Comparison of Conventional and Gain-Clamped Semiconductor Optical Amplifiers for Wavelength-Division-Multiplexed Transmission Systems

D. T. Schaafsma, E. Miles, and E. M. Bradley

***Abstract*—We compare the output spectra and data streams of a conventional 1550-nm semiconductor optical amplifier (SOA) with its gain-clamped (GCSOA) counterpart, in order to assess the impact of gain clamping on cross-gain modulation (XGM) and difference frequency generation (DFG). Whereas the conventional SOA exhibits a large amount of crosstalk due to XGM, there is virtually no XGM present in the GCSOA. However, the XGM effect in the SOA shows evidence of diminished efficiency at moderate input levels. We observe much higher DFG levels from the GCSOA (roughly 10 dB greater than the SOA). These DFG levels are such that cascaded wavelength cross-connect devices, in-line amplifiers, and even optical gates could experience inhibited performance.**

***Index Terms*—Cross-gain modulation (XGM), optical gate, semiconductor optical amplifier (SOA), wavelength cross-connect, wavelength-division-multiplexed (WDM) network.**

I. Introduction

ONE OF THE principal drawbacks to the use of semiconductor optical amplifiers (SOA's) as replacement in-line amplifiers in wavelength-division-multiplexed (WDM) networks is their propensity for high channel-to-channel crosstalk, usually through the mechanism of cross-gain modulation (XGM) [1]–[4]. Gain-clamping of SOA's [5], [6] presents a solution to this problem by running a continuous lasing mode at the edge of the gain band, essentially providing a reservoir to dampen large gain fluctuations closer to the center of the band. In contrast, conventional (unclamped) SOA's have recently regained focus as wavelength cross-connect devices for WDM networks [7], [8], where XGM (among other mechanisms [9]) is exploited to transfer data from one wavelength channel to another. In addition, both types of SOA exhibit a large degree of nonlinear wavelength conversion, generically referred to herein as difference frequency generation (DFG). These applications would seem to mandate that gain-clamped (GC) SOA's be free from XGM effects, while conventional SOA's should be optimized for XGM or nonlinear effects, but to our knowledge, their are no direct GCSOA–SOA comparisons in the literature which focus on the relation between the XGM and DFG mechanisms.

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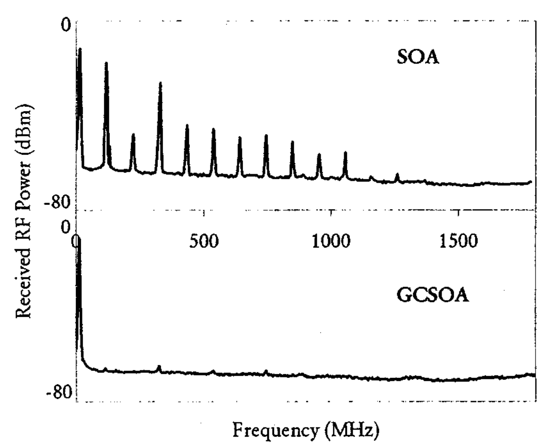

Fig. 1. Received RF spectra of CW target channel (CH2) output from the SOA (top trace) and GCSOA (bottom trace), at identical input and current injection levels. The background level in both cases was approximately −70 dB.

In this study, we compare two commercial devices with nearly identical construction [10] save for the gain-clamping mechanism (SOA: Alcatel 1901, GCSOA: Alcatel 1921). Both devices had a transparency threshold near 40 mA, a recommended operating current of 150 mA (maximum 250 mA), and saturation output power between 9–13 dBm (bidirectional). Two DFB laser sources were used, one modulated (CH1) and one continuous-wave (CW) (CH2), with nominal wavelengths at two adjacent points on the ITU grid ($\lambda_1 \approx 1548$ and $\lambda_2 \approx 1549$ nm). The wavelength spacing between the two lasers could be temperature tuned to as great as 5 nm; unless otherwise noted, all data below were taken with a channel spacing of approximately 2.5 nm and square-wave modulation of CH1 at approximately 100 MHz (in order to make comparisons well below the relaxation oscillation frequencies of the amplifiers). Both DFB lasers had slope efficiencies in the range of 0.06-0.07 mW/mA, and were input to the amplifiers through a standard 1×2 3-dB coupler and an attenuator used to set the total input attenuation per channel to roughly 10 dB. Cascaded bandpass filters were used on the output of the amplifier to isolate the desired channel, with over 40 dB of rejection.

