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# Semiconductor Optical Amplifiers (SOAs) in Multi-Channel Environments

Applications Note No. 0003

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## Semiconductor Optical Amplifiers (SOAs) in Multi-Channel Environments

The expansion of WDM network connectivity means that a greater amount of functionalities will be implemented directly in the optical domain. In the short term, to meet the cost performance, network architectures will evolve based on the manipulation of bands of wavelength channels. Amplification of bands of wavelengths simultaneously reduces the effective cost of amplification in many metro and long haul applications. The amplifier must provide a fixed gain independent of the number of wavelengths being amplified and in addition, must not show any transient effects in the output power per channel on variation of the input power that may occur on adding or dropping of channels(s) under dynamic interconnection. Typical application sectors may be at the transmitter, receiver or within optical nodes where the manipulation of bands is executed at the expense of increased loss (Figure 1).

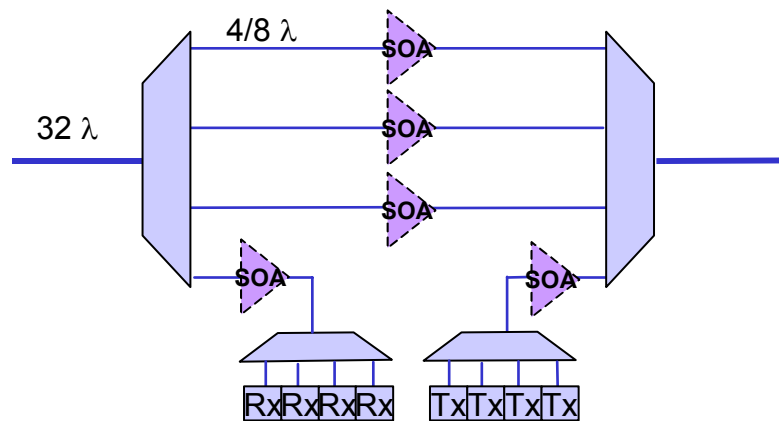
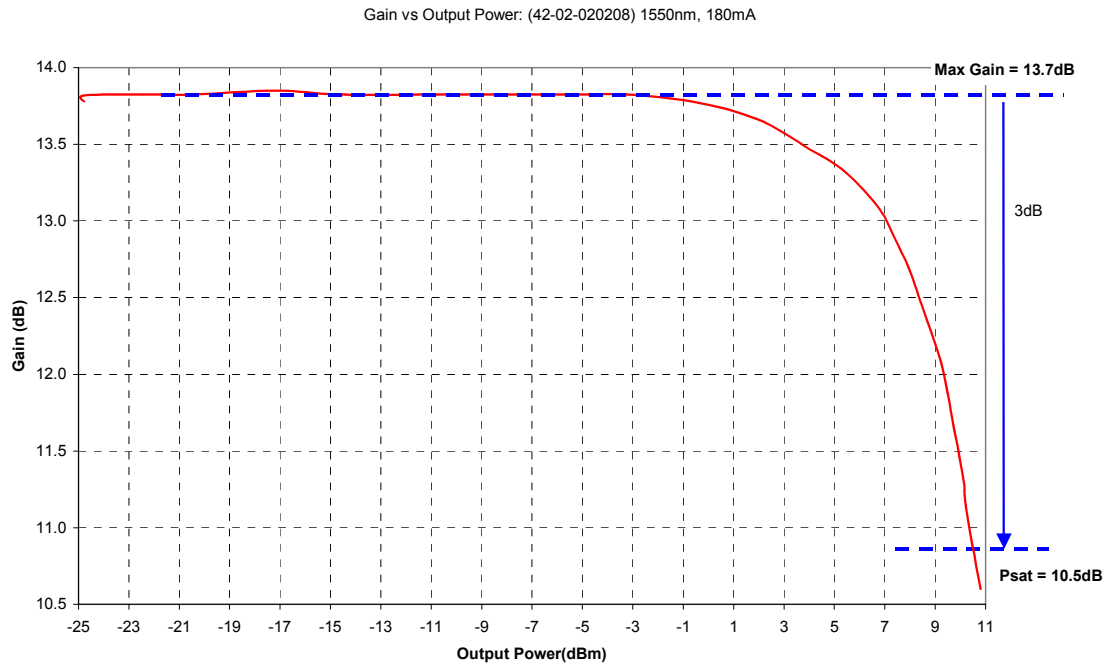


Figure 1: SOAs in multi-channel (band) applications. Highlighted are three sectors; in-line band amp within the node to manage loss; a booster after a bank of transmitters; a pre-amplifier prior to a bank of receivers.

