

SIGNAL GENERATION BY MIXING MODULATED OPTICAL CARRIERS IN FEED-BACKED SEMICONDUCTOR OPTICAL AMPLIFIERS

A. C. Bordonalli, J. A. Guimarães, J. L. Benitez, E. Conforti and C. M. Gallep

Departamento de Microonda e Óptica - Faculdade de Engenharia Elétrica e de Computação
Universidade Estadual de Campinas – UNICAMP
Caixa Postal 6101, CEP: 13083-970, Campinas, SP – Brazil

ABSTRACT

The gain-crossed property of semiconductor optical amplifiers is experimentally investigated. It was observed that optically feed-backed saturated amplifiers could achieve similar performance as that of cascaded amplifiers, offering up to 10 dB gain to two 8-nm-apart modulated optical carriers. Due to saturation, the amplifier gain mechanism is altered, leading to a mixing effect that causes the frequency components of the optical signals to be exchanged. For optical carriers modulated at 250 MHz and 400 MHz, this mixing effect produced, after photodetection, up and down-converted electronic components at 150 and 650 MHz, respectively.

1. INTRODUCTION

Recently, photonic generation of RF, microwave and millimeter-wave signals has been widely studied. This technique uses the optical fiber as the transmission medium for considerably stable carriers that are generated in a wide range of RF and microwave frequencies, with applications on mobile communication [1][2], satellite communications [3], and subcarrier multiplexed systems [4]. Techniques such as optical phase-lock loop [5][6], injection locking [7] and mode-locking [8] have demonstrated the feasibility of the optoelectronic conversion and generation of RF and microwave carriers.

Nevertheless, some of the techniques mentioned above are considerably complex and require accurate and tedious optical and/or electrical designs. A simple scheme for signal generation proposed in [9] was modified to observe the effects of cascaded semiconductor optical amplifiers (SOA) on the mixing of intensity modulated optical carriers [10]. It was experimentally shown that cascaded SOAs were able to mix two distinctly modulated optical carriers separated by 8 nm. As expected, a spectrum analyzer showed that the photocurrent produced after filtering out one of the optical carriers had harmonic mixing contents corresponding to the sum and difference of the individual optical carrier modulation frequencies. The experiment was conducted for optical carriers modulated at 250 and 400 MHz. It was possible to produce, after photodetection, up and down-converted electronic components at 150 and 650 MHz. It was observed that the use of additional SOAs tends to improve the power level of the up and down converted frequency components in comparison with a 1-SOA experiment due to SOA stronger saturation. However, the use of cascaded SOAs may still be a premature option due to the actual device costs and the limits imposed on the maximum allowed coupling power. In spite of simple, the cascaded SOA technique for RF and

microwave carrier generation requires a careful design in order to guarantee acceptable power levels for the up and/or down converted signals with low cost and device safekeeping.

In this paper, an alternative approach to the cascaded SOA scheme for RF and microwave signal generation is presented. To minimize the number of SOAs used, an optically feed-backed SOA (FB-SOA) set-up is proposed. In this way, the optical signals will be re-injected into the SOA after one trip, ensuring a deeper saturation state for each device, and, therefore, higher power levels for the up and down converted frequency components. In order to compare the two SOA signal generation schemes, a 2-SOA cascaded experiment was reproduced using the same optical carrier modulation frequencies as in [10]. Then, the optically feed-backed SOA experiment was implemented using only one semiconductor optical amplifier. In this particular case, it was possible to observe that the FB-SOA approach can offer a performance similar to that of the cascaded scheme. However, it is believed that the FB-SOA configuration is able to offer better results than the cascaded experiment as some possible modifications in the experimental set-up can allow up to 9 dB more optical power injected into the SOA and 3 dB more optical power coupled into the photodetector.

2. THEORY AND EXPERIMENTS

Fig. 1 illustrates the mixing mechanism for two amplitude-modulated optical carriers that are being simultaneously coupled into a SOA. One of the carriers is generated by a transmitter laser (TO) and is modulated at a frequency f_{TO} . The other is produced by a local oscillator laser (LO) and modulated at a frequency f_{LO} . If the coupled optical power is enough to deeply saturate the semiconductor optical amplifier, the carrier population in the gain region of the SOA decreases significantly, resulting in a considerable reduction of the amplifier gain. However, since the carrier dynamics within the SOA are very fast, the saturation condition causes the SOA gain to become sensitive to any variations that the photon number inside the SOA cavity can suffer. In this way, the SOA responds in tune with the fluctuations of the coupled optical power originated from the optical intensity modulation. Therefore, the optical gain is simultaneously modulated at both optical carrier modulation frequencies f_{TO} and f_{LO} in such a way that the SOA becomes unable to distinguish and separate the optical carriers and their own harmonic contents from each other. As a result, the modulated gain induces both carriers to be modulated at f_{TO} and f_{LO} at the SOA output. This effect, known as cross-gain saturation, is the main responsible for the SOA mixing characteristics.

