Linearity and chirp investigations on Semiconductor Optical Amplifier

as an external optical modulator

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This paper provides an overview of the basics and application possibilities of the multifunctional Semiconductor Optical Amplifier (SOA) in Sub-Carrier Multiplexed (SCM) systems. The paper focuses on the linearity investigation of the device. It describes the frequency dependence of the modulation and the harmonic products, the effects of the bias current and the optical power, the mismatch between the light and the electrical signal, the temperature and optical reflection sensitivity. It is shown by numerical simulation and measurements that by using SOA as an external modulator, the device provides acceptable nonlinear distortion for SCM telecommunication systems. Finally, the frequency chirping in external SOA modulator is treated for different operation conditions.

1. Introduction

Optical sub-carrier multiplexing (SCM) is a scheme where multiple signals are multiplexed in the radio frequency (RF) domain and transmitted by a single optical wavelength. The sub-carriers usually are in the range of the microwave and millimeter waves, because the optically transmitted channels are converted into/from the RF domain. There are combined system, which utilize both baseband and subcarrier signals.

The literature suggests the application of SCM in several systems for transmission and distribution the microwave or millimeterwave signals. A popular application of SCM technology in fiber optic systems is analog cable television (CATV) distribution. Typical application is the remote antenna feeding in radar systems, where the high frequency signal must be transmitted to the antenna with low loss.

SCM has also been proposed to transmit multi-channel digital optical signals using direct detection for local area optical networks, microwave signal distribution in picocell-based communication systems, combined wireless data communication systems. SCM is used in the picocellular wireless (possibly mobile) telecommunication systems, where several radio channels are needed in certain cells. In the fiber-radio systems the huge bandwidth of the optical transmission allows the radio frequency carriers to be directly transported over the optical fiber without the need for frequency conversion or multiplexing/demultiplexing functions. Therefore, complex processing equipment can be located in a local exchange, thus simplifying field installation and maintenance procedures. The system is very flexible, it can easily be extended to contain more terminals, the number and frequency of subcarriers can be modified according to the traffic.

In the complex systems the baseband signal is transmitted in parallel with the subcarrier information. The photonic switched networks with label on subcarrier utilize both baseband and subcarrier information. A baseband digital label is modulated onto a RF subcarrier and then multiplexed (electronically or optically) with the baseband packet on the same wavelength.

Current technologies utilize several separate optical elements in the presented systems. It would be beneficial if a multi-functional optical element were provided to reduce number of the components, size, maintenance, production costs and complexity. However, the inherent design trade-off between different functions demands more advanced design. The special devices have better parameters than the multifunctional device. The degradation has to be minimized, hence the study of the potential multifunctional devices is very important.

2. The Semiconductor Optical Amplifier

The Semiconductor Optical Amplifier is based on the same technology as a semiconductor laser diode, but the cavity reflections are blocked by using antireflection techniques. So, the SOA is a semiconductor based, small size, potentially cheap, electrically pumped device, which has large optical bandwidth. Moreover, the semiconductor technology offers a wide flexibility in the choice of the operating wavelength by just appropriately choosing the material composition of the active layer. The small size and compatibility with semiconductor laser sources and semiconductor detectors offer the possibility of photonic integration with other active or passive optical components.

It amplifies the incoming weak optical signal directly in the optical regime without any optical-electrical, electrical-optical conversion. The stimulated emission provides the amplification, the absorption means optical loss, the spontaneous emission is the source of noise. It is a random process, which is statistically stationary and will cause fluctuations in both amplitude and phase of optical signal. The operation can be described by the multimode rate equations, like semiconductor lasers. However the total carrier density is time and spatial dependent and a term for the optical injection is added.

The operation of the multifunctional SOA-modulator is based on the following phenomenon. The electrical bias current of the SOA is modulated, therefore the material gain is modulated, and consequently in case of continuous wave input the intensity of the output power is also modulated [1]. If small signal sinusoidal current modulation is considered, the electrical signal consists of an invariant and a sinusoidal modulation parts, hence the number of carriers and photons are also time dependent and the shape of these parameters are similar to the shape of the modulation [2]. The device amplifies the incoming optical signal and adds an intensity modulated component. The intensity modulated optical signal can be detected by traditional pin photodiode. The magnitude and purity of the signal depend on the modulation signal, the bias current, the input power and the operation parameters of the SOA [3].

The SOA modulator requires low modulation power, the detected electrical power is high because of the optical gain of the SOA in contrary to the optical insertion loss of other external modulators. In SOAs the gain dynamics are determined by the carrier recombination lifetime (few hundred picoseconds), hence the modulation bandwidth is limited by the electrical circuits. However, the SOA has remarkable optical noise and the optimal operation demands more advanced amplifier-modulator working state planning.