The SOA can meet the needs of these expanding networking scenarios as amplifiers as long as operation in its linear regime is maintained. In this mode, it exhibits the characteristics of any linear amplifier permitting its use in pre-amplifier (see Kamelian Application Note No. 0002), power booster (see Kamelian Application Note No. 0001) and multi-channel gating/amplification applications. The intrinsic cost, size and integration capability advantages will ensure that the SOA plays a key role in these applications.

## Semiconductor Optical Amplifiers

**Linear operating regime:** in amplification, the linear region is the preferred operating regime since an exact, amplified replica of the input is required (Figure 2). The resulting gain modulation causes interference noise in the frequency domain, specifically inter-channel crosstalk between different wavelength channels. Thus one of the key operating issues to ensure linear functionality is the management of the input power levels in order to control the degree into which the device is driven into saturation, especially crucial in multi-wavelength applications where a band of channels are amplified, sharing the available output power.



*Figure 2: Gain vs. output power for a typical SOA (at 1550nm) highlighting the linear region and 3dB compression point. Gain control can be achieved easily through change in the drive current but the available linear regime also changes.*

**Output saturation power:** for more detail on the output saturation power performance of typical SOAs refer to Kamelian Application Note No. 0001: "SOAs as Power Boosters". Also detailed is the wavelength dependence of the output saturation power, especially relevant in multi-channel operation. These parameters can be optimised for any particular application by accurate movement of the gain peak. In multi-wavelength applications at transmitters, the output power is the primary design parameter of interest; the more output power the SOA provides then the more output power per channel can be obtained. This is also the case in intra node loss management. It is not so critical for pre-amplifier applications.

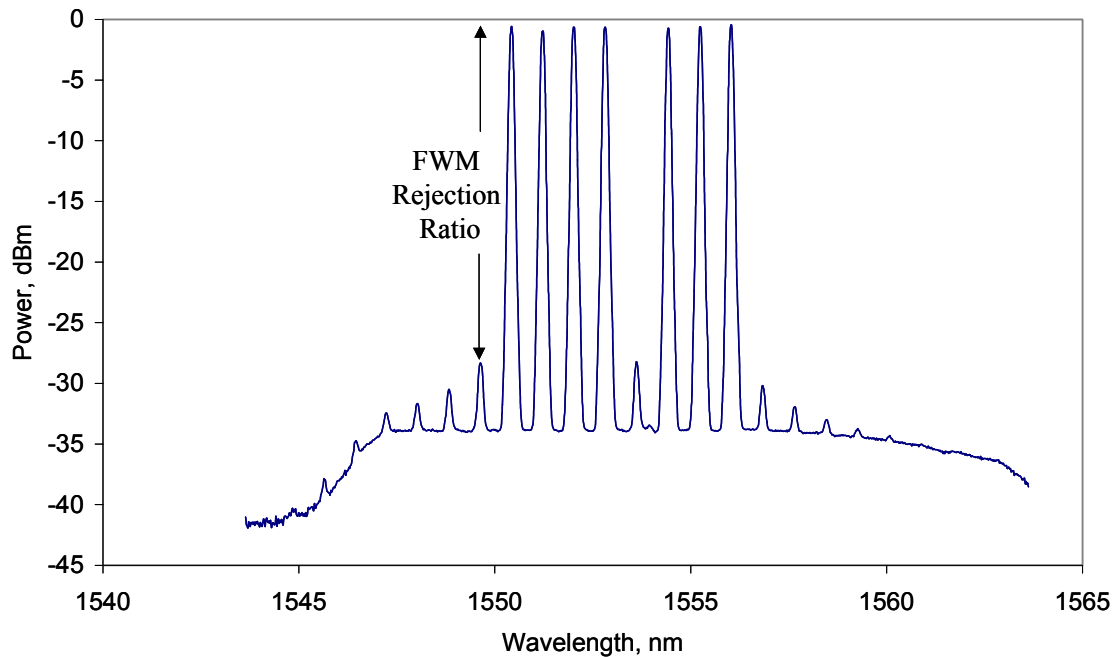
**Chirp in gain compression:** for more details on the evolution of chirp as a function of gain compression refer to Kamelian Application Note No. 0001: "SOAs as Power Boosters". In multi-channel scenarios, the level of chirp produced is proportional to the amount of gain compression the signals are subject to. This is as a consequence of the gain modulation causing patterning on each of the channels in the time domain. Thus each channel of the multi-wavelength multiplex will be subject to chirp.