As expected, the SOA showed pronounced XGM effects, over a relatively wide range of optical input levels. Fig. 1 shows a typical RF spectrum of the CW channel (CH2) output from the SOA

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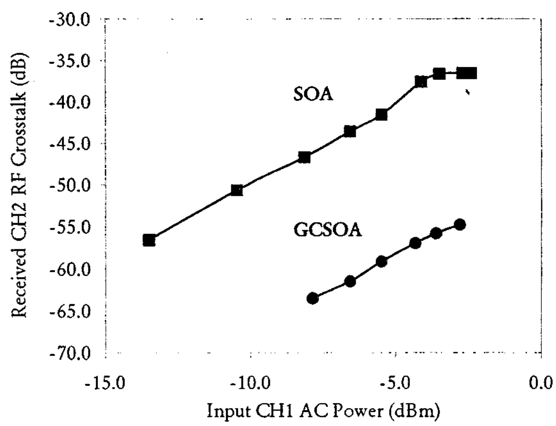

Fig. 2. Received RF intensity versus modulation intensity input on CH1 for both the SOA (squares) and GCSOA (circles).

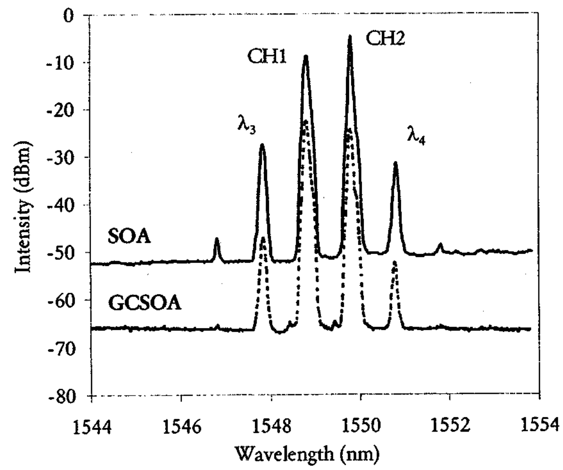

Fig. 3. Output of the two amplifiers (solid = SOA, dotted = GCSOA) with similar CH1 and CH2 input conditions, showing the peaks arising from the DFG effect (λ_3 and λ_4). The two curves have been offset vertically from each other for clarity, but the relative scales are identical. The slant of the SOA baseline (increasing with increasing wavelength) is most likely due to increased levels of ASE coming from the amplifier.

(top trace), with CH1 modulated at ~ -8 dBm peak-to-peak optically. Though at this input level, the XGM was strong enough to be detectable in the ASE of the amplifier (i.e., with no CH2 input), when CH2 was input to the SOA at roughly -15 dBm, the received RF signal jumped by some 35 dB. This implies that the XGM effect on CH2 was quite strong, as evidenced further by Fig. 2. When the CW level of CH2 was held constant and the modulation level of CH1 varied, the amount of XGM increased sharply from zero and then reached saturation at about -5 dBm, as the squares in Fig. 2 indicate. In this experiment, the output filters were set to attenuate CH1 by over 70 dB relative to CH2, and the filtered output was then attenuated 20 dB further before coupling into the photoreceiver, so this saturation level is more likely that of the amplifier than the detector.