The SOA can provide the branching function in the SCM systems. It operates as a modulator to add a new channel, as a detector to drop the needed channel and as an in-line amplifier to amplify the other channels, simultaneously. It realizes a compact, small size and cost-effective radio repeater for signal distribution [4]. The achieved functions are similar in Fiber-to-the-Home Networks, where simple optical network unit is needed for the customer [5].

The compact SOA-modulator can solve the optical sub-carrier label swapping problem in sub-carrier label packet switched all optical systems. The wavelength conversion and all-optical regeneration can be achieved through cross-phase modulation (XPM) performed in a SOA based active Mach-Zehnder interferometer. Current modulation of the SOA in one or both arms of the wavelength converter is used to add the new label [6].

3. Linearity investigation

Cascadability is critically important in optical SCM networks where several electrical subcarriers are transmitted on the same optical signal. Degradation of the transmission system will occur due to the crosstalk between the subcarriers (nonlinearity) and noise expansion (ASE) [7].

The traditionally used electro-optical modulator shows high nonlinearity, because it has a cosine type characteristic. The photo-detector and the optical fiber can be treated as near linear device. The SOA-modulator can improve the nonlinear behavior of the system, if it provides lower nonlinear distortion than the electro-optical external modulators.

The second and third order intermodulations will be considered, because of the crosstalk between the channels and the partial up-conversion of the baseband payload into the subcarrier. As the number of subcarriers increases the linearity becomes a more and more serious problem because many third order mixing products appear in the used band.

3.1. Simulation results

The SOA model uses a pair of coupled partial differential equations, the wave and the rate equations. The model takes into account the detailed nonlinear carrier recombination rate:

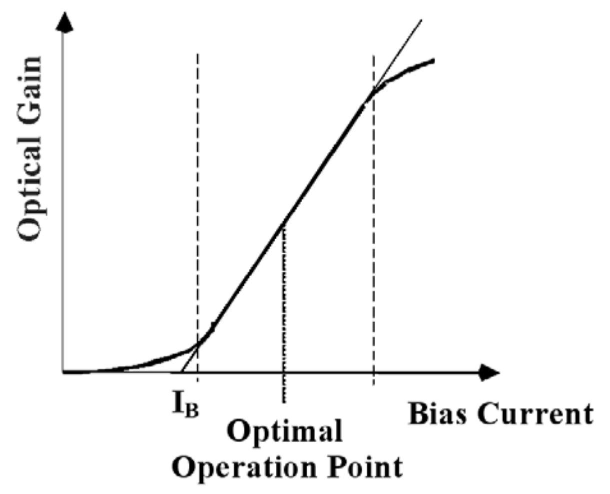
$$R(N) = A \cdot N + B \cdot N^2 + C \cdot N^3 \tag{1}$$

Here *N, A, B,* and *C* are the spatial dependent carrier density, the non-radiative recombination rate, the radiative recombination coefficient and the Auger recombination coefficient, respectively.

The carrier density is obtained by solving the spatial dependent rate equation, and the propagation of the electromagnetic field inside the amplifier is governed by solving the wave equation. The time dependent amplifier's output power is calculated by solving numerically the coupled rate and wave equations.

There are two types of the nonlinear distortion of the SOA [8]. The static distortion is caused by the nonlinearity of the amplifier output power-current curve under continuous wave condition. The dynamic distortion is caused by signal-induced carrier density modulation. During the simulation the nonlinearity of the amplifier is characterized by using a single tone modulation. The static distortion is calculated directly from the optical gain – current curve [9] shown in *Figure 1*.

Figure 1. Static distortion, optimal bias point of SOA



The main objective is to select the most linear region of the curve over a wide bias current range, and then to place the dc operating point roughly at the middle of this region. It is strongly dependent on the input optical power.

With the optimal operation conditions, the calculated values of the static nonlinear distortions are less than the dynamic distortions, hence static distortions will not be taken into account.

The dynamic nonlinearity is calculated by numerical analysis of the output optical power. *Figure 2* represents the optical power (Pdc, broken line), the signal levels for the fundamental (P1), the second (P2) and the third (P3) order harmonic products versus the bias point. The operation is strongly nonlinear near the threshold. As the bias current increases the modulation product becomes constant, but the value of the harmonic products decrease significantly.

