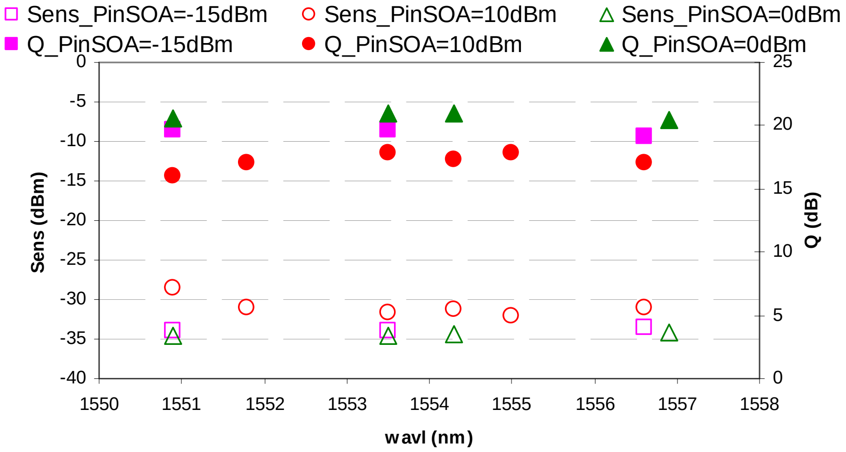

Figure 17: Sensitivity and Q for 8 channel launched, when different channel is detected at the receiver. System performances are fairly constant across the C band for low SOA input power (Pin≤0dBm), while degradation for the shorter wavelength channels is visible at higher power (Pin=10dBm) due to crosstalk effects

5. 10 Gbit/s SOA power booster

In a metro or access scenario, when a power booster amplifier is used to extend the reach over tens of km of fibres, the system performances will be affected not only by the amplifier characteristics, but also by the fibre non linearities when high powers are launched into the system. This phenomenon will have different effects depending on the type of fibre used, i.e. with normal or anomalous dispersion. As it has been previously demonstrated[3], there is a synergy between SOA based amplification and transmission over anomalous dispersion fibres, like SMF-28. In fact, when high power short pulses are injected into the SOA and saturate it, the resulting SOA output spectrum is broader due to Self-Phase Modulation (SPM). This SPM induced frequency chirp can compensate for the negative SMF-28 dispersion, improving the transmission performances. The chirp induced by the EAM will also influence the system performances.

The SOA was tested in the 10Gbit/s WDM transmission system shown in fig. 18, when 60kms of SMF-28 fibre are inserted after the amplifier (refer to annex 1 where the fibres are inserted into the system via the switch). The details of the testing conditions are listed in Table 4.

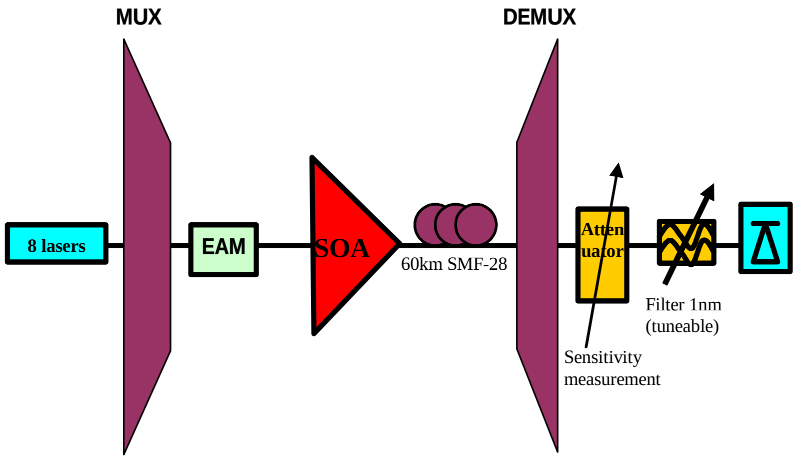

Figure 18: 10Gbit/s WDM Transmission with SOA as a power booster

Parameter	Value
SOA Bias Current	500mA
SOA Temperature	20˚C
EAM Reverse DC Voltage	3.1
EAM RF drive	2.9V_{pk2pk}
RF pattern	2^{31}-1, NRZ, PRBS
EAM Input Power (Pin)	+13dBm
EAM Extinction Ratio (XR)	10.4dB at 1553nm

Table 4: Operating conditions for SOA and EAM

Results in terms of Sensitivity and Q (when the 4th channel was detected at the receiver) as functions of per channel and total SOA input power are shown in figure 19 and 20. As for the back to back case, the performances for the different channel count cases coincide up to Pin/ch=-6dBm. Therefore there is no evidence of crosstalk up to SOA total output power of 14.9dBm.

