kamelian

Semiconductor Optical Amplifiers (SOAs) as Power Boosters

Applications Note No. 0001

Semiconductor Optical Amplifiers (SOAs) as Power Boosters

There is a growing need to manage the increase in loss budgets associated with optical networks comprising optical nodes which facilitate and promote dynamic wavelength routing. These nodes are complex at the optical level and in order to provide the necessary functionality, introduce a loss overhead which has ramifications in respect of system designs (Figure 1a). There is also an evolutionary move to deploy tuneable laser sources in network architectures for maximum flexibility and utilisation of the wavelength resource. In general, the output power levels of tuneable lasers are modest, especially since external modulation is required at data rates up to and beyond 10Gbit/s introducing additional insertion losses, resulting in the need to boost the signal prior to transmission. In addition, the ability to perform a limited amount of channel power equalisation on each wavelength in a WDM multiplex is of benefit (Figure 1b).

SOAs provide a low cost route to providing amplification in such scenarios where it is advantageous to embed the amplification within the node design or on transmitter line cards. Longer term they permit higher degrees of integration to be invoked which then translates into smaller footprint, more cost effective solutions. In this respect SOAs have a clear advantage over alternative solutions such as EDFAs. See Kamelian Data Sheet on the OPB for typical SOA parameters for this application.

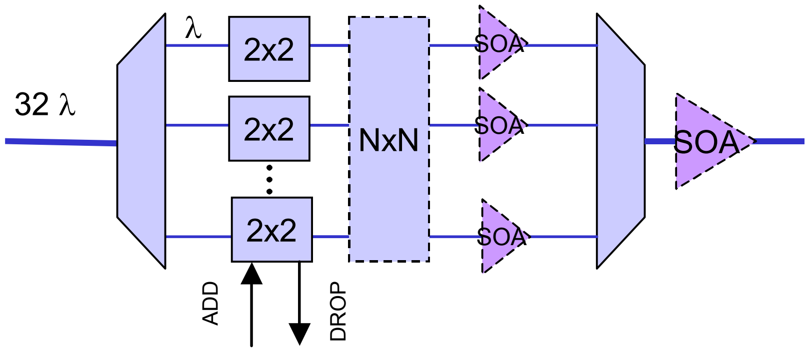


Figure 1a: *SOAs used in optical/add drop to manage the extra losses associated with the introduction of advanced dynamic re-configurability.*

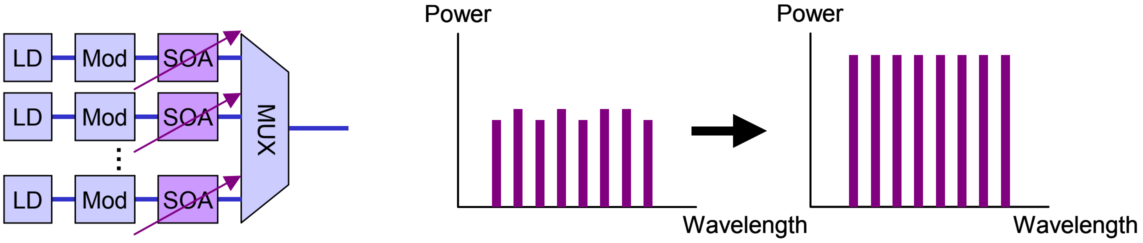


Figure 1b: *SOAs used in transmitter modules where in addition to boosting the signal, a limited amount of channel equalisation is required.*

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. Operating an SOA outside this region causes distortion since at high output powers, the gain saturates and compresses (Figure 2). The resulting gain modulation causes patterning in the time domain, because the gain recovery time of an SOA is typically of the same order as the data modulation speeds. 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 (see also Kamelian Application Note No. 0003: "SOAs in Multi-Channel Environments").

In order to provide some level of channel equalisation, the gain of the SOA can be controlled by changing the bias current applied. However if the bias current is lowered to lower the gain, the saturation output power and hence the linear region also reduces which in turn limits the dynamic range of the variation in gain for a certain output power (Figure 2).