Figure 2. Dynamic distortion products versus bias point

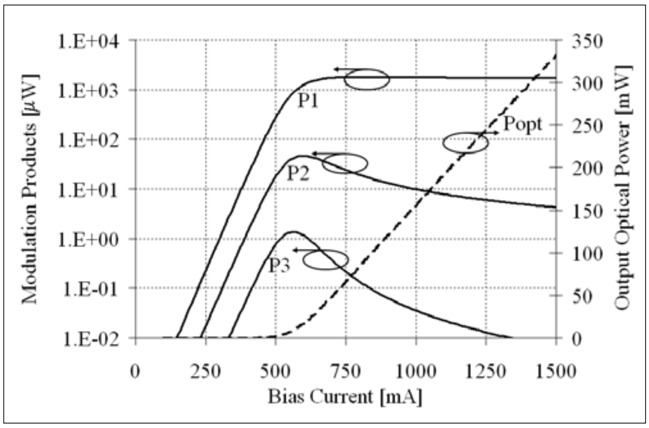
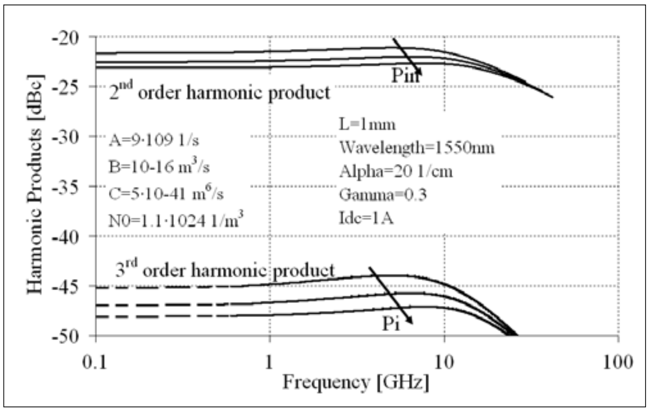


Figure 3 shows the relative second and third order harmonic distortion as a function of the modulation frequency for various input optical powers. The input optical power will not affect the relative value of harmonic products when the level of the input optical power is very low. The nonlinearity can be improved when the input optical power increases, because of the saturation effect *(Figure 4)*. The simulation results show that the nonlinearity can be improved, but the modulation efficiency decreases in the saturation regime.

Figure 3. Second and third order harmonics



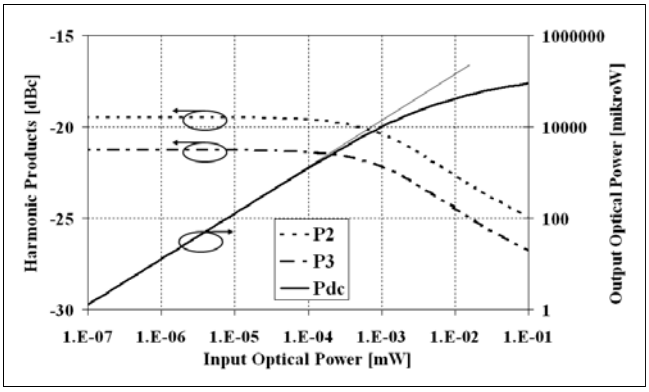
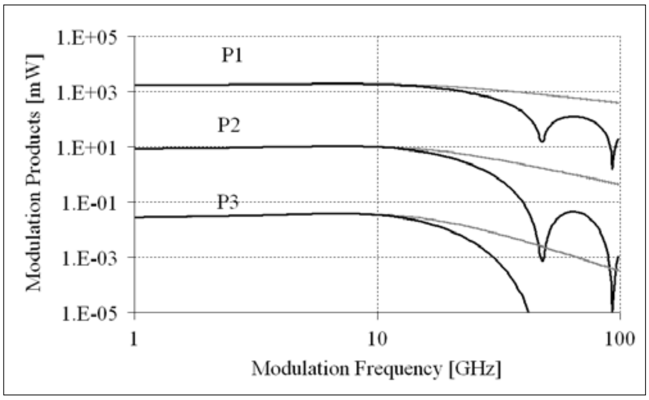


Figure 4. Saturation effect

The previous model assumed that the velocity of the traveling microwave signal was matched exactly with that of the optical signal. The next model applies to a more realistic situation where the current modulation propagates with a speed different from the optical signal. The phase velocity of the microwave is in the range of 7-12% of the velocity of light in vacuum for frequencies in the range of 5-40 GHz [10].

Thus the phase index for the microwave propagation on the electrode (n_μ) is in the range of 14.3-8.3. *Figure 5* shows a calculation for harmonic products in case of the typical co-propagating effect (n_μ=10) compared with the matched situation. The mismatch leads to dips in the modulation response and reduces the modulation bandwidth, but the bandwidth remains in the range of 10 GHz because of the SOA's rapid response time.