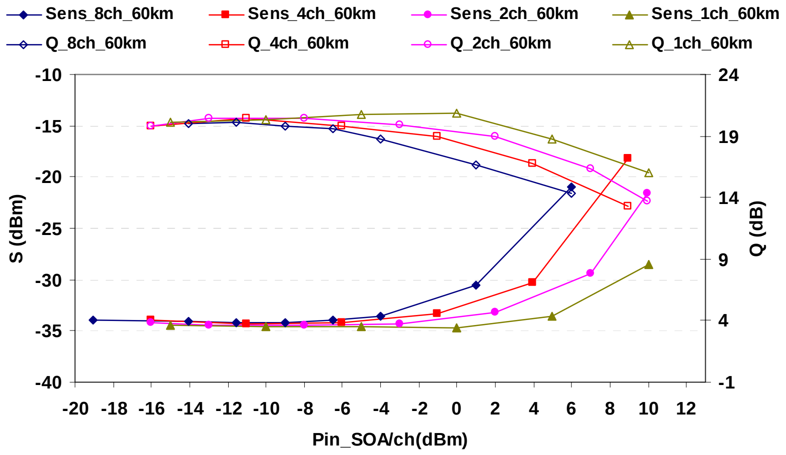

Figure 19: Sensitivity and Q for the transmission over 60kms of SMF-28 versus per channel SOA input power for different channel counts: Blue curve, 8 channels, Red curve, 4 channels, Pink curve, 2 channels, Green curve 1 channel

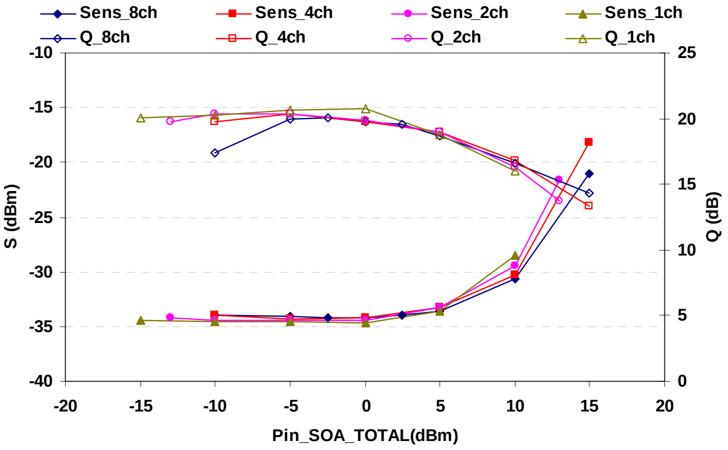

Figure 20: Sensitivity and Q for the transmission over 60kms of SMF-28 versus total SOA input power for different channel counts: Blue curve, 8 channels, Red curve, 4 channels, Pink curve, 2 channels, Green curve 1 channel

If we compare the data of the back to back and transmission test for 1 and 8 channels, we can see, in fig. 21, that the transmission results follow the same trend of the back to back ones (refer to annex 2 for details on the proper DC biasing of the EAM). The discrepancy at high Pin/ch between the back to back and transmission data for the single channel case (purple and green data) is probably due to fibre non linearities effects, that degrade the single channel transmission more than the WDM case. In fact, in the multi-channel case the probability of having the maximum or minimum signal input power is diminished in proportion to the number of channels. This assumption is also supported by the relative shift in the input power per channel at which the penalties are observed. In the absence of these averaging effects, the penalties should occur at the same total power, or at 9dB lower per channel power. As visible in fig. 21, the single channel performances start degrading at Pin/ch=0dBm, therefore only 6dB higher power than the multi-channel case.