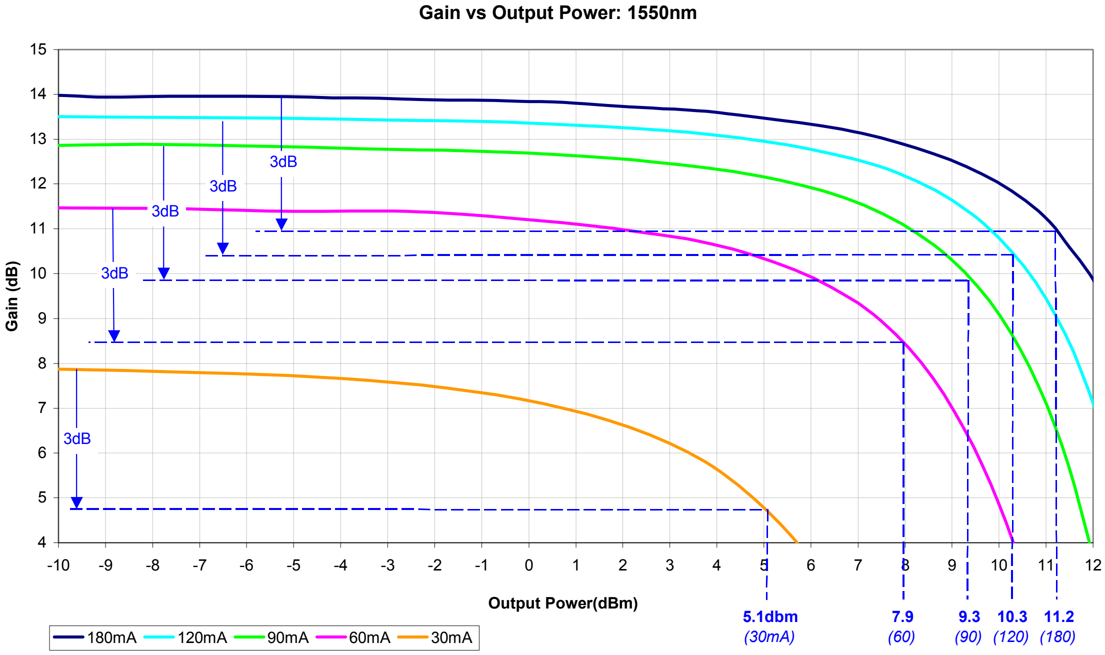


Figure 2: Gain vs. output power for a typical SOA showing the linear region of operation and the 3dB output saturation power. Also shown is SOA behaviour in this respect with variation in the control drive current. Thus for any particular SOA design the output saturation power reduces with a reduction in gain.

Output saturation power: due to fundamental device physics, for maximum output power, SOAs are designed such that the gain peak occurs at lower wavelengths with respect to the desired operating band. The SOA operating regime therefore occurs on the long wavelength tail of the gain profile (Figure 3, typically offset by around ~50nm from the beginning of the operating bandwidth).