**Four Wave Mixing (FWM) in gain compression:** with multi channel operation in gain compression, the many optical signals subject to dynamic gain (and index) modulation, produce mixing products due to the non-linear characteristic of the SOA which beat at a frequency determined by their optical frequency separation. Consequently many sidebands are generated in the optical spectrum, and in the case of amplification of bands of wavelengths that are evenly spaced input signals, the net effect is the generation of crosstalk terms interfering with the desired signals. What seem low levels of crosstalk can produce significant power penalties due to coherent beat noise phenomena.

The level of FWM-generated crosstalk in addition to being dependent on the properties of the material and the length of the interaction region is also strongly dependent on channel spacing

and output power level per channel which in turn is a product of the input power per channel and device gain.

Figure 3 shows a typical SOA output optical spectrum for an 8 channel multiplex at 100GHz spacing (within c band), ~0dBm output power per channel. Defining the FWM rejection ratio to be the difference between the strongest signal and the maximum crosstalk term, a rejection ratio of ~30dB is obtained with this scenario. This rejection ratio will reduce with reduction in the total output power per channel (and vice-versa) and increase with closer channel spacing (and vice-versa).



*Figure 3: SOA output optical spectrum for an 8 wavelength multiplex at 100GHz spacing, 0dBm per channel showing the level of FWM-generated crosstalk terms.*

**Transient behaviour:** another consequence of operating in gain compression concerns the amplification of bands of wavelengths under dynamic network conditions. Dynamic power changes on the dropping and adding of wavelengths causes gain transients on the remaining channels. The timescales associated with SOAs in gain saturation are of the order of the data rate, featuring nsec transient behaviour.

Figure 4 shows the effect on the gain imparted on a remaining channel when most (7 out of 8) of the band of channels is dropped. The timescales associated with the SOA are almost instantaneous when compared to those associated with an EDFA (msec). The level of gain variation without applying methodologies to correct for this effect, is dependent on how deeply the SOA is driven into gain compression (Figure 5) which in multi channel environments is determined by the number of wavelengths being amplified and the output power per wavelength requirement.