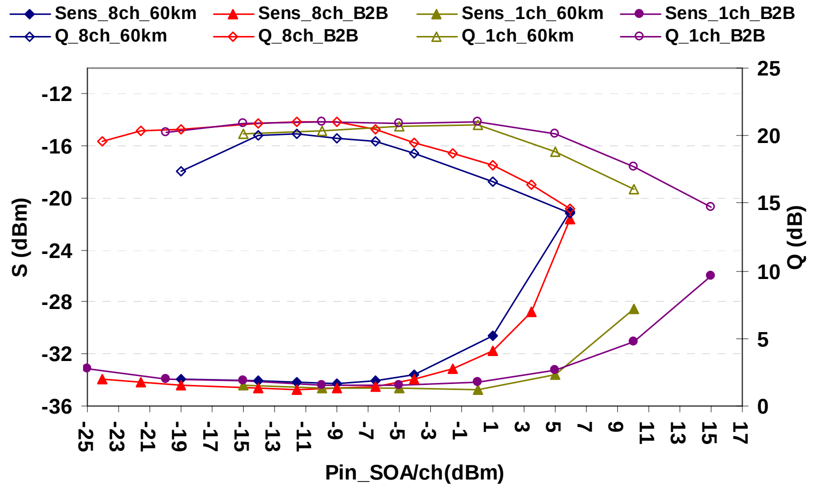

Figure 21: Comparison between Back to Back (red and purple data) and Transmission performances (Blue and Green data) for 1 and 8 channels. The Back to back data are for an EAM DC bias =2.7V, while the transmission data have a EAM DC bias=-3.1V

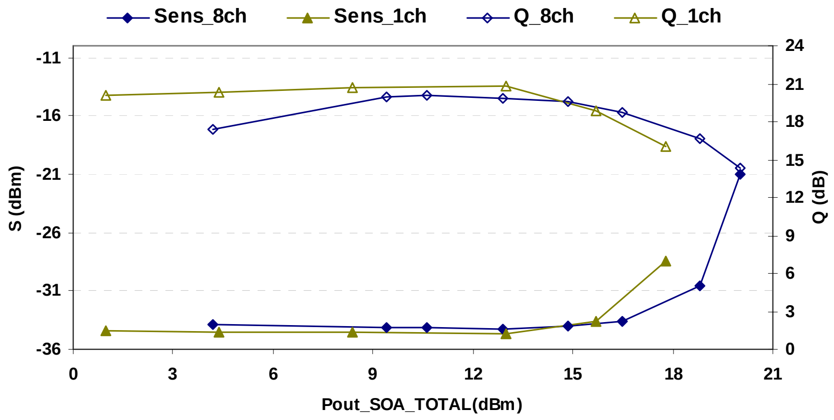

Figure 22: Sensitivity and Q for the transmission over 60kms of SMF-28 versus total SOA output power for different channel counts: Blue curve, 8 channels, Green curve 1 channel

The eye diagrams for the single and WDM scenario (fig. 23 and 24) support the above discussion. While the eye diagrams for low SOA input power, look similar for the 1 and 8 channel cases, this is not true at higher powers. In fact, in the single channel eye for 0dBm, there is evidence of jitter in the falling edge of the eye, making it asymmetric. This is indicates that the recovery dynamics of the SOA are pattern dependent, determined by whether or not the SOA has achieved a steady condition. The eye diagram at Pin=10dBm is almost not visible, degraded by not only the deep saturation of the SOA, but also probably by fibre non linearities. In fact, comparing this eye diagram with one obtained at the same SOA input power for the back to back case (fig.13), we notice how the latter is not as deformed and suffers only from the SOA non linearities. The 8 channel eye diagrams, instead, do not degrade as much. Although they get closer at 15dBm as in the back to back case (fig.15), there is not much overshoot as the one present in fig. 23. This supports the previously described averaging phenomenon which improve the WDM performances as the channel count increases, as also visible in fig. 25.