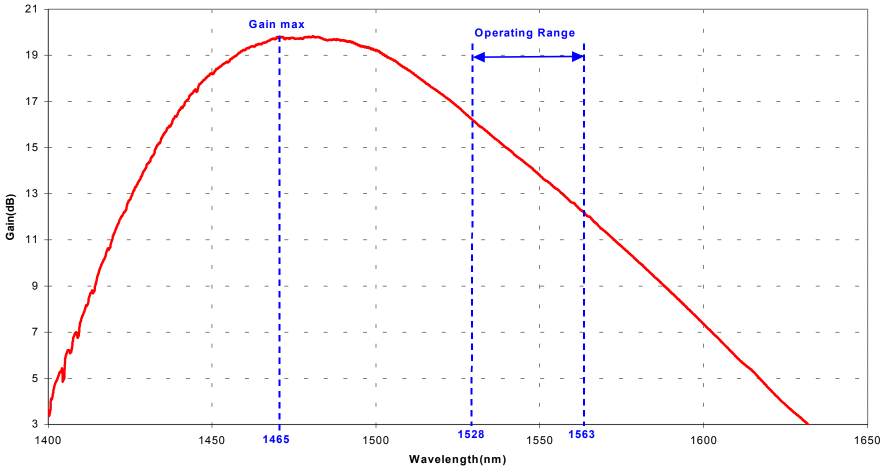


Figure 3: Gain vs. wavelength relationship showing the design strategy that yields a high saturation output power across, in this case, the c band. The wavelength of the peak gain is offset in order to function on the longer wavelength segment of the profile.

The wavelength dependence of SOA characteristics translates into trade-offs in parameters with respect to wavelength (also refer to Kamelian Application Note No. 0002: "SOAs as Pre-Amplifiers"). This also applies to the output saturation power and this variation must be taken into consideration in any designs operating over a specified wavelength range (Figure 4). It must be noted that the all SOA parameters are quoted as a min or max values (as appropriate) across that specified wavelength band. These parameters can be optimised for any particular application by accurate movement of the gain peak. In booster applications, the output power is the primary design parameter of interest.

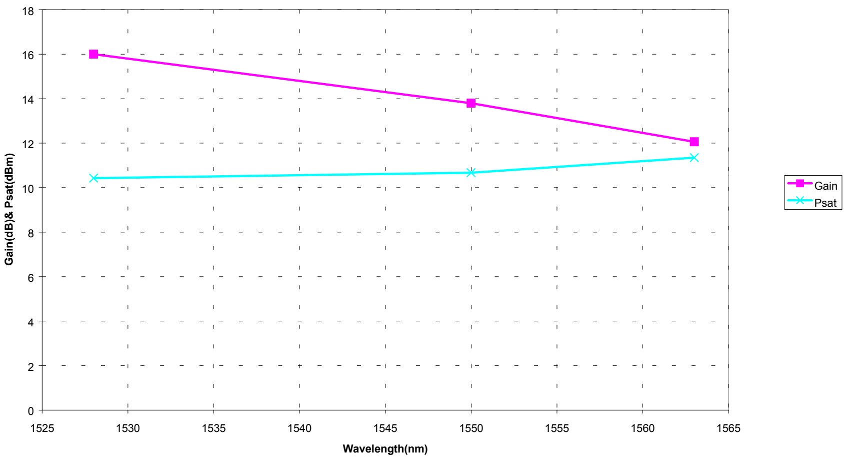


Figure 4: Variation of output power saturation for a typical SOA across the c band (1529nm to 1563nm). This device has a gain peak centred at 1465nm.

Chirp in gain compression: operation of an SOA in gain compression not only results in patterning but also produces chirp (frequency variations) of the amplified optical signal. The level of chirp produced is proportional to the amount of gain compression the signal is subject to, the net effect of additional chirp being to increase the power penalty (and hence attainable transmission distance) of the link due to resulting increase in dispersion. Unlike directly modulated lasers the chirp induced is of opposite sign; lasing occurs through current injection to increase the output power whilst the SOA imparts gain through carrier depletion.

Figure 5 shows the amount of chirp induced as function of the degree of gain compression for a typical SOA.