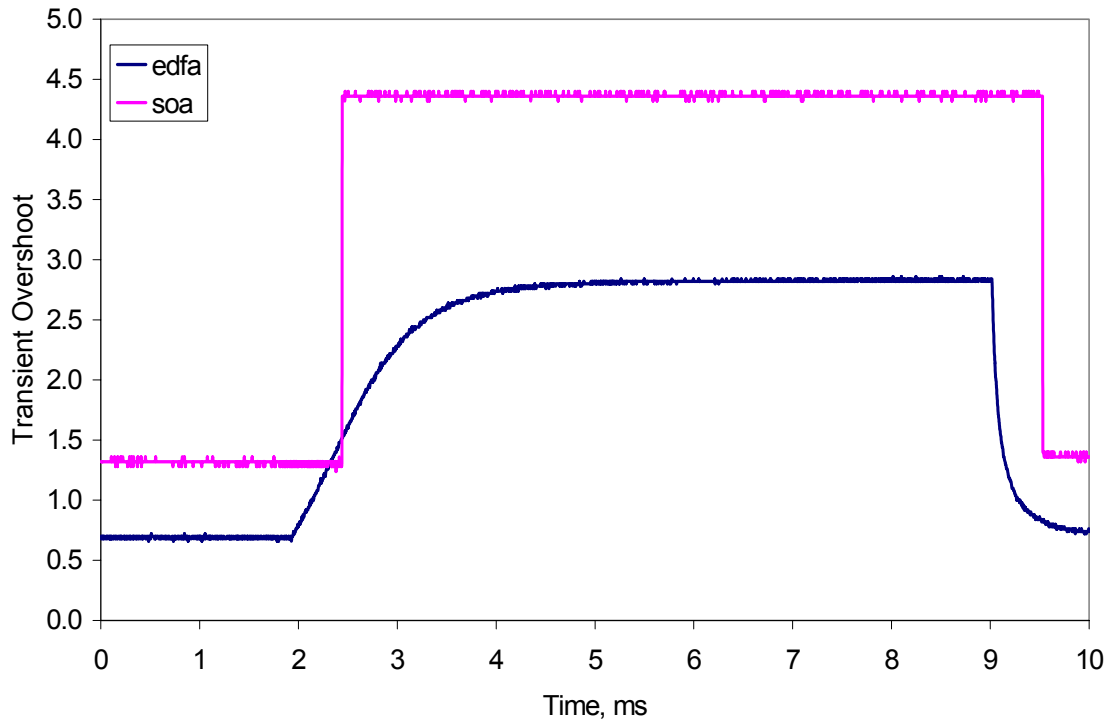


Figure 4: The transient behaviour of a typical SOA and EDFA on the remaining channel when 7 out of a band of 8 channels are dropped. The SOA response is on nsec timescales whilst the EDFA responds in msec. n.b. the units on the vertical axis are arbitrary.

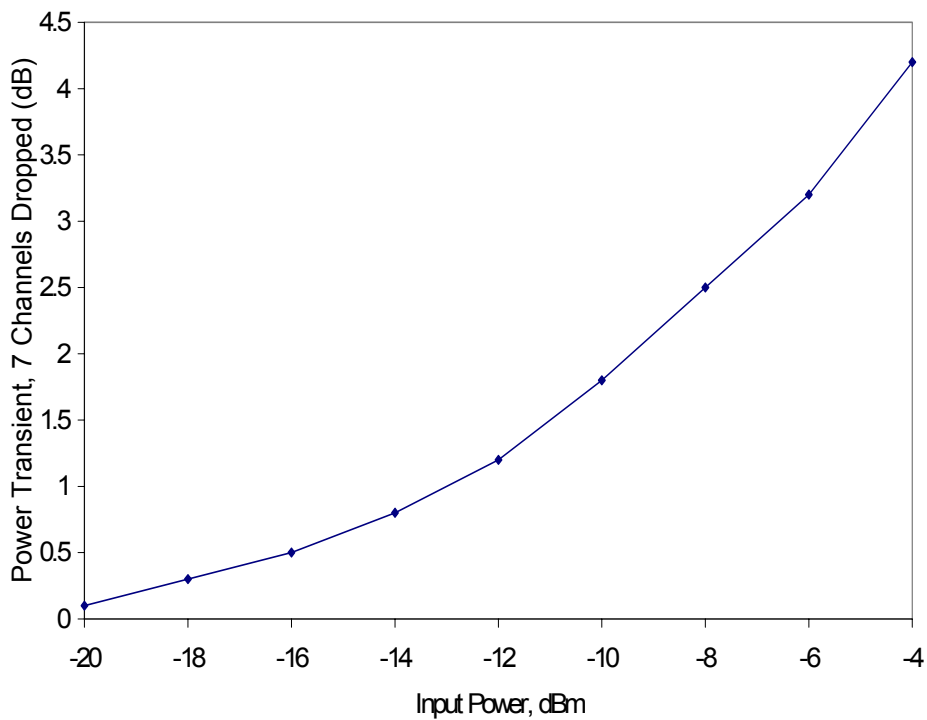


Figure 5: The change in gain experienced by the remaining channel when 7 out of a band of 8 channels are dropped as a function of input power. The further the device is driven into saturation the more marked the change.

