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# Semiconductor Optical Amplifiers (SOAs) as Pre-Amplifiers

Applications Note No. 0002

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## Semiconductor Optical Amplifiers (SOAs) as Pre-Amplifiers

Practical optical receivers introduce thermal noise into a communications link, translating into a minimum receiver power below which error free detection of the incoming optical data signal is not possible. This minimum power is typically characterised by the receiver sensitivity, which defines the received signal strength for a particular bit error rate (BER). The use of an optical amplifier prior to a receiver to boost the signal power enables error free operation to be obtained for considerably reduced signal powers at the input to the optical amplifier (Figure 1). This is relatively easily achieved by incorporating SOAs onto either a receiver line card or co-packaged with a photodiode in a butterfly-style package. Optical isolators and/or filters can be used under certain circumstances to improve receiver sensitivity but at the expense of cost and complexity. In this mode the SOA also provides a signal equalisation function, effectively providing automatic gain control directly in the optical domain which is relevant, for example, in network fault conditions where the increase in optical power incident on the receiver may cause damage.

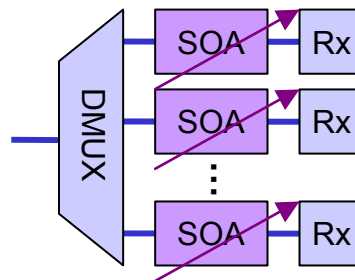


Figure 1: SOA pre-amplified receiver.

The performance of the receiver, most often described by the channel BER is governed by the signal to noise ratio (SNR) at the detector,  $SNR = \frac{\langle i_{sig}^2 \rangle}{\langle i_{noise}^2 \rangle}$ . The signal photocurrent due to the signal power is proportional to the incoming optical signal power and the gain of the SOA. The noise term  $\langle i_{noise}^2 \rangle$  includes all of the contributing noise signals present within the receiver:

- noise sources from within the receiver e.g. thermal noise, dark current;
- the signal shot noise;
- the shot noise from the spontaneous emission;
- the beat noise between the signal and spontaneous emission;
- the beat noise between the various spectral components of the spontaneous emission spectrum.

The most marked performance enhancement in terms of receiver sensitivity occurs when the receiver is driven into the signal-spontaneous limited regime. At this point, the signal strength is sufficiently large such that the noise processes within the detector are dominated by the beat between the signal power and the spontaneous emission that falls within the signal bandwidth. The noise figure (NF) of the amplifier plays a critical role here; lowering the NF will in turn lower improve the attainable sensitivity (i.e. reduce the signal power level required to achieve a specified BER performance). Without a narrow band filter (~1nm) after the SOA and prior to the photodiode, significant levels of spontaneous emission are delivered directly onto the receiver pin; consequently significant further improvements can be achieved by introducing a narrow band optical filter before the pin. See Kamelian Data Sheet on the OPA for typical SOA parameters for this application.

## 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 (refer to Kamelian Application Note No. 0001: "SOAs as Power Boosters").

In pre-amplifier applications the demands on the output power levels are modest, typically around  $-5\text{dBm}$ ; high gain is the important parameter in order to drive the configuration into the signal-spontaneous regime, the optimum operating condition. A further advantage accrues since the SOA inherently exhibits a gain equalisation capability allowing the power on the photodiode to be regulated to a pre-set level. This allows the receiver performance to be optimised as well as protecting sensitive receivers against surges of power. This function is simply executed through the control of the SOA drive current (control signal derived either post receiver or via an optical tap/monitor photodiode arrangement) which in turn changes the gain. Although the linear regime reduces with decreasing gain, the low output power requirement means that the SOA pre-amplified receiver offers a significant input dynamic range ( $>15\text{dB}$ , Figure 2).