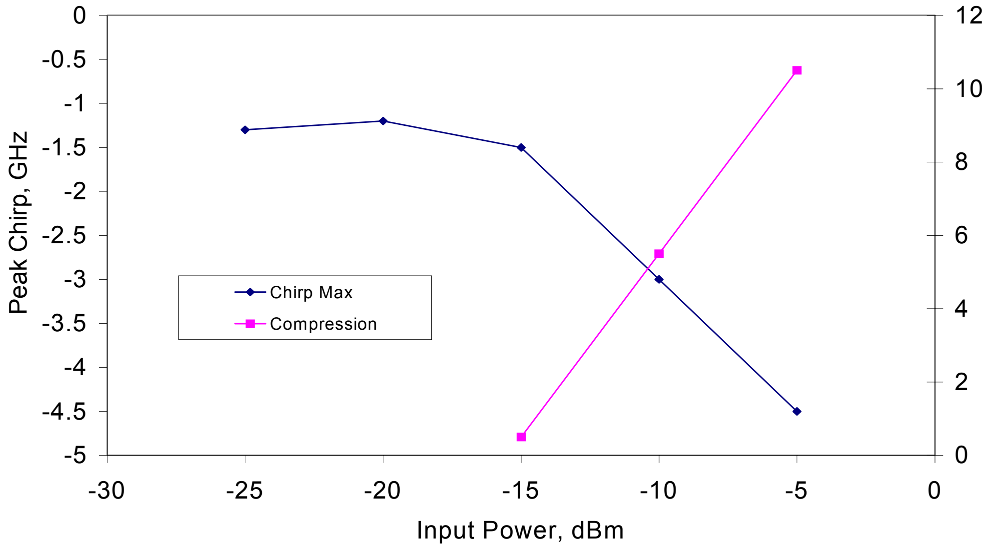


Figure 5: Chirp as a function of gain compression.

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". In transmitter booster applications, the NF will play a role but is not as critical as in pre-amplifier applications. In optical nodes the NF is crucial in defining overall system performance.

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 <0.5dB is available. For the wavelength dependence of PDG refer to Kamelian Application Note No. 0002: "SOAs as Pre-Amplifiers". In transmitter applications, there is a well defined polarisation state emanating from the laser and PDG is not a critical issue as long as the SOA provides the output power for the required gain. In mid-span optical node uses, the PDG is important since a random polarisation enters into the node.

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. In DWDM applications, the SOA provides the required bandwidth easily.

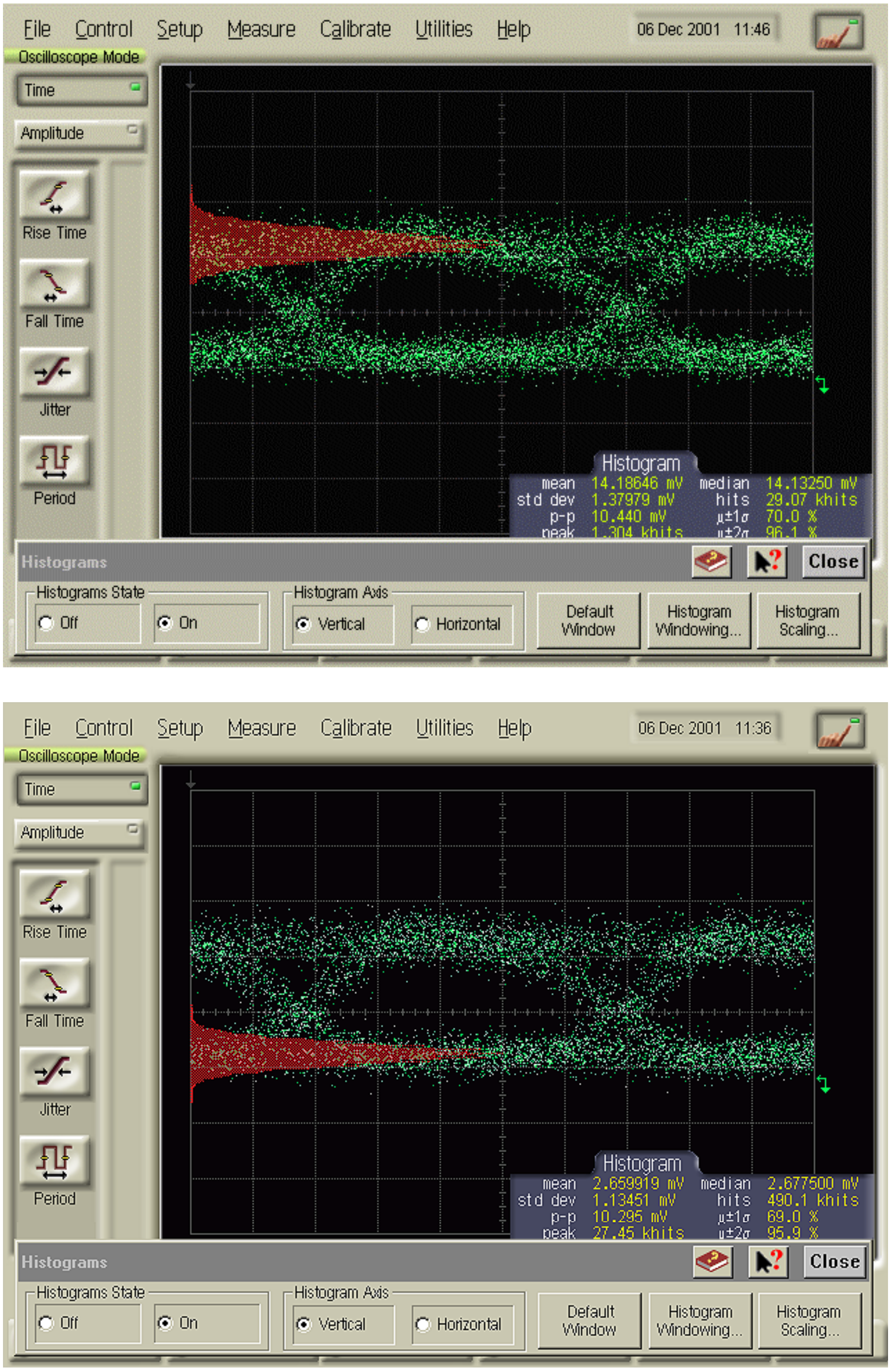
Multi-wavelength operation: the SOA can operate in single and multi-channel environments. For further details of the performance of the SOA as a power booster in multi-channel scenarios see "Kamelian Application Note No. 0003: "SOAs in Multi-Channel Environments".