In contrast, the GCSOA showed little crosstalk due to XGM, even at very high input levels. As shown by the bottom trace in Fig. 1, with identical input and output conditions to the SOA experiment, CH2 amplified by the GCSOA showed little RF content (crosstalk) even near 0 dBm input. There was no detectable XGM in the ASE output of the amplifier. The circles in Fig. 2 show the ac level response of the GCSOA, indicating that there is very little XGM even at very high modulated channel input power levels. The apparent 20 dB difference between the SOA data in Fig. 2 (squares) and the GCSOA data (circles) is further augmented by the fact that the SOA data was taken with 20 dB of attenuation in the line before the receiver (in order to avoid saturating the detector), whereas the GCSOA was taken with no attenuation (since the CH2 intensity was much lower and the risk of saturation correspondingly reduced). It is thus likely that the GCSOA reduction in XGM effects versus the conventional SOA is closer to 40 dB overall. Though there is noticeable RF content in the CW-channel output of the GCSOA for channel spacings narrower than 1 nm or so, this is more than likely due to incomplete filtering. We have also compared return-to-zero (RZ) and nonreturn-to-zero (NRZ) signals, since it is also of interest to assess the bit-replication efficiency of XGM (and the modulation frequency dependence thereof), with the result that the GCSOA reduction of XGM is approximately the same for RZ as NRZ. Ultimately, gain clamping appears to be extremely effective at eliminating XGM crosstalk, as it has been purported to be.

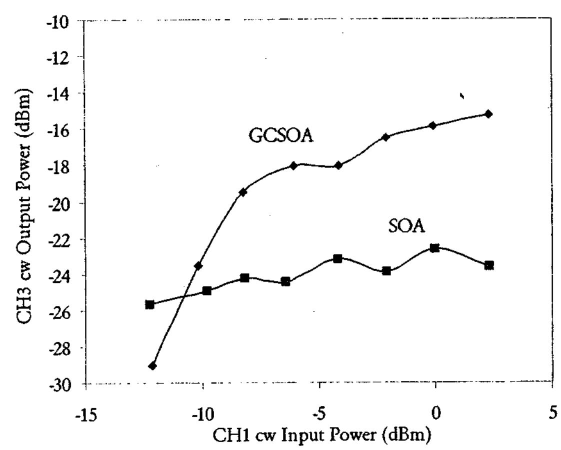

Fig. 4. Comparison of CW DFG output power versus CH1 CW input power for the GCSOA and SOA. The CH2 input and wavelength spacing were held constant, so that the input conditions for both amplifiers were equivalent.

However, this is not the end of the story of the differences between SOA and GCSOA. As has been often observed [11], [12], both amplifiers exhibit significant DFG, even at relatively low optical input levels. Fig. 3 shows typical output spectra of the SOA (solid line) and GCSOA (dotted line) with two channels input, where the DFG peaks have been identified for reference as λ_3 and λ_4. We observed identical behavior of these bands with changing CH1–CH2 separation input to the SOA and GCSOA, where both amplifiers showed a roughly 10 dB drop in relative DFG band intensity as the spacing between the channels was increased from 0.5 to 4.5 nm.

More surprisingly, the GCSOA exhibited much higher DFG conversion efficiency than the SOA (some 10 dB greater at the end of the power range), as shown in Fig. 4. (Though the position of the λ_3 and λ_4 peaks changed with input peak separation, it did not change with input power levels. We note that the extinction of the DFG peaks with increasing input peak separation

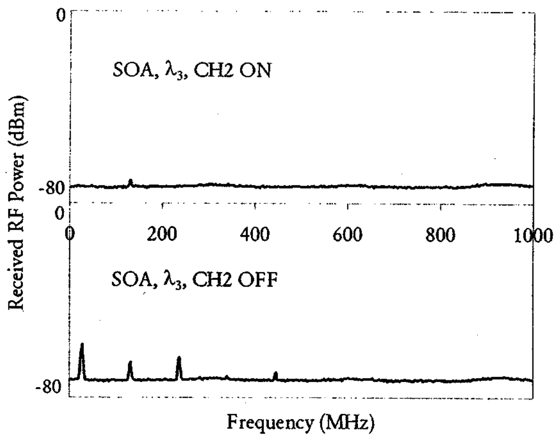

Fig. 5. Received RF spectra of DFG sideband (λ_3) with CH2 on (top trace) and off (bottom trace).

is roughly equal for both amplifiers.) This is an important consequence for the GCSOA as an inline amplifier, even if these DFG bands are purely CW.