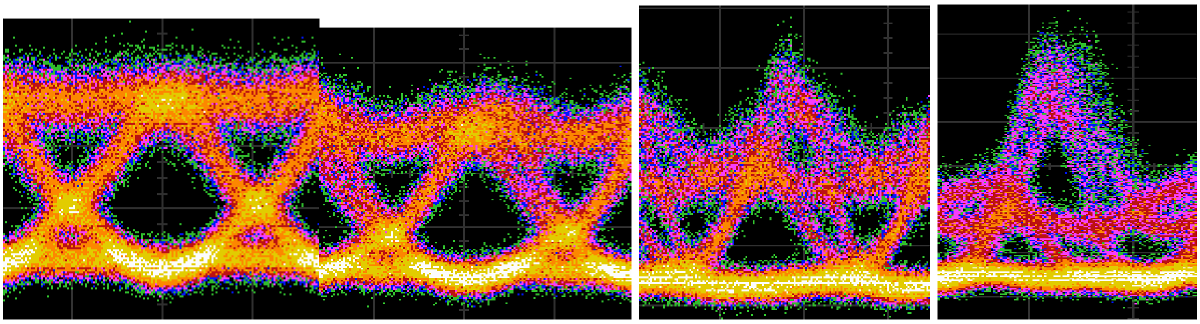

Figure 23: From left to right, eye diagrams for 1 channel transmission over 60km of SMF-28 for SOA input power of -10, 0, 5, 10dBm

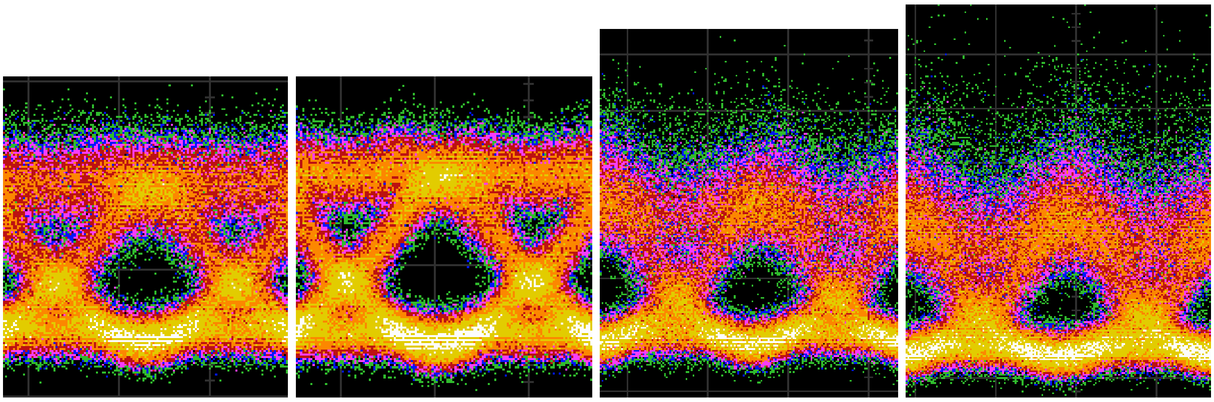

Figure 24: From left to right, eye diagrams for 8 channel transmission over 60km of SMF-28 for SOA total input power of -10 (Pin/ch=-19dBm), 0 (Pin/ch=-9dBm), 10 (Pin/ch~1dBm), 15dBm (Pin/ch~6dBm)

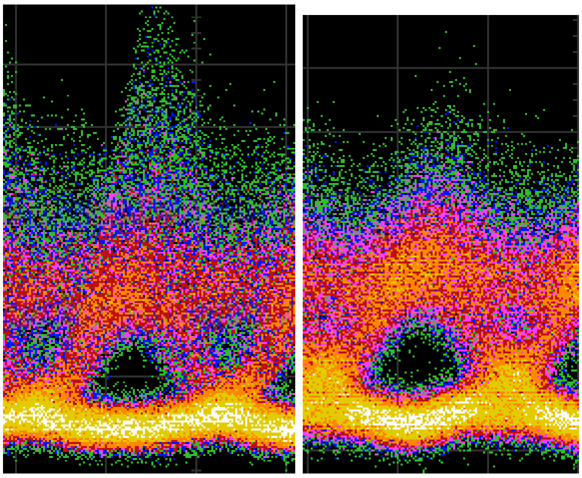

Figure 25: From left to right, eye diagrams for 2 and 4 channel transmission over 60km of SMF-28 for SOA total input power of 10dBm (Pin/ch=7 and 4dBm respectively)

The WDM system performances were again evaluated when different channel is detected at the receiver ed. The performances are very similar across the C band when the SOA Pin=0dBm, that is when the system is at its best. The Q and Sensitivity values are worse for the short wavelength channel when the SOA Pin=10dBm: the non SOA linearities, particularly FWM, affect more the short wavelength channels.