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.

Power Booster Characterisation

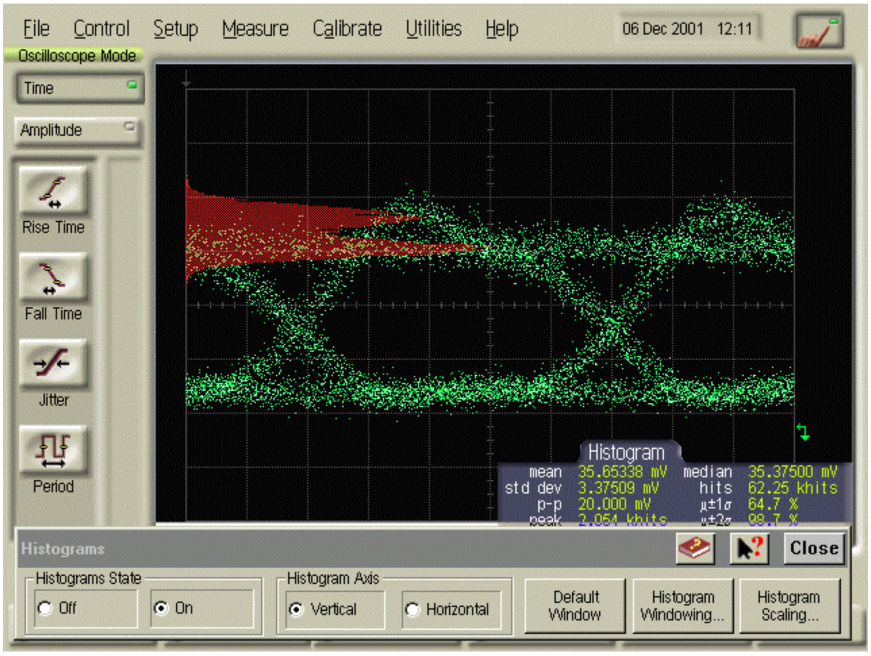
Gain compression: Figure 6 and Figure 7 show typical eye diagrams from SOA outputs in the linear region of operation and in gain compression respectively. Although patterning is clearly evident in the latter case, the eye diagram remains relatively open nonetheless. Figure 8 re-enforces this behaviour highlighting that operation of the SOA in gain compression up to certain limits does not introduce a significant power penalty. Please note that this measurement does not consider the effect of the accompanying chirp (see above).