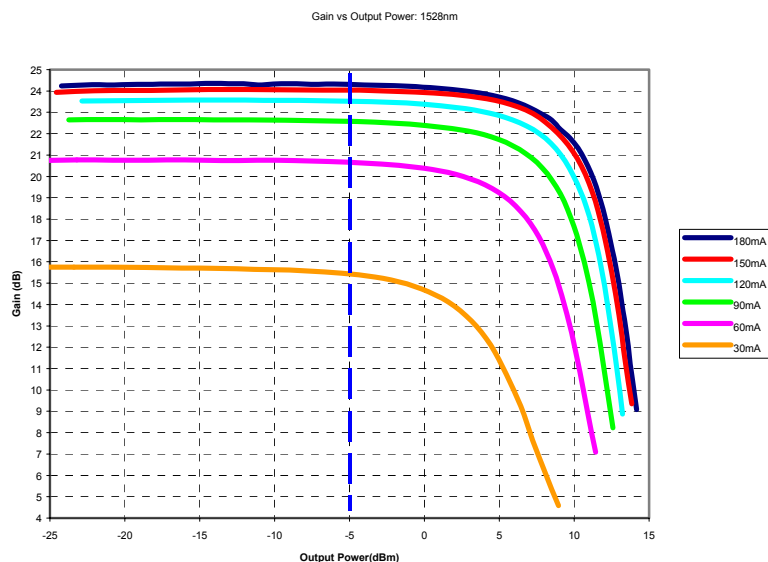


Figure 2: Gain vs. output power of a typical SOA. In pre-amplifier applications the output power requirement is low (here the  $-5\text{dBm}$  level is highlighted) enabling wide input power dynamic range operation.

**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 SOA fundamental lower limit for the noise figure is not substantially different from any phase insensitive linear amplifier e.g. erbium doped optical fibre amplifier (EDFA). Traditionally the major difference in the NFs between the two has been the efficiency of the input coupling to optical fibre. This is no longer the case since with proper on chip design and techniques that improve coupling, noise figures of  $<6\text{dB}$  can be realised. The NF is a critical parameter in this application and should be as low as possible since it determines the lowest achievable sensitivity value.

The wavelength dependence of SOA characteristics translates into trade-offs with respect to wavelength (also refer to Kamelian Application Note No. 0001: "SOAs as Power Boosters"). This also applies to the NF (Figure 3); this variation must be taken into consideration in any designs operating over a specified wavelength range. 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.