**Noise figure (NF):** the amplification process is always accompanied by spontaneous emission, where photons of random phase and polarisation are added to the signal. The noise performance of an optical amplifier is characterised by the NF, defined as the amount of degradation in the signal to noise ratio caused by the amplification process. The NF performance of typical SOAs is defined in Kamelian Application Note No. 0002: "SOAs as Pre-Amplifiers". The NF is especially crucial in pre-amplification applications.

**Polarisation dependent gain (PDG):** in any optical communication system the state of polarisation at any in-line component is unknown, since installed optical fibre does not preserve the state of polarisation. Thus, typically, the SOA has to be polarisation insensitive. Through chip design know-how, very low polarisation dependent gain (<0.2dB) has been achieved. For the wavelength dependence of PDG refer to Kamelian Application Note No. 0002: "SOAs as Pre-Amplifiers". THE PDG performance is important in mid span loss compensation and in pre-amplification roles.

**Wide optical bandwidth:** SOAs exhibit a ~80nm optical gain bandwidth at the 3dB drop from the peak gain. Access to a wider bandwidth is possible if the minimum system gain required (at the extremities) is lower (refer to Kamelian Application Note No. 0004: "SOAs in CWDM Systems"). Centring the gain peak very accurately during the material growth stage means that the SOA can meet the amplifier needs for all of the low loss transmission window of optical fibres. For typical WDM band applications, the bandwidth requirement is easily met.

**Data rate transparent:** the SOA is able to amplify at data rates ranging from Mbit/s up to and beyond 40Gbit/s. In this respect it is a future proof technology compatible with any upgrade scenario since it is also protocol independent.

**Small form factor, amenable to integration:** the SOA is housed within a standard 14-pin butterfly package, the subject of a multi source agreement (MSA) with other leading SOA suppliers which guarantees system providers with common optical/mechanical specifications. The size of the package represents a significant improvement on competing optical amplifier solutions. Longer term, Kamelian's know-how in on-chip mode expansion technology promotes a manufacturable solution to the integration of the SOA with other components to yield low cost, highly functional modules.

### Multi-Channel Characterisation

**Gain compression:** Figure 6 is a typical eye diagram for one of the channels of an 8 channel multiplex (100GHz spacing) after transmission over 60km of standard single mode optical fibre (SMF28). The SOA was used at the transmitter as a booster and provided 15dB gain at an output saturation power of +10dBm (across the c band) when driven at 180mA. The input power per channel was -18dBm (representing a total average power of -12dBm) and the eye diagram is subject to dispersion (see test bed of Figure 6). This extends the observations made about operation in gain compression detailed in the Kamelian Application Note No. 0001: "SOAs as Power Boosters".

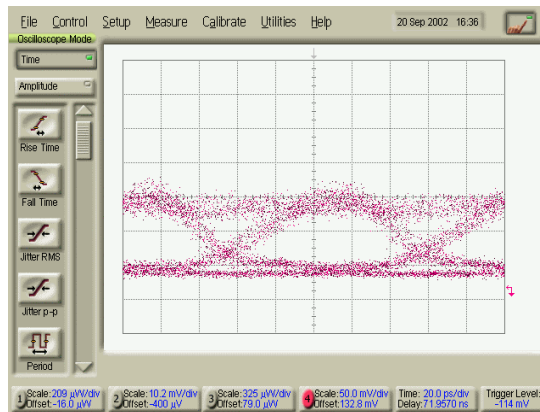


Figure 6: Output eye diagram of a SOA amplified channel (one of 8 at a 100GHz spacing) after 60km of transmission on standard single mode fibre.

**Power booster in multi-channel transmission** the performance of SOAs as power boosters can only be evaluated within a systems context. Figure 7 is a schematic of a generic systems test bed comprising multi sources (DFBs located on the ITU grid within the c band) and a link length of 60km of standard single mode fibre (SMF28). This enables to characterisation of the power booster in single and multi channel environments (see Kamelian Application Note No. 0001: "SOAs as Power Boosters"), including the combined effect of the factors associated with operation in gain compression e.g. chirp, patterning, FWM.