Now, if the LO optical signal is filtered out after the SOA and the remaining signal is photodetected, the photocurrent will contain harmonics at the frequencies $f_{TO} + f_{LO}$ and $f_{TO} - f_{LO}$. By properly choosing f_{TO} and f_{LO} , both the up-converted ($f_{TO} + f_{LO}$) and the down-converted ($f_{TO} - f_{LO}$) signals can be located within a specific frequency range (RF or microwave).

In [10], it was shown that the combined use of cascaded SOAs and a local oscillator laser for RF and/or microwave carrier generation purposes ensures gain saturation. Therefore, the cross-gain saturation effect is achieved in a faster and more improved way than by SOA direct current modulation, even for systems where the optical power of the LO and TO are low. Fig. 2 shows the block diagram of the cascaded SOA experimental set-up. The TO laser is directly modulated at f_{TO} via its bias current and the LO laser signal is externally modulated at f_{LO} by a Mach-Zehnder intensity modulator. Both modulated signals pass then through an optical fiber coupler and are injected into the SOA1 active region. A mixed signal is generated after the SOA1 and coupled into the SOA2 for new amplification and enhancement of the mixing process. The output of the SOA2 passes through an optical filter centered at f_{TO} and is photodetected. The photocurrent produced is amplified and coupled into a spectrum analyzer. Polarization controllers are used to match the polarization of laser beams with that of the wavefronts inside the SOA cavity. Isolators are used to avoid undesired reflections and SOA-to-SOA coupling.

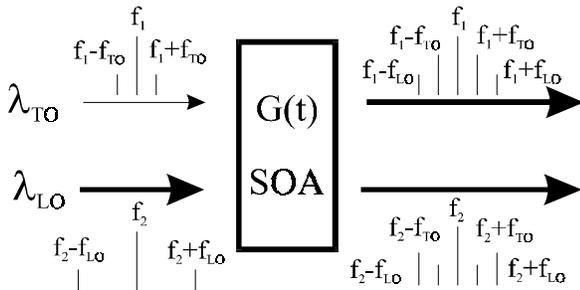


Fig. 1 - Block diagram showing the SOA mixing property.

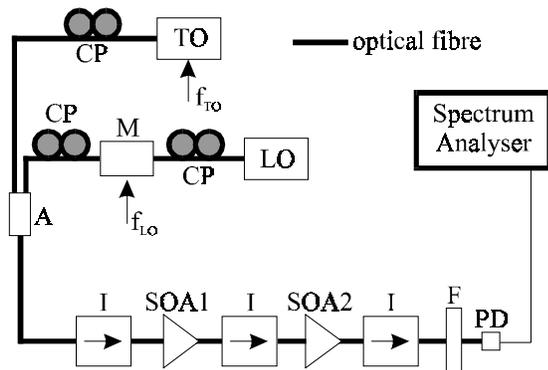


Fig. 2 - Block diagram of the cascaded SOA set-up. TO: transmitter laser; LO: local oscillator laser; M: optical modulator; CP: polarization controller; SOA1 and SOA2: semiconductor optical amplifiers; A: fiber coupler; I: isolators; F: optical filter; PD: photodetector.

Fig. 3 shows the block diagram of the optically feed-backed SOA experiment. In comparison with Fig. 2, the modifications in the experimental set-up take place after the fiber coupler A, now referred as fiber couple A1. Both modulated signals pass through the fiber couplers A1 and A2, and are coupled into the SOA. The mixed signal at the SOA output is re-injected into the SOA for new amplification and enhancement of the mixing process after A3, the isolator I, and, again, A3. Then, the optical signal passes once more through A2 and is coupled into an optical filter centered at f_{TO} . Finally, the filtered optical signal is photodetected. The photocurrent produced is amplified and coupled into a spectrum analyzer.