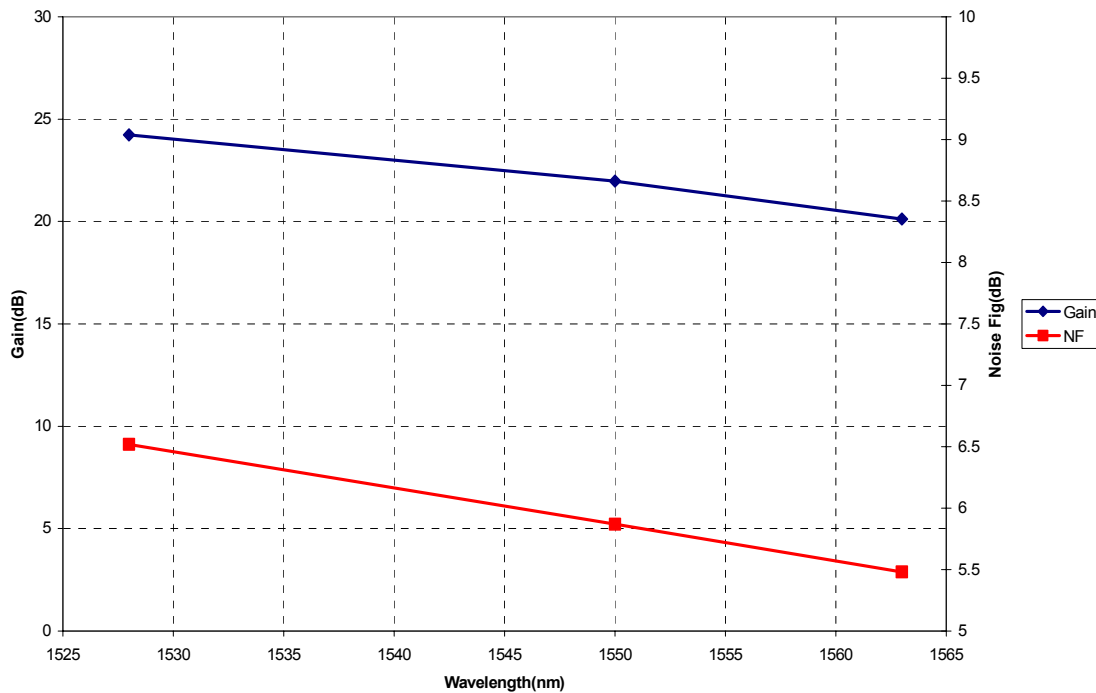


Figure 3: Variation of noise figure vs. wavelength (across c band) for a typical SOA.

**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. Since the SOA is placed after a long transmission link, lowering of the PDG value is necessary to obviate any performance degradation due the drift in the signal input polarisation state.

The wavelength dependence of SOA characteristics translates into trade-offs with respect to wavelength (also refer to Kamelian Application Note No. 0001: "SOAs as Power Boosters"). This also applies to the polarisation dependent gain (Figure 4); this variation must be taken into consideration in any designs operating over a specified wavelength range. 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.

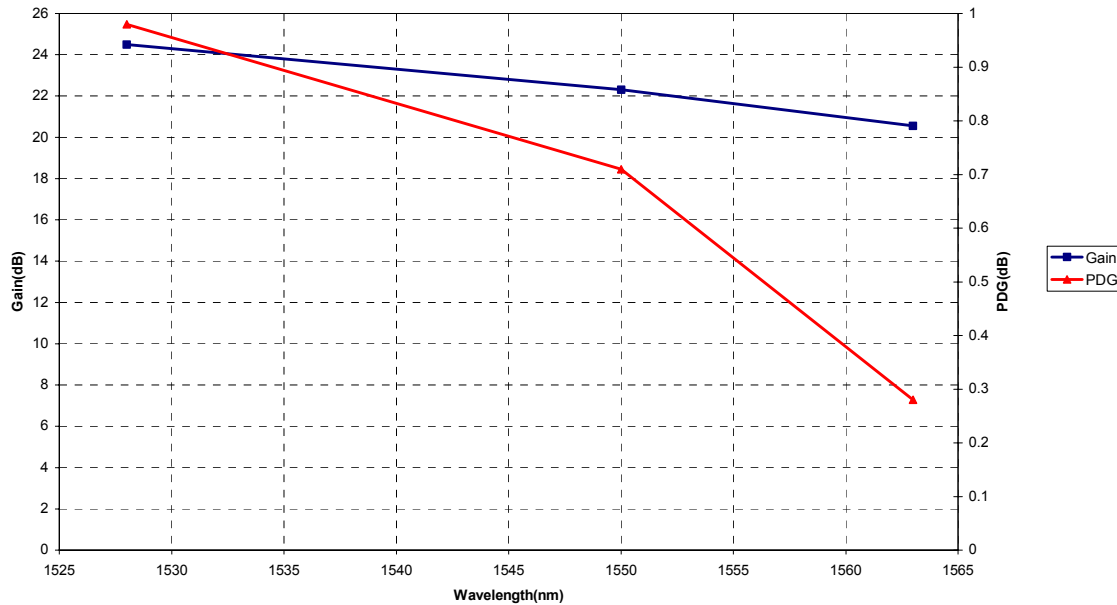


Figure 4: Variation of PDG vs. wavelength (across c band) for a typical SOA.

**Wide optical bandwidth:** SOAs exhibit a  $\sim 80$ nm 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 pre-amplifier 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. This is especially relevant in this application since a co-packaged SOA and pin tandem can be housed in a standard butterfly package.