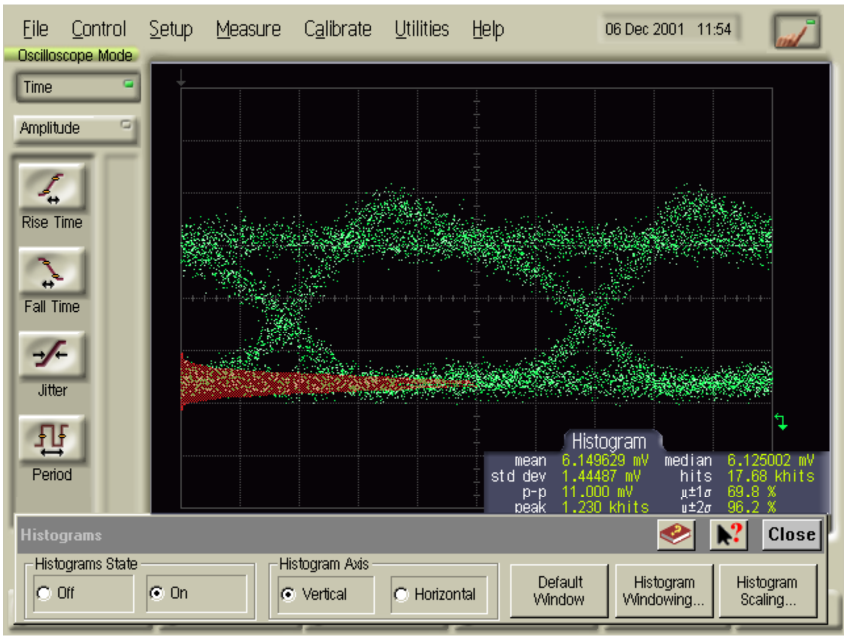
```
     mean  14.18646 mV   median  14.13250 mV
  std dev  1.37979 mV      hits  29.07 khits
      p-p  10.440 mV      μ±1σ  70.0 %
     peak  1.304 khits    μ±2σ  96.1 %
```

```
     mean  2.659919 mV   median  2.677500 mV
  std dev  1.13451 mV      hits  490.1 khits
      p-p  10.295 mV      μ±1σ  69.0 %
     peak  27.45 khits    μ±2σ  95.9 %
```

Figure 6: Typical output eye diagrams for an SOA operating in the linear regime. Also shown are the probability density functions (pdf) for the '1' and'0' level. No appreciable patterning is evident.



```
    mean  35.65338 mV   median  35.37500 mV
 std dev  3.37509 mV      hits  62.25 khits
     p-p  20.000 mV       µ±1σ  64.7 %
    peak  2.054 khits     µ±2σ  98.7 %
```



```
    mean  6.149629 mV   median  6.125002 mV
 std dev  1.44487 mV      hits  17.68 khits
     p-p  11.000 mV       µ±1σ  69.8 %
    peak  1.230 khits     µ±2σ  96.2 %
```

Figure 7: Typical output eye diagrams for an SOA operating in gain compression. Also shown are the probability density functions (pdf) for the '1' and'0' levels. Although patterning is evident, the eye opening remains clear and acceptable BER performance is maintained deep into gain compression (see Figure 8).