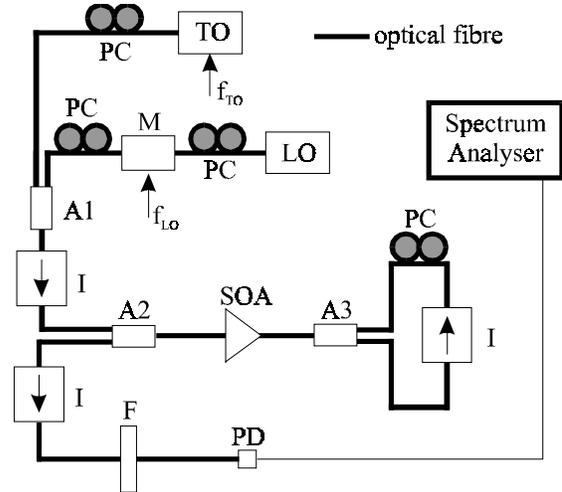
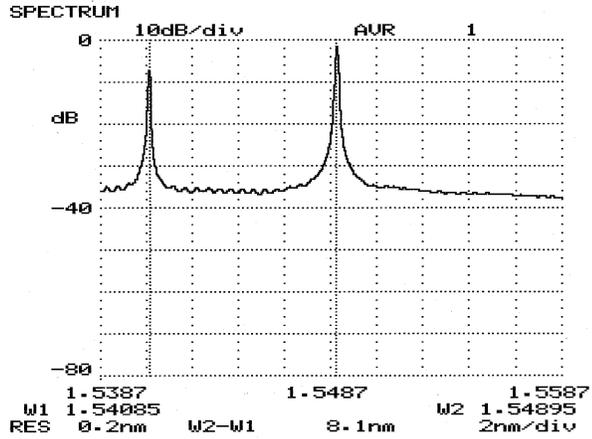


Fig. 3 - Block diagram of the FB-SOA set-up. TO: transmitter laser; LO: local oscillator laser; M: optical modulator; PC: polarization controller; A1 to A3: fiber couplers; SOA: semiconductor optical amplifier; I: isolators; F: optical filter; PD: photodetector.

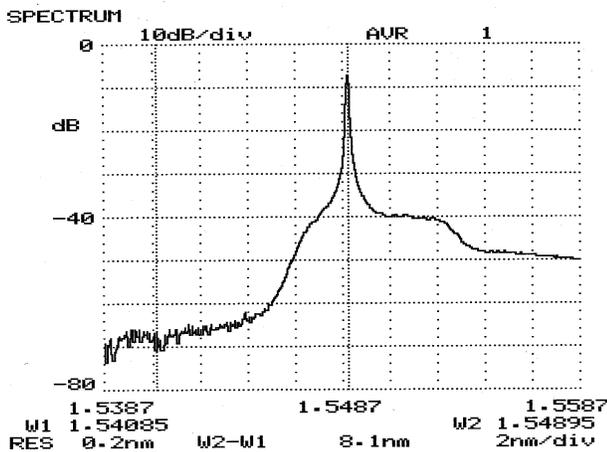
3. EXPERIMENTAL RESULTS

The TO laser source was a pigtailed non-tunable external cavity semiconductor laser (E-Tek Ind.) operating at $\lambda_1 = 1548.95$ nm and at a bias current of 120 mA. This laser was directly modulated at $f_{TO} = 250$ MHz by a Wavetek 2500A signal generator. The LO laser source was a pigtailed tunable external cavity semiconductor laser (Photonetics) with operating wavelength set 8.1 nm apart from λ_1 , that is, at $\lambda_2 = 1540.85$ nm. The LO bias current was 60 mA and its output signal was modulated by an external modulator (Sumitomo Inc.) at $f_{LO} = 400$ MHz using a HP 8657A signal generator. During the two experiments, the SOAs (E-Tek Ind.) were biased at 120 mA. It is necessary to point out that each SOA bias was set at the maximum value recommended by the manufacturer. This limited any further non-linear desired contributions other than the deep saturation on the mixing process. A 300kHz-6GHz photodetector (HP 83411A) was used to detect the optical signals after the 6-nm bandwidth optical filter centered at 1550 nm. Fig. 4(a) shows the optical spectrum for both signals before the optical filter. The optical spectrum analyzer markers indicate the 8-nm distance between the carriers. Fig. 4(b) shows the optical spectrum after the optical filtering. The optical filtering was used at the

photodetector input as a way of preventing any excessive noise contributions from the LO signal (e. g., RIN) and the SOAs (e. g., amplified spontaneous emission) into the generated up and down converted signals. Limitations in the direct modulation response of the TO laser prevented higher optical carrier modulation frequencies than the value listed above.