## Pre-Amplifier Characterisation

**SOA pre-amplified pin plus limiting amplifier at 10Gbit/s:** the BER performance for the three cases in Figure 5 is summarised in Figure 6.

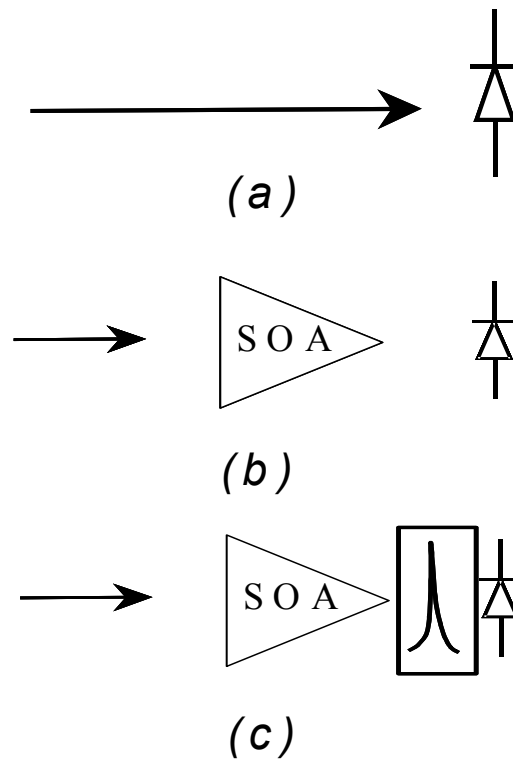


Figure 5: Scenarios for the characterisation of SOA pre-amplified configurations (a) back-to-back (b) SOA without filter (c) SOA with filter.