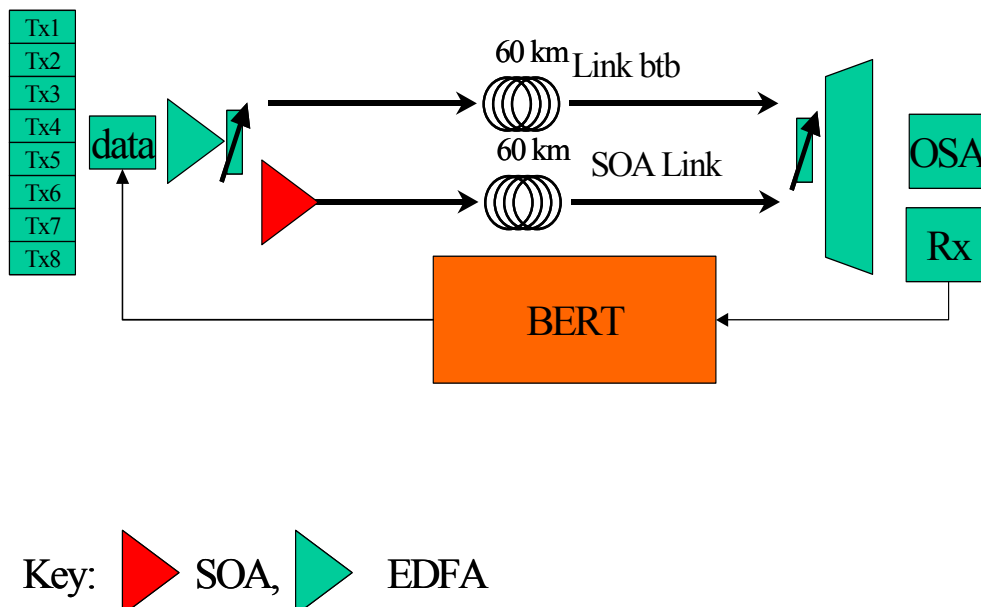


Figure 7: Systems test bed used in the characterisation of the power booster.

There are two scenarios of interest;

- the back-to-back (btb) measurement which includes the SOA but excludes the effect of the transmission link. Therefore the effect of the SOA in terms of patterning and FWM but excluding the effect of chirp which introduces an additional dispersion overhead is the reference measurement. The EDFA is simply used as a means to manage the additional loss introduced by the optical fibre.
- SOA as a booster followed by the 60km length of single mode fibre. Now the additional issue of chirp in multi channel operation is characterised and a relationship to a power penalty owing to the use of the SOA in this mode is defined.

Figure 8 summarises the power penalty for the btb (defined above) and SOA boosted cases as a function of input power. The SOA had a gain of 15dB and an output saturation power of +10dBm, operating at 10Gbit/s. No appreciable increase in the power penalty was evident over the operating range up to  $-14$ dBm input power per channel (total average input power of  $-5$ dBm for 8 channels). The additional increase in chirp is the major cause of this increase. Figure 9 summarises the operating space for this particular scenario, relating the input power per channel to the number of channels for penalty free transmission.