(a)



(b)

Fig. 4 - Optical spectrum for both the TO (1548.95 nm) and LO (1540.85 nm) signals before (a) and after (b) the optical filter.

By referring back to Fig. 2, in order to observe the implications of employing cascaded SOAs in RF and microwave signal generation, an experiment was firstly conducted using only SOA1. Fig. 5 shows the measured power spectrum of the photodetector signal, where it is possible to observe six main frequency components. The highest level harmonics correspond to the TO and LO modulation frequencies (~ 48 dBm and ~ 50 dBm, respectively) at 250 e 400 MHz. A second harmonic for f_{TO} is also present in Fig. 4 (~ 78 dBm), due to the direct laser modulation and the characteristics of the modulation source. The upper and down-converted components at 650 MHz and 150 MHz, respectively, presented considerably lower power levels

than those of the modulation harmonic frequencies (over 35 dB less). It is believed that the amount of optical power coupled into the SOA was insufficient for its proper saturation, which lead to a poor mixing effect. However, the SOA mixing effect was proved to be responsible for the up and down-converted components as both disappeared from the spectrum when SOA1 was removed from the experiment. Finally, a frequency component next to the 150 MHz (right) was also detected. It is believed to be a noise signal, as it was present when no signal was coupled into the spectrum analyzer. Fig. 6 shows the power spectrum after the addition of SOA2. The use of cascaded SOAs tends to improve the mixing effect as deeper saturation can be reached. As a result of the enhanced saturation condition, the second SOA amplifies more dynamically the less intense harmonics of the optical signal. By comparing Fig. 6 with Fig. 5, it can be seen that the up and down-converted components were amplified by around 20 dB after SOA2. Thus, the addition of extra SOAs could additionally increase the power level of the up and down converted signals, mainly the latter one, which is of greater interest for microwave and/or RF applications.

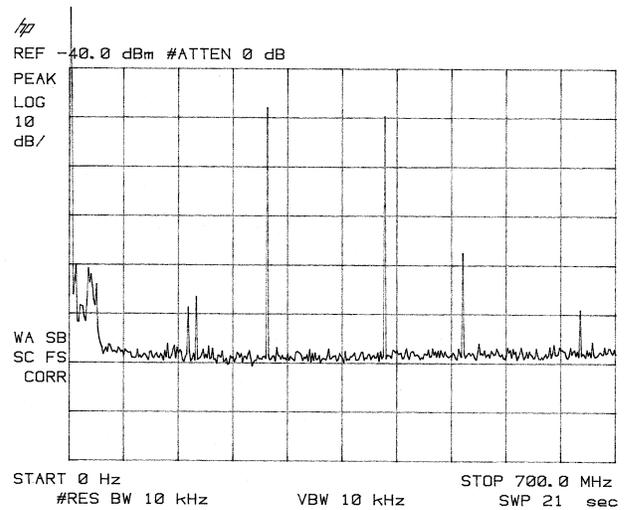


Fig. 5 - Photodetector output signal spectrum for the 1-SOA system.

By referring back to Fig. 3, Fig. 7 shows the power spectrum of the photocurrent for the FB-SOA experiment. Despite the use of only one SOA in the optical feedback arrangement, the up and down converted frequencies harmonics are present in Fig. 7 and have higher power levels (~ 73 dBm and ~ 80 dBm, respectively) than the 1-SOA experiment results shown in Fig. 5, suggesting a improved performance.

By comparing Fig. 6 and 7, it is possible to verify that the up converted harmonic power is around 3 dB lower than the result obtained in the 2-SOA experiment. Also, the fundamental frequencies at 250 and 400 MHz in the FB-SOA case presented lower values than those observed for the same frequencies in Fig. 6. These results may imply that the FB-SOA configuration can only offer better results when compared to the 1-SOA case. However, it is necessary to point out that a considerable amount of optical power was lost in the fiber couplers. Compared with the 2-SOA experiment, there were a 3 dB loss in A2 and a 6 dB loss in A3, which contributed to minimize the SOA cross-gain

saturation effect, and a 3dB loss in A2, which is responsible for lower power levels reaching the photodetector. As a consequence, it is expected the fundamental frequencies and the components $f_{LO} + f_{TO}$ and $f_{LO} - f_{TO}$ to have lower power levels. Modifications in the experimental set-up could lead to an improved system power management. For instance, an optical circulator could replace the fiber coupler A2, providing an extra 3dB for both the SOA saturation process and the photodetection. Also, the coupler A3 could be replaced by a mirror, resulting in a 6 dB excess power for the SOA cross-gain effect.