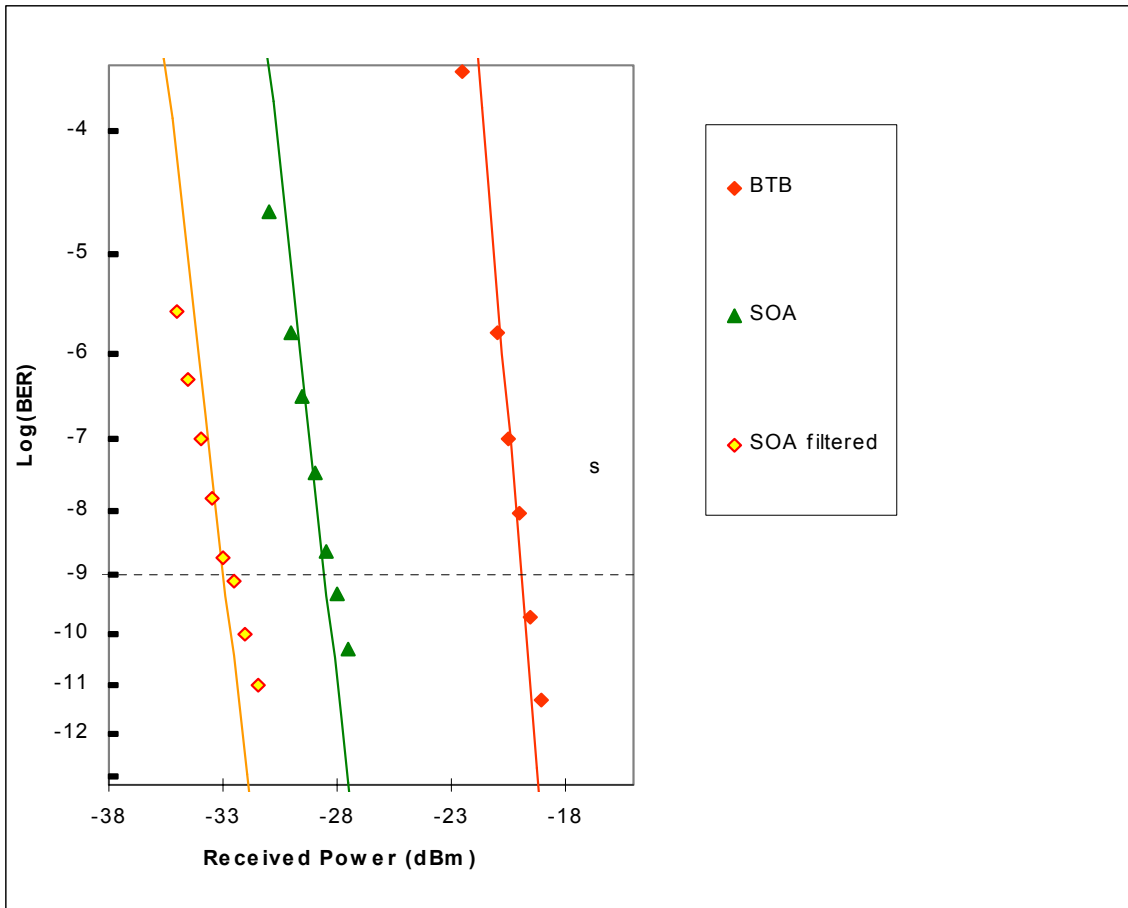


Figure 6: BER characterisation of an SOA pre-amplified pin receiver at 10Gbit/s. Displayed is the (a) back-to-back performance (b) SOA pre-amplified pin without filter (c) SOA pre-amplified pin with narrow band filter.

The characterisation was undertaken with a high gain >20dB low noise figure (~6dB) SOA which yielded a -29dBm receiver sensitivity without a narrow band filter (9dB improvement on the back-to-back) extended to -32dBm sensitivity with the introduction of an optical filter. The input dynamic range of the tandem (case b) is defined in Figure 7 showing the relationship between power incident on the photodiode (input power) and the power penalty. The use of an SOA has resulted in a significant dynamic range (~30dB), extended further by the SOA’s capability to effectively manage high input power levels (~+3dBm) whilst maintaining an acceptable BER (10<sup>-9</sup> in this case).