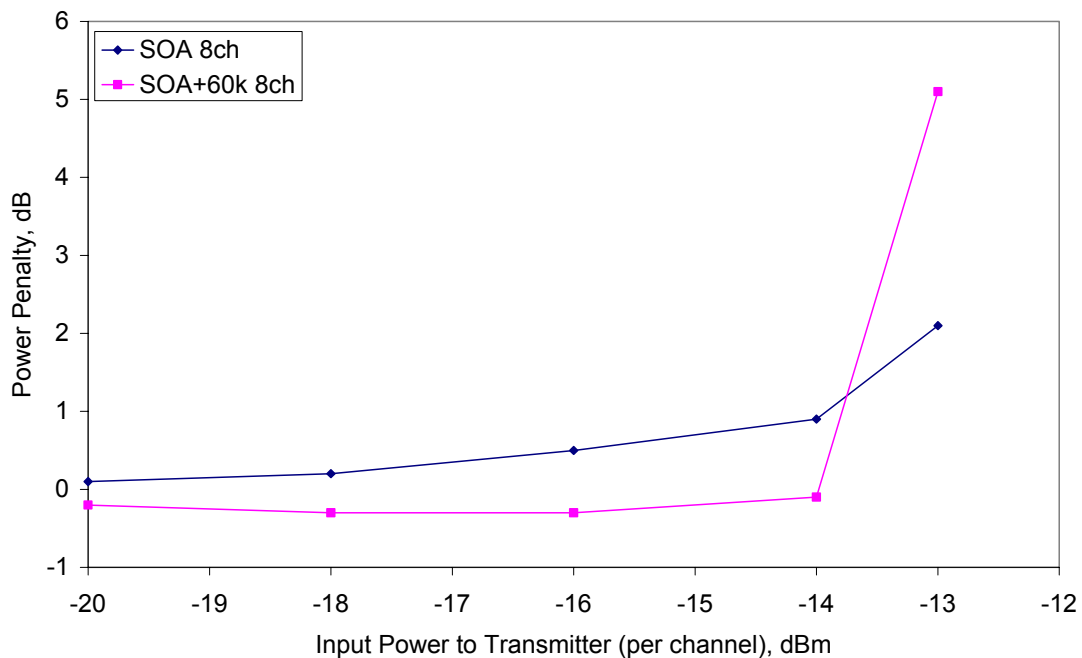


Figure 8: Power penalty as a function of input power per channel (up to a maximum of 8 at a 200GHz spacing) into an SOA followed by 60km of transmission.

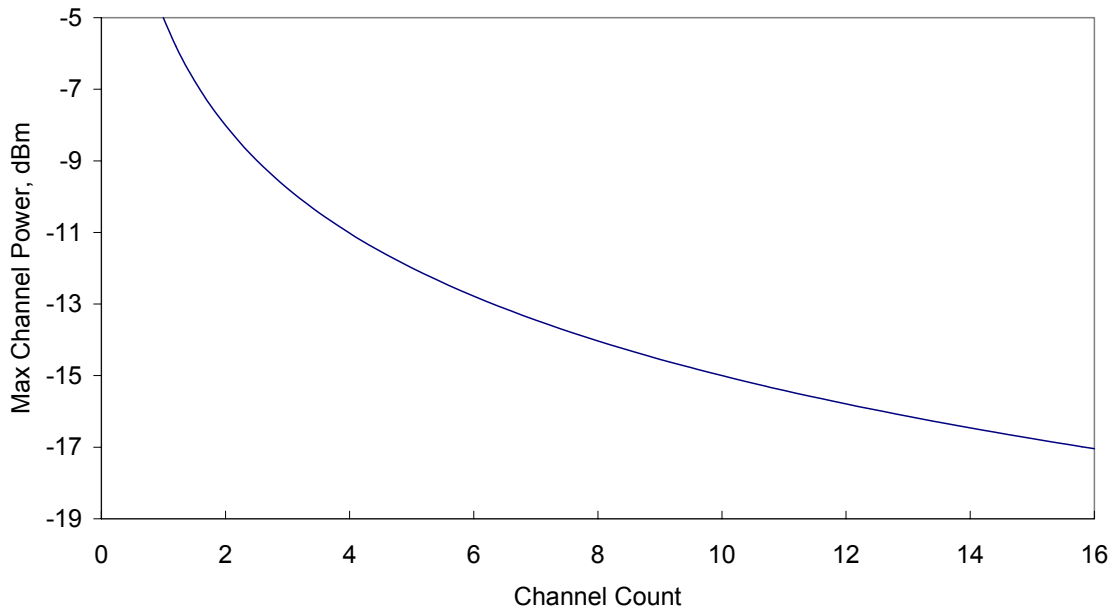


Figure 9: Relationship between input power per channel and the number of channels in multi channel transmission using an SOA as a power booster. The channel spacing was at 200GHz, the SOA gain was 15dB, the output saturation power +10dBm and the transmission distance was 60km (SMF28).