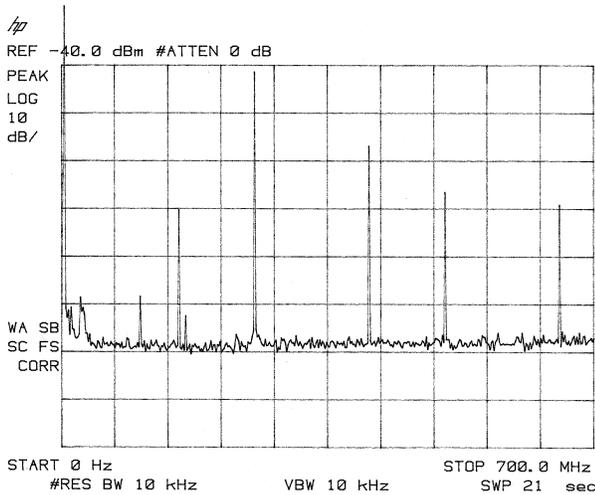


Fig. 6 - Photodetector output signal spectrum for the 2-SOA system.

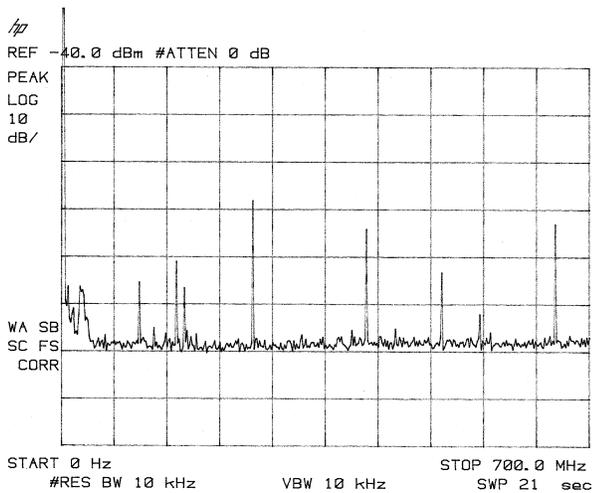


Fig. 7 - Photodetector output signal spectrum for the FB-SOA experiment.

The measured phase noise of the up-converted signal is better than -70 dBc/Hz for a 100 kHz offset. This measurement was limited by the noise floor of the spectrum analyzer. The harmonic amplitude was seen to be susceptible to the laser amplitude oscillation (RIN noise and feedback phase interference due to thermal variations). Also, frequency jittering

was observed. Therefore, the quality of the converted signal relies not only on the improvement of the experimental set-up, as mentioned before, but also on quality of the optical sources employed.

4. CONCLUSIONS

It was shown that it is possible to improve the mixing properties of SOAs for the generation of RF and microwave signals by using them in an optical feedback configuration. In this case, the use of only one optically feed-backed SOA can improve the power levels of the up and down converted frequency components in comparison to the equivalent 1-SOA experimental results.

By comparing the FB-SOA and the 2-SOA experiment, it can be noticed that the former has the potential to produce superior results when compared with the 2-SOA cascaded configuration, if the original experimental set-up of Fig. 3 is remodeled. Suggestions are the inclusion of an optical circulator and a SOA feedback mirror. Also, the TO modulation frequency used in the experiment was limited by the amplitude modulation response of the directed modulated laser. For higher up-converted harmonic frequencies, it is recommended the use of a second external modulator.

The techniques described above can be applied in systems that use optical fibers to carry information that will be lately converted in electronic signals within the RF and microwave range. However, the use of SOAs for signal generation may still be delayed by device costs and coupling power limitations. Fortunately, long term projections predict that SOAs are liable to become less expensive components with improved anti-reflection coating power limitations. The simplicity of the FB-SOA technique, though, can compensate for the number of SOAs used in cascaded configurations providing, potentially, the same results.

The authors would like to thank CNPq, CAPES, FAEP/UNICAMP, FAPESP, and MCT-Pronex, Brazil, for the financial support.

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