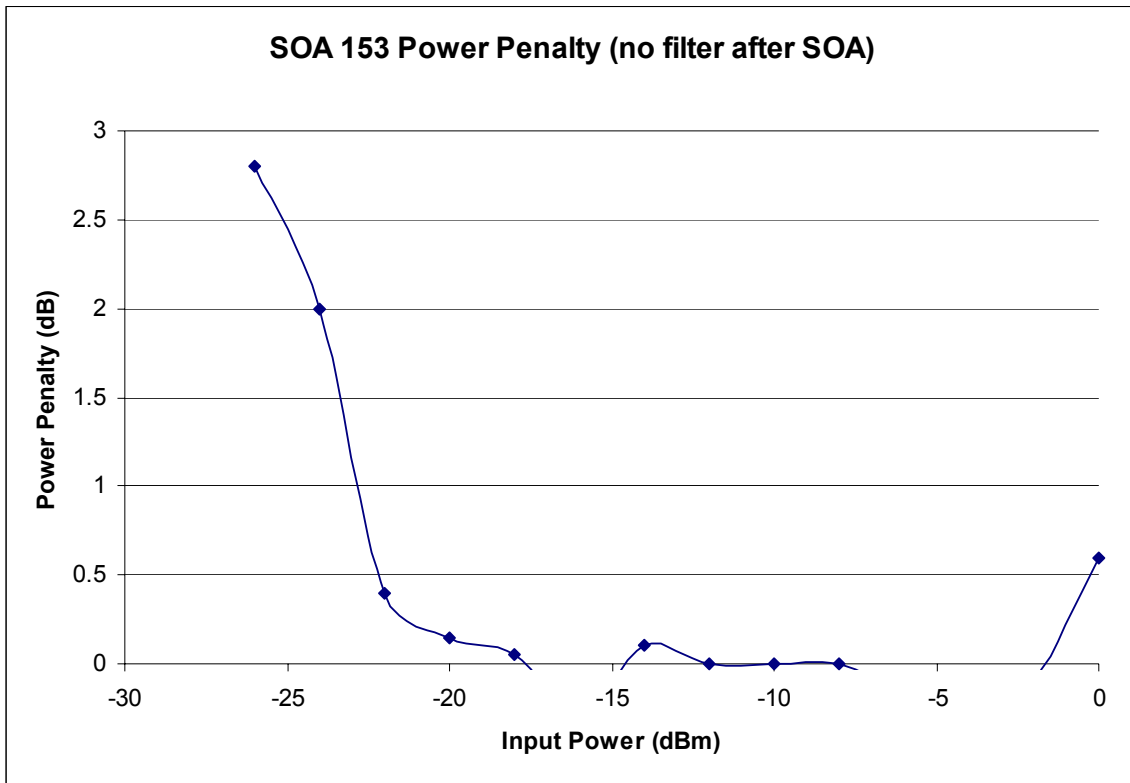


Figure 7: *Input power dynamic range as a function of power penalty for an SOA pre-amplified pin receiver with no filter prior to the photodetector.*

**SOA pre-amplified waveguide pin at 40Gbit/s:** in this case the photodetector was a waveguide pin, the output signal of which was not subject to first stage electrical amplification (through a trans-impedance amplifier). Thus the output signal level of the SOA was important; the SOA used was a high gain, low noise device providing  $\sim 9$ dBm output saturation power. The BER performance for this combination is summarised in Figure 8. A  $>17$ dB improvement on the un-amplified receiver sensitivity of  $\sim 0$ dBm is obtained. Figure 9 displays the receiver performance with swings in the input power level; a 15dB dynamic range was measured for a BER of  $10^{-9}$ .