**SOA multi-channel pre-amplification at 10Gbit/s:** the characterisation was undertaken with a high gain >20dB low noise figure (~6dB) SOA in the receiver configuration of Figure 10. Figure 11 summarises the relationship between the power penalty and the input power level for one (of 8) wavelength channels.

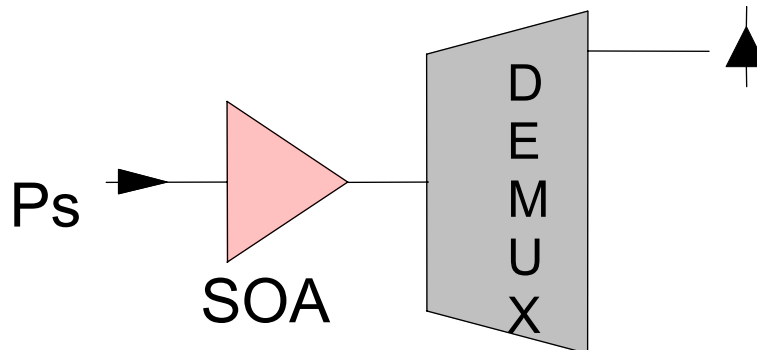


Figure 10: SOA pre-amplified multi-channel receiver configuration.

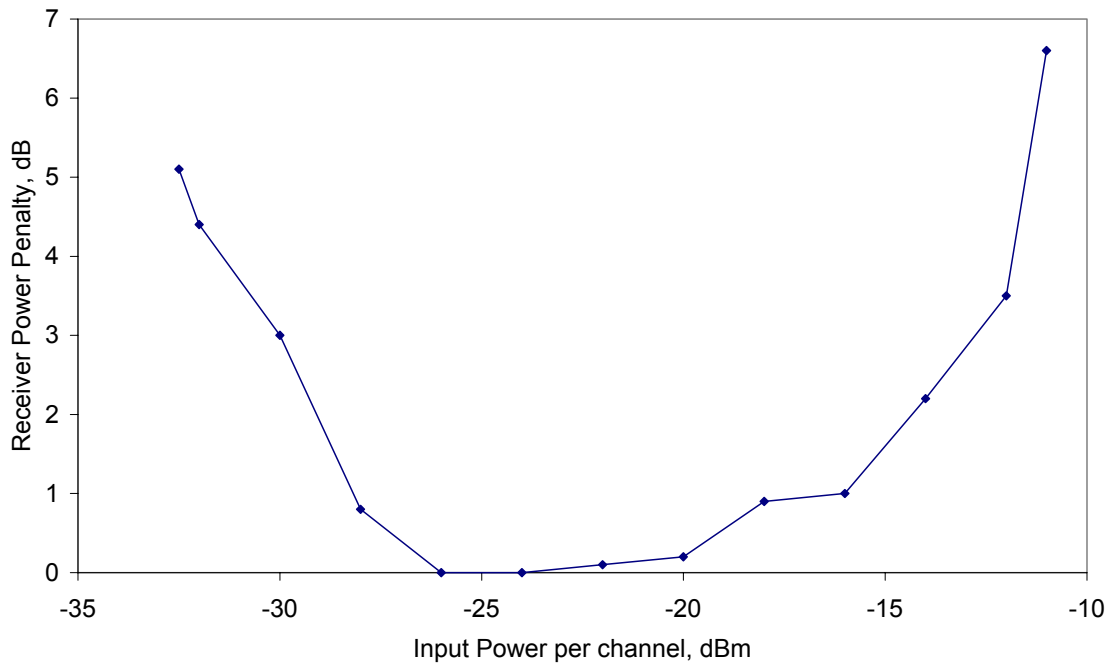


Figure 11: Power penalty as a function of input power for one channel (out of total of 8, spaced at 200GHz) at 10Gbit/s for an SOA pre-amplified receiver.

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