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Introduction: Photonic switch blocks in all-optical networks will need space switches. Contrary to many other types of gates and switches, semiconductor optical amplifiers (SOA) are attractive as gates since they feature the high on-off ratios of 40-50 dB that are needed to overcome the severe penalty induced by crosstalk [1]. At the same time they compensate for switch block losses. The input power dynamic range (IPDR) of the SOA-gate is, however, limited by spontaneous emission at low input powers and extinction ratio degradation due to gain saturation at high input powers [2]. This will severely restrict the number of switch blocks that can be cascaded. In order to reduce the influence of the extinction ratio degradation, a gain-clamped SOA (GC-SOA) has been proposed [3] for which the gain is clamped by a laser oscillation inside the amplifier resulting in a higher IPDR.

Here, we asses the cascadability of conventional SOAs and GC-SOAs in a WDM network using a detailed theoretical model. The analysis shows far superior cascadability of GC-SOAs at a channel bit rate of 2.5 Gbit/s in systems with up to at least 16 channels.

Device structures and comparison conditions: The superior performance of the GC-SOA is due to a higher saturation input power. This is illustrated in Fig. 1 [4], showing the measured and calculated gain versus signal input power for a 450 μm long conventional SOA (structure described in [2]) and a 1000 μm long GC-SOA (described in [5]). Note, the excellent agreement between measurements and theory. As can be seen in Fig. 1, the gain of a conventional SOA decreases as the input power increases, whereas, the gain of the GC-SOA remains constant until the amplified signal is comparable to the power of the lasing mode. Furthermore, as described in [6] and shown in Fig. 1, increasing the bias current results in an increased saturation input power, while the unsaturated gain remains constant. As a result, larger IPDR can be obtained using GC-SOAs biased at high currents compared to conventional SOAs [4]. In order to make a fair comparison between the GC-SOA and the conventional SOA, equal unsaturated gains of 21 dB are used. This is accomplished by shortening the device length of the SOA from 450 μm to 250 μm. We emphasise, that this is in favour of the SOA since a short SOA has a lower noise figure and a higher saturation input power compared to a long SOA [2].
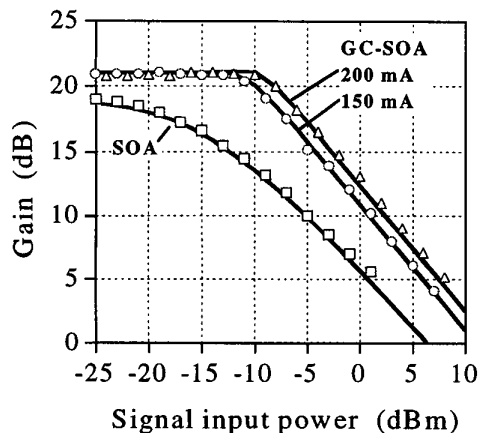

Fig. 1 Measured (dots) and calculated (lines) gain as function of the input power for a 450 μm long SOA operated at 40 mA and a 1000 μm long GC-SOA operated at 150 and 200 mA. The GC-SOA is realised as a DBR laser with two Bragg regions of lengths 200 μm and an active region of length 600 μm.

Results: The static gain characteristics shown in Fig. 1, which is for a single wavelength, predict a superior dynamic performance of the GC-SOA in a multi wavelength system. This is verified in Fig. 2, showing the extinction ratio at the output of the gates versus signal input power per channel at 2.5 and 10 Gbit/s for the conventional SOA (Fig. 2.a) and the GC-SOA (Fig. 2.b). The calculations are performed with 4 and 8 channels with a 2 nm channel spacing, which is seen as a realistic approach in a multi

channel system. We emphasise, that the channels are modulated independently of each other (NRZ-format). Furthermore, the input extinction ratio of all channels is 13 dB, while the shown output extinction ratio is that of channel 1.
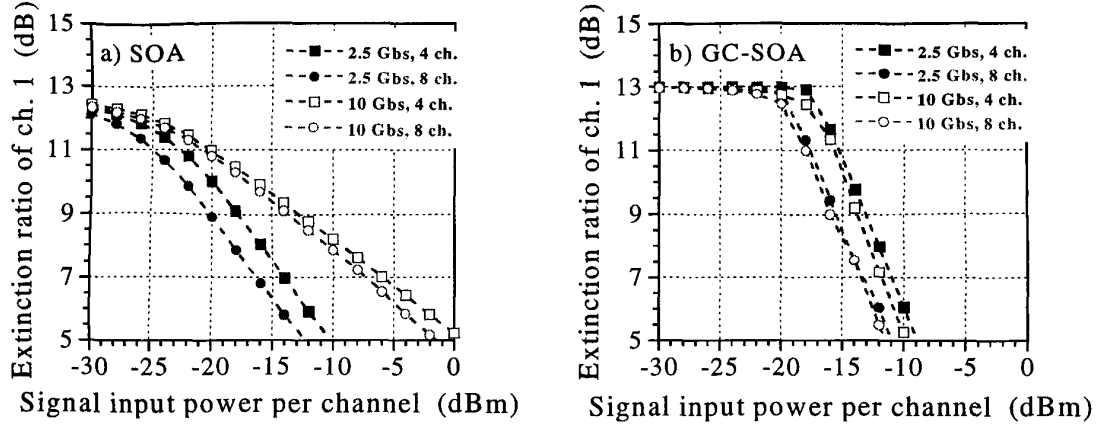

Fig. 2 *Calculated extinction ratio at the output of the a) SOA and b) GC-SOA (biased at 200 mA) as function of the signal input power per channel with the number of channels and the channel bit rate as a parameter. The channel spacing is 2 nm and input extinction ratio for all channels is 13 dB.*

A fundamental difference between the SOA and the GC-SOA can be seen in Fig. 2. For the SOA, the extinction ratio decreases as the signal input power increases or the number of channels increases. However, increasing the channel bit rate to 10 Gbit/s improves the extinction ratio since the influence of gain modulation from other channels becomes less pronounced. For the GC-SOA, there is no degradation of the extinction ratio before the amplifier starts to saturate but in contrast to the conventional SOA, there is no improvement by increasing the channel bit rate. This is due to the limited (13-14 GHz) relaxation frequency of the GC-SOA, which causes pulse pattern effects that limits the performance [4],[6]. Nevertheless, for input powers below the saturation point of the GC-SOA, clearly the SOA performance is worst.