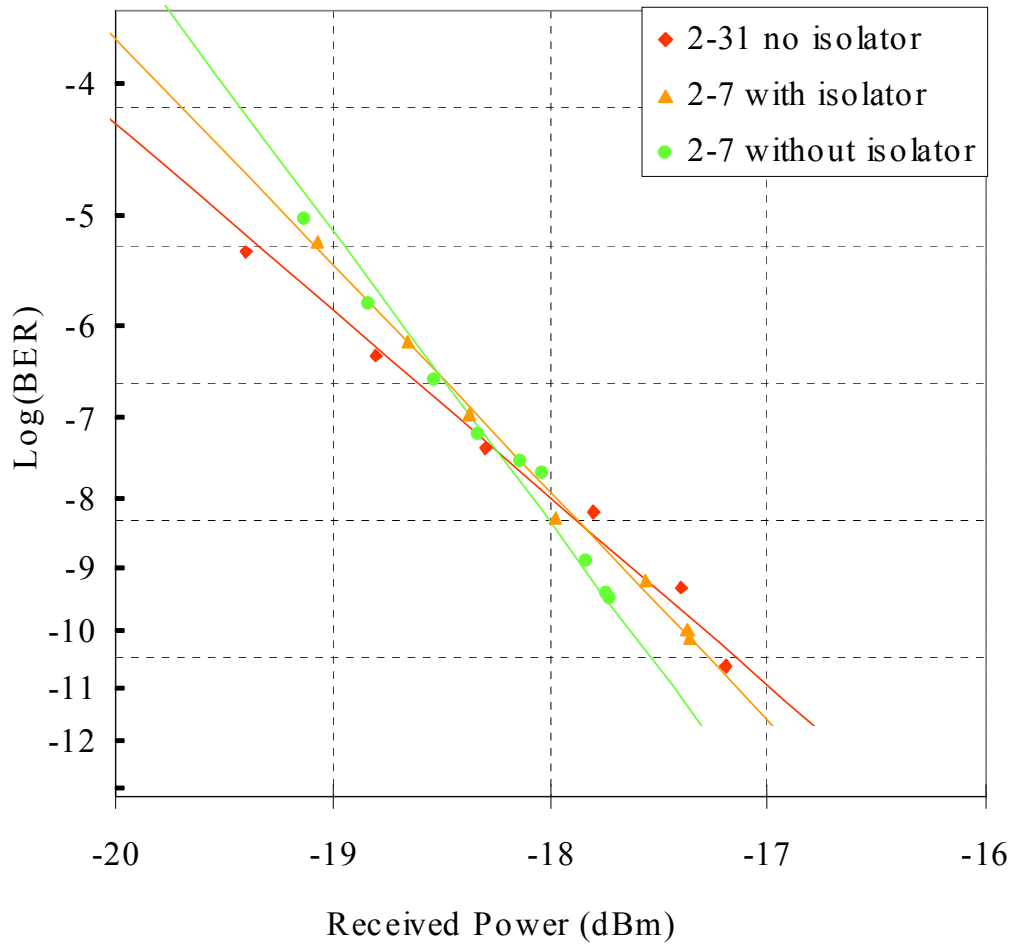


Figure 8: Summary of the BER characterisation at 40Gbit/s; a receiver sensitivity of  $-17.4\text{dBm}$  was achieved (un-amplified sensitivity is  $0\text{dBm}$ ).

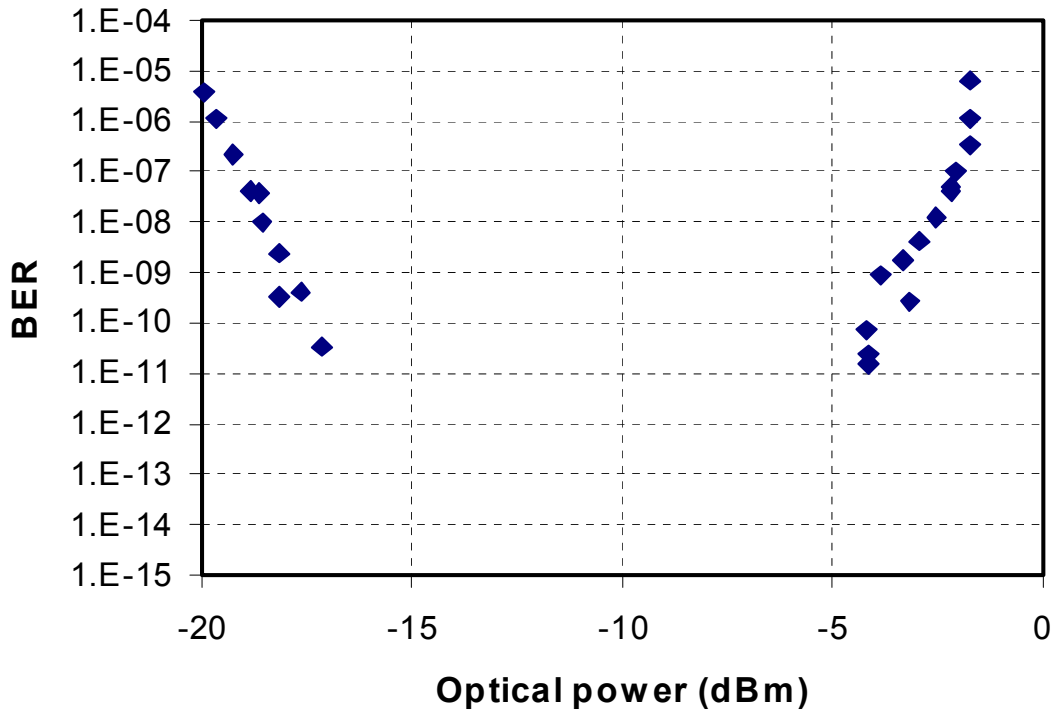


Figure 9: SOA pre-amplified waveguide pin photodetector performance with swings in the input power level; a 15dB dynamic range was measured for a BER of  $10^{-9}$ .



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SAM-DOC-00-0012 v2.0