Despite this, the overall WDM performances with the SOA as a power boosters are very good. The system is linear over a wide range (20dB at least) of SOA per channel input power, in this way even more SOAs could be cascaded for further overall gain and longer fibre spans.

6. SOA in dynamic channel count application

With increasing internet demands, a future proof network should be reconfigurable, with channels that could be added, dropped, routed across different rings. Also, the use of burst switching system, where only bursts of data in a WDM network channel is assigned to each user, increases the multiplexing capabilities of the network. In this scenario, where some channels are dropped or added at kHz frequencies, a quick amplifier with recovery time of the order of μsec or better, is required in order to maintain constant power along the line. As it has been previously shown, Erbium Doped Fibre Amplifiers (EDFAs) react strongly to such slow changes in average powers with their millisecond gain dynamics. The timescales of the SOA (of the order of nsec) are almost instantaneous compared to the EDFA ones. This has been verified with the setup shown in fig. 26. Two tunable lasers, representing 2 WDM channels (channel 1 and 2), one switched at 20kHz and another one not modulated, are multiplexed via a coupler and injected into the SOA, which is biased at 500mA and kept at 20˚C. The output of the amplifier is filtered at channel 1 or 2 wavelength and received by a Lightwave converter which electrical output is fed into a real time oscilloscope.

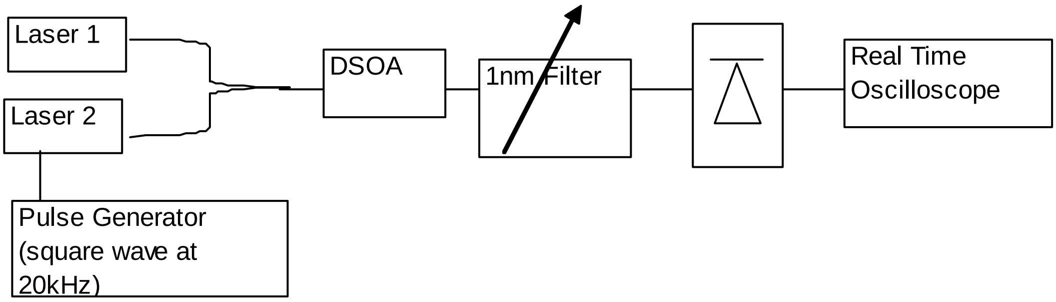

Figure 26: set up to assess switching behaviour of our L-SOA

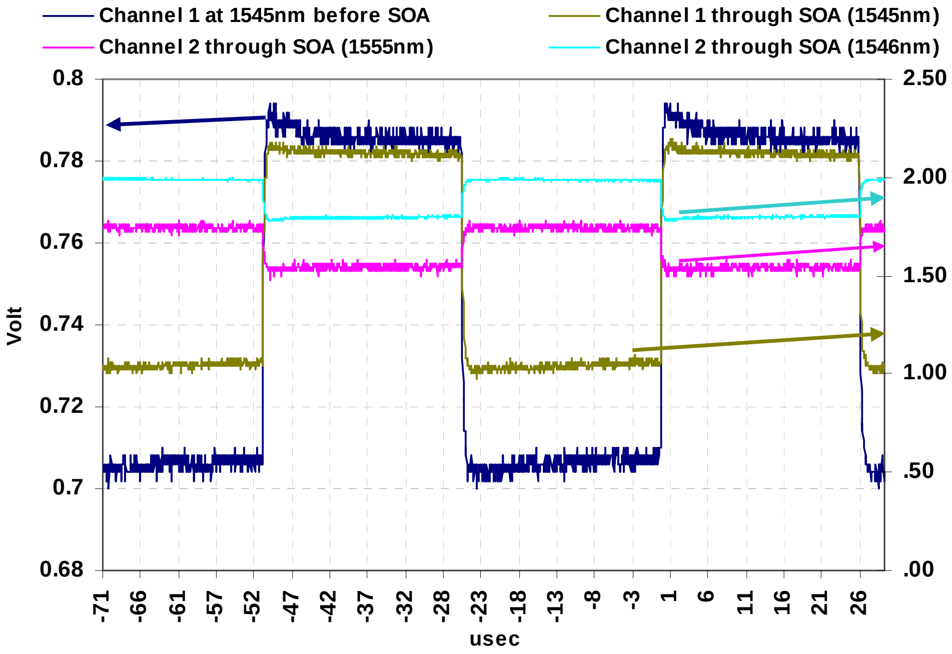

Figure 27: SOA response to dynamic channel reconfiguration when one channel is added and dropped at 20kHz, while another channel is kept: blue curve represents the SOA modulated channel 1 at 1545nm, the green curve represents the SOA channel 1 output. Blue and pink data are the SOA output when a 1546 or 1555nm un-modulated channel 2 is sent to the amplifier