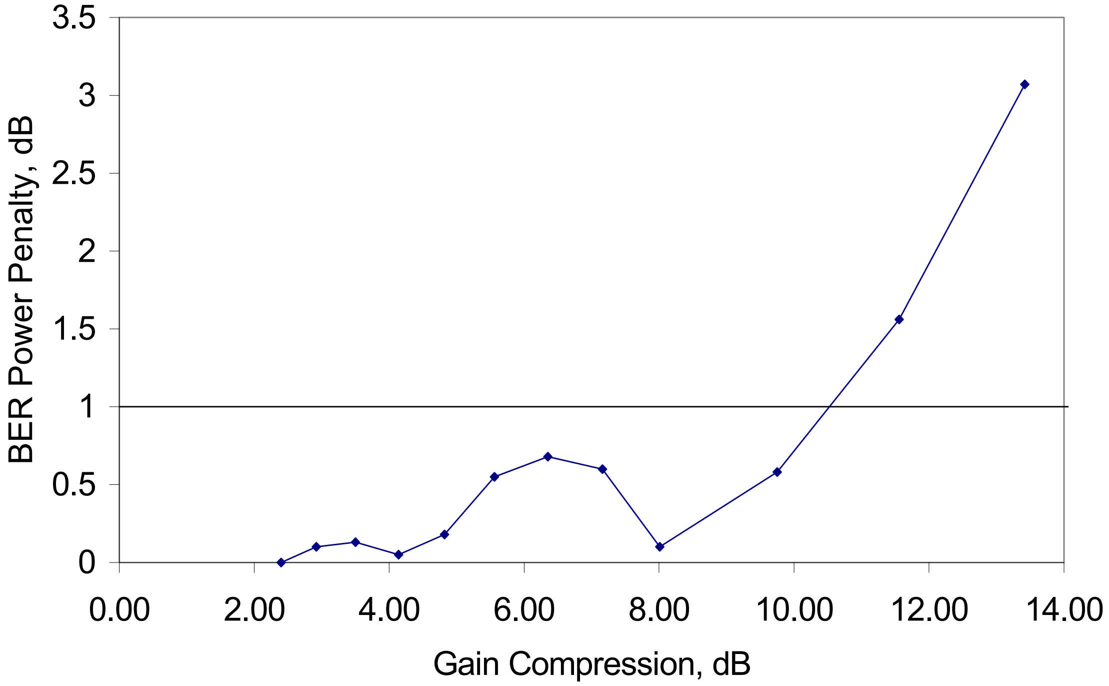


Figure 8: BER vs. gain compression for a typical SOA. Operating significantly into gain compression does not result in an appreciable power penalty.

Power booster in transmission: the performance of SOAs as power boosters can only be evaluated within a systems context. Figure 9 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 the characterisation of the power booster in single and multi channel environments (see Kamelian Application Note No. 0003: "SOAs in Multi-Channel Environments"), including the combined effect of the factors associated with operation in gain compression e.g. chirp, patterning.

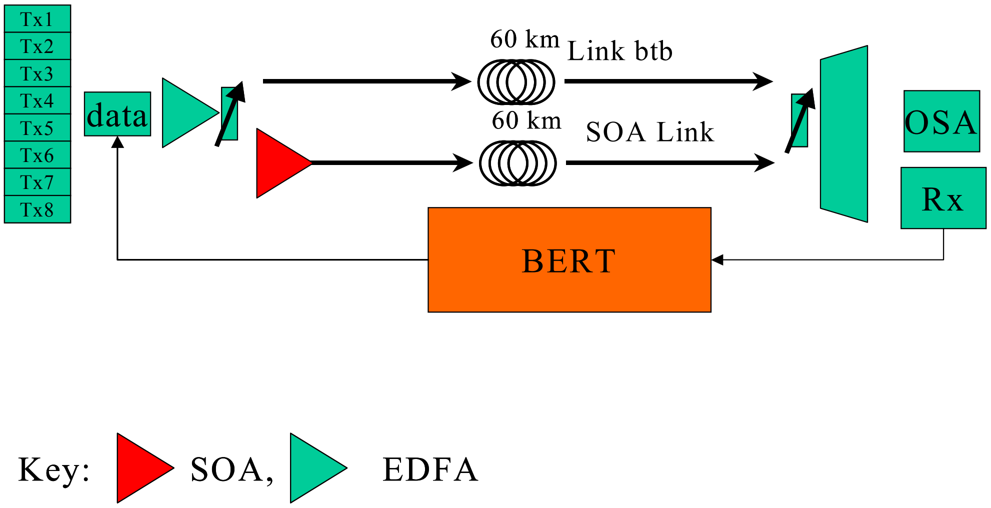


Figure 9: Systems test bed used in the characterisation of the power booster.