As we have demonstrated previously [13], these DFG bands (λ_3 or λ_4) are devoid of RF crosstalk in the GCSOA, and Fig. 5 shows that this also holds true for the SOA. With approximately -5 dBm of modulation on CH1 and the post-amplifier filters set to select λ_3 only, the received RF spectrum (top trace) contained almost no structure. We note from the wavelength spectra of Fig. 3 that the DFG peaks are approximately 20–25 dB below the CH2 peak. Recall that we also observed modulation of the ASE due to XGM, with filtering set to select CH2 only and with an added 20 dB of attenuation downline of the filters. It thus seemed logical to expect that the ASE modulation would be even more pronounced in the λ_3 RF spectra, where there was no added attenuation, but as shown by Fig. 4, this was not the case. In addition, it is reasonable to expect that the 20 dB offset of the λ_3 DFG peak would be compensated by the 20 dB attenuation of CH2 in the received RF spectra, so that we would expect λ_3 modulation to show up at a comparable level to what was observed for CH2. Since this also was not the case, we conclude that there was no XGM impact on the λ_3 peak.

Furthermore, when CH2 was turned off (and all other settings left as above), the received RF levels in the λ_3 band actually increased, as shown in the bottom trace of Fig. 4. As before, we can easily attribute this to ASE modulation (since CH1 was again isolated by more than 70 dB), but the question arises as to why this modulation does not appear when CH2 is on. Naturally, if we fix the CH1 ac and dc levels, and then add in another signal on CH2, this will reduce the amount of available gain to some degree. XGM begins to happen when the time-averaged available gain reaches zero. However, if all of the inputs to the amplifier are well above saturation, then there is no means by which XGM can occur, since there is no available gain under these conditions. In essence, a large CW signal on CH2 input to the SOA will at some point begin to function in the same manner as the lasing line in the GCSOA. So we expect that a significant CH2 input (even CW) will begin to moderate the XGM effect on other channels. Fig. 4 shows that this effect is significant enough at modest CH2 input levels (~ -15 dBm) to nearly eliminate the background modulation of the ASE.

Where then is the connection between XGM and DFG? In applications where one or more SOA's are used as wavelength cross-connects, DFG adds a slight amount of dc offset to each ITU wavelength channel at each amplifier stage. Even though filters might be used to isolate channels, there is still a problem in that even the target channel will have some additions from DFG due to other channels; the DFG peaks and the ordinary channel peaks will align to within any practical WDM filter specification. These levels continue to grow with further amplification, eventually reducing the cross-connect efficiency by reducing the amount of XGM which can occur. After a sufficient number of cross-connect stages, the network signal may be completely lost because the dc levels are sufficiently large that XGM cannot be used to copy data from one channel to another.

In addition, cascaded CW offsets will eventually degrade the transmission SNR performance of an optical network, even where wavelength cross-connects are not used. In using a GCSOA to defeat crosstalk problems arising from XGM, one may effectively introduce a new set of problems arising from DFG offsets. Even without multiple GCSOA stages, subsequent linear amplification of these CW offsets can deprive other in-band signals of available gain, and any data transcribed into the DFG bands will of course introduce noise into the corresponding communications channel.

Though the SOA is now becoming obsolete for XGM (with the advent of cross-phase modulation (XPM) and interferometric converters), there are still some applications for these devices which may be detrimentally affected by these other effects. For the GCSOA, in-line applications may not be as common in the future as optical gate applications, but even in this mode, the high DFG conversion efficiency of the device may still be a concern. In fact, in WDM applications where GCSOA's are used without narrowband filtering to gate a single channel, these DFG signals could introduce significant levels of crosstalk into other WDM channels. Fortunately, high-finesse optical filtering is becoming a more cost-effective option in high-channel density systems.

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