As visible in fig. 27, when modulated channel 1 is injected into the SOA (input power~1dBm) the response of the SOA (green curve) doesn't suffer from any amplifier dynamics. When the un-modulated channel 2 of same power is injected into the SOA, the amplifier output shows only an expected cross gain modulation due to the high amplifier input power. Therefore, in a dynamic network, when one or more channels are dropped, the remaining channels will suffer from gain variation, due to cross gain modulation, the level of which is dependent on how deeply the SOA is driven into gain compression, but the SOA response is almost instantaneous when compared to the one of an EDFA.

7. Conclusions

CIP Linear SOA has been successfully used as a power booster in a 10Gbit/s WDM network, with acceptable levels of crosstalk, for SOA per channel input power equal at least to -6dBm, corresponding to a total output power of ~15dBm. Transmission over 60km of SMF-28 was proven not to suffer from further degradation, compared to the back to back case. The fast SOA gain dynamics support this amplifier utilisation in today and tomorrow fast reconfigurable networks.

Annex 1 WDM TEST RIG

The 8 channel 10Gbit/s WDM rig is shown in figure a. Eight lasers centred around 1554nm, 100GHz spaced, go through a Multiplexer. They are amplified by a commercially available EDFA (EDFA B) and, via a polarisation controller (not indicated in fig. 7), they are modulated by a CIP EAM (40G-SR-EAM-1550). The Modulator is driven by a 2.9V peak to peak RF bias and a proper DC bias. The data rate used is 10Gbit/s, with a format of 2^31-1 NRZ, PRBS. The output passes through 2.2km of dispersion compensating fibres to decorrelate the different channels. A further EDFA amplifies the signal (EDFA D), to allow the study of SOA saturation for high input power into the SOA. To compensate for the EDFA gain profile, the 8 channels are equalised after the EDFA D, so that the SOA sees the 8 channels with equal intensity. An attenuator is inserted right after the EDFA to be able to vary the SOA input power. The SOA input and output power are monitored via two 90/10 coupler connected to a power meter or a optical spectrum analyser (not shown in fig. a). A length of 60km of single mode fibre (SMF-28) can be inserted into the system via a switch. The fibre length was chosen to match the SOA gain at 1550nm (13dB). The 8 channels are then demultiplexed by a Corning AWG and a JDS switch. While 10% of the signal is sent to a EAM-DEMUX for Extinction ratio measurements (XR), not indicated in fig.7, 90% of the signal goes to the receiver part. The attenuator at the receiver input gives the Sensitivity value. Its output is amplified and then filtered (via a 1nm bandwidth filter) and then detected by a Lightwave converter for Bit Error Rate (BER) and Q evaluation. Part of the signal from the Lightwave converter is fed into a clock recovery circuit (not shown in fig. a).