There are two scenarios of interest:

- the back-to-back (btb) measurement which excludes the SOA but includes the effect of the transmission link. Therefore the effect of dispersion generated within the link provides 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 issues with operating in gain compression are included. In the case of single channel amplification, the characterisation takes into consideration patterning and chirp and relates this to a power penalty owing to the use of the SOA in this mode.

Figure 10 summarises the power penalty of the btb 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 –5dBm input power (representing the 3dB gain compression point for the device under characterisation. Driving the SOA output further into compression results in an increase in additional chirp which impinges on the power penalty. This operating range can be extended through an increase in the output saturation power. More insight into this behaviour is presented in the Kamelian Application Note No. 0003: "SOAs in Multi-Channel Environments"

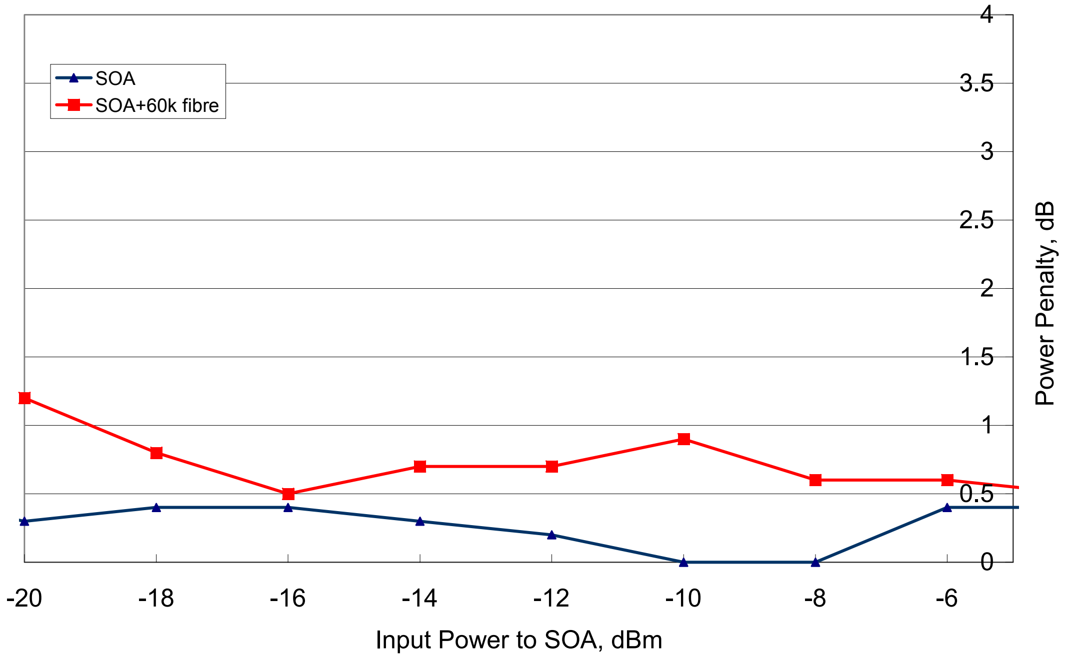


Figure 10: Power penalty as a function of input power per channel into an SOA as a power booster. The btb provides a reference allowing data to be extracted on the impact on performance of the SOA in this mode of operation.

Block 6, Kelvin Campus,
West of Scotland Science Park,
Glasgow, UK
G20 0SP

Tel: +44 (0)141 948 1180
Fax: +44 (0)141 948 1189

www.kamelian.com

SAM-DOC-00-0011 v2.0