In WDM networks several space switches will be concatenated. Therefore, the cascadability of optical gates is important. The superior dynamic characteristics of the GC-SOAs in a multi wavelength system, as seen in Fig. 2, can be used to substantially increase the cascadability of optical switches. This is illustrated
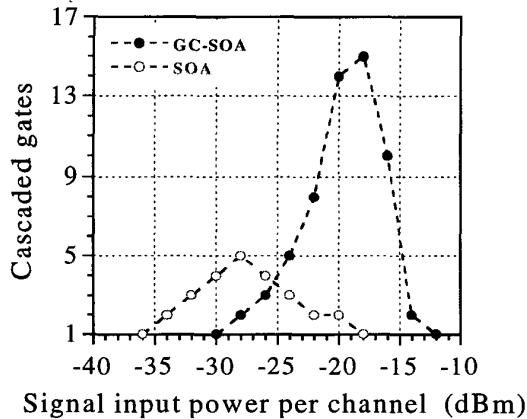

Fig. 3 *Number of GC-SOAs and SOAs that can be cascaded (@ 1dB penalty) as function of the signal input power per channel (using 4 channels with 2 nm channel spacing). The channel bit rate is 2.5 Gbit/s.*

in Fig. 3, showing the number of GC-SOAs and SOAs that can be concatenated (@ 1 dB penalty) versus the signal input power per channel. The calculations are performed with 4 channels at a channel bit rate of 2.5 Gbit/s. As seen in Fig. 3, a higher number of SOAs can be concatenated at low input powers. This is because the SOA has a noise figure of only ~5 dB, while the GC-SOA has a noise figure of ~11 dB. The higher noise figure of the GC-SOA is due to a longer amplifier section and the passive Bragg region in the front of the amplifier. Since the cascadability at low input powers is limited by ASE accumulation rather than extinction ratio degradation, the lower noise figure for the SOA results in better performance. Increasing the input power increases the signal-to-noise ratio and consequently the cascadability of both types of gates.

At high input powers, however, the extinction ratio degradation becomes a limiting factor as shown in Fig. 2. This is much more severe in SOAs compared to GC-SOAs. Therefore, far superior performance is achieved for the GC-SOA as shown in Fig. 3 even when compared to a short cavity SOA gate. As seen, 15 GC-SOAs can be cascaded (@ input power of -18 dBm per channel), compared to a maximum of only 5 SOAs (@ input power of -28 dBm per channel). This makes GC-SOA gates very attractive for large scale optical networks, where cascadability is an important issue. The superior performance is also illustrated in Fig. 4 showing the maximum number of GC-SOAs and SOAs that can be cascaded (@ 1 dB penalty) at 2.5 and 10 Gbit/s as function of the number of channels. As seen in Fig. 4, the use of GC-SOAs at 2.5 Gbit/s allows a much higher number of gates to be cascaded.
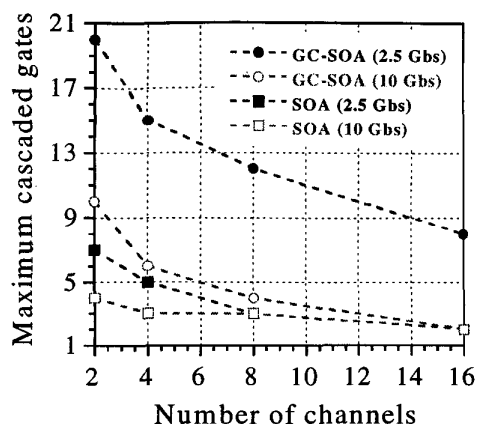

Fig. 4 Maximum number of GC-SOAs and SOAs that can be cascaded (@ 1dB penalty) as function of the number of channels. The channel bit rate is 2.5 Gbit/s and 10 Gbit/s, while the channel spacing is 2 nm.

At a channel bit rate of 10 Gbit/s, the ASE accumulation starts to become a limiting factor for the cascadability. Furthermore, the influence of the relaxation oscillations in GC-SOAs also limit the performance [4],[6]. This is evident from Fig. 4, where the cascadability of both gates has decreased and even more important the improvement in cascadability of the GC-SOA compared to the conventional SOA has also decreased. Still, the GC-SOA performs equal or even better at 10 Gbit/s compared the short cavity SOA at 2.5 Gbit/s.

Conclusion: A detailed theoretical investigation of the cascadability of conventional SOAs and GC-SOAs has been carried out in an optical multi channel system. It has been shown that the extinction ratio degradation experienced in a SOA increases as the input power or the number of input channels increases, whereas, there is no extinctio ratio degradation in the GC-SOA independently of the input power or the number of input channels until the amplifier saturates. Thereby, superior cascadability is achieved for the GC-SOAs, even compared to short cavity SOA gates, making them very attractive for network applications where high switching speeds and cascadability are required. The advantages are, however, reduced at high bit rates due to a limited relaxation frequency. Therefore, it will be an important challenge to fabricate GC-SOAs with high relaxation frequencies needed for high speed operation.

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