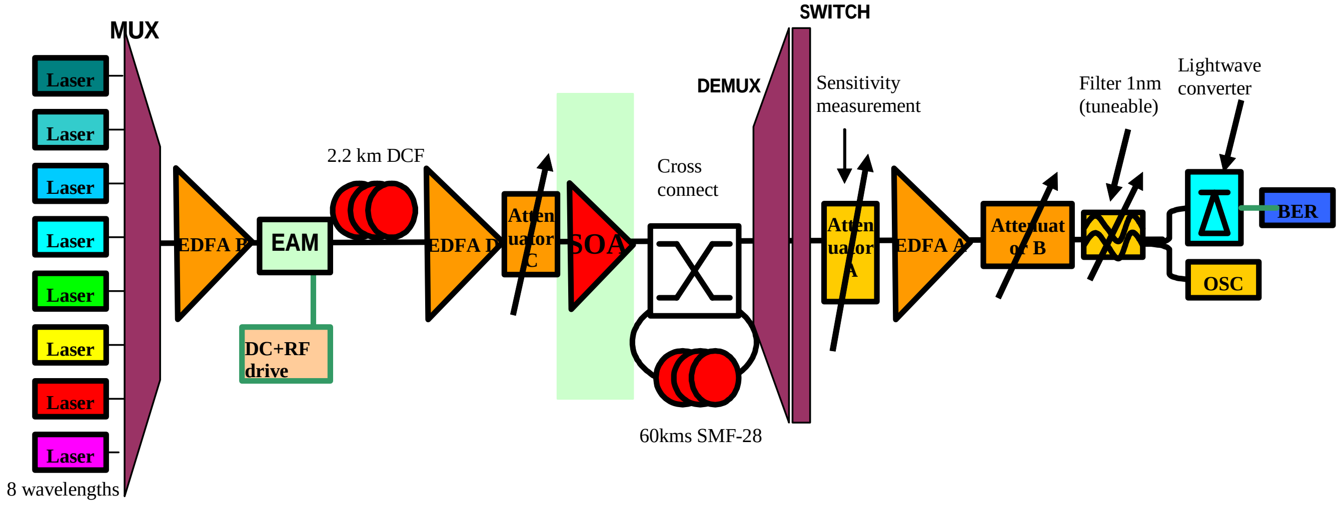

Figure a: 8 channel WDM test rig. 60kms of SMF-28 can be inserted into the system via the switch

In the back to back configuration, with the eight channels switched on and amplified to have a EAM input power of +13dBm, the DC bias of the EAM was set to -2.7V to achieve the best system sensitivity when the channel 4 was received. The polarisation state of the EAM was adjusted to have the EAM in its TM mode. In a transmission configuration, the EAM DC bias was set to -3.1V, and the EAM was again in its TM mode.

Annex 2 EAM Operating Conditions

When using an EAM in a transmission, the voltage chosen for the modulator will strongly influence the overall performances. In fact, as the chirp from the modulator varies with the voltage, adjusting the EAM bias for best system performances equals to optimise the chirp to compensate for the dispersion of the fibres. In paragraph 5, the EAM bias was set at -3.1V in order to achieve the best system sensitivity after 60km of SMF-28. Meanwhile, in paragraph 4, in the system with no SMF-28 fibre, the voltage was optimised to -2.7V. In a back to back configuration, a DC voltage lower than -2.7V, would have degraded the system performances; a degradation would have incurred also if, in the transmission over SMF-28, a EAM DC voltage lower than -3.1V was chosen. In figure b, we compare the Q and Sensitivity for 8 channels, in a back to back configuration, for EAM DC voltages equal to -2.7 and -3.1V.

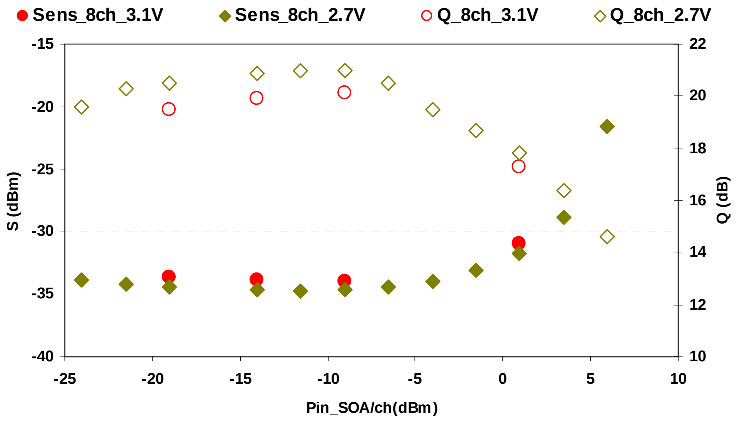

Figure b: Sensitivity and Q for 8 channel, back to back for a EAM DC bias equal to -2.7 (green markers) and -3.1V (red markers)

As expected, a slight degradation is visible for the higher bias case, with poorer Sensitivity and Q values for -3.1V DC voltage, but the data sets follow the same trend. Therefore, in paragraph 5, even though the absolute Q and Sensitivity values for the transmission data at -3.1V and the back to back ones at -2.7V, differ, the data sets follow the same trends, that is the introduction of 60kms of fibre doesn't degrade the system performances.

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