Figure 5.
Mismatch between the microwave and the light propagation velocities



3.2. Experimental results

In the two-tone inter-modulation experiments the SOA was biased and modulated by the sum of two microwave signals. The output noise (P_{noise}) and signal levels were measured for the fundamental (P1), the second (P2) and the third (P3) order mixing products. For characterizing the level of third order nonlinearity, the third order intercept point, IP3, or the spurious suppression in dBc is used. When the nonlinearity is investigated together with noise, the figure of merit is the spurious free dynamic range, SFDR. The determination of SFDR, IP2 and IP3 are presented in (2) and *Figure 6*.

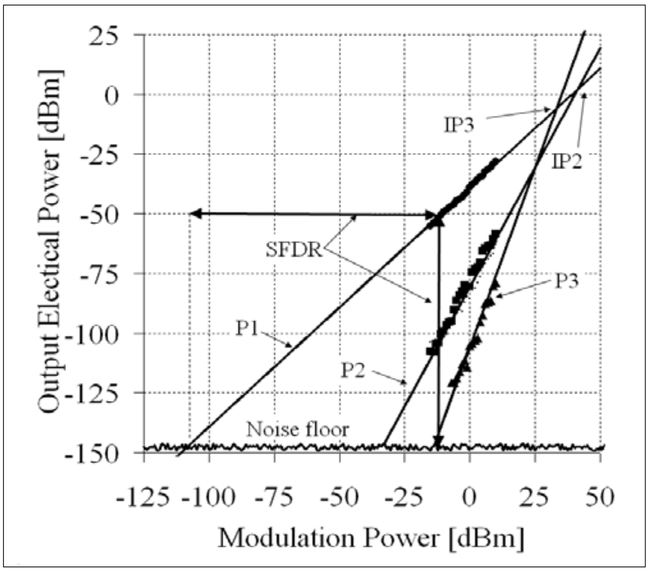


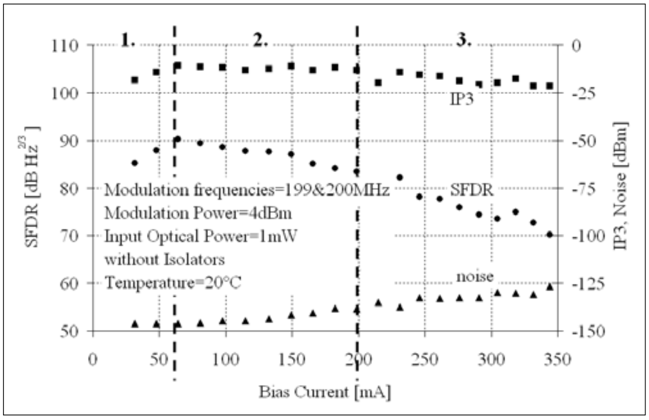
Figure 6. Determination of SFDR, IP2, IP3

$$
\begin{aligned}
SFDR &= \frac{P_{in}(P_3 = noise)}{P_{in}(P_1 = noise)} = \frac{P_1(P_3 = noise)}{P_{noise}}\\
IP2[dBm] &= 2\cdot P_1[dBm] - P_2[dBm]\\
IP3[dBm] &= \frac{1}{2}\cdot\left(3\cdot P_1[dBm] - P_3[dBm]\right)\\
SFDR[dB] &= \frac{2}{3}\cdot\left(IP3[dBm] - P_{noise}[dBm]\right)
\end{aligned}
\qquad (2)
$$

In the linear regime the SOA modulator shows low, not measurable nonlinearity because the noise generated by the SOA will dominate in the system. The intermodulation products overcome the noise floor in case of high modulation indices. The device ensures efficient SFDR for the general optical networks (>90 dB).

Figure 7 shows the noise level, IP3 and SFDR versus SOA working state. The results show that in the first part of the graph the device is strongly nonlinear. The IP3 and the SFDR improve versus the bias current. In the second part the modulation and inter-modulation products do not change significantly but the noise level rises, hence the SFDR decreases. Finally, the inter-modulation products also start rising and the degradation of the SFDR is faster.

Figure 7. Nonlinear behavior of SOA modulator



The nonlinear behavior is also temperature sensitive, because the operation of semiconductor devices depends on the temperature. *Figure 8* shows the SFDR and the IP3 versus temperature. From the measurement results, it is clear that the linearity decreases when the temperature increases, hence temperature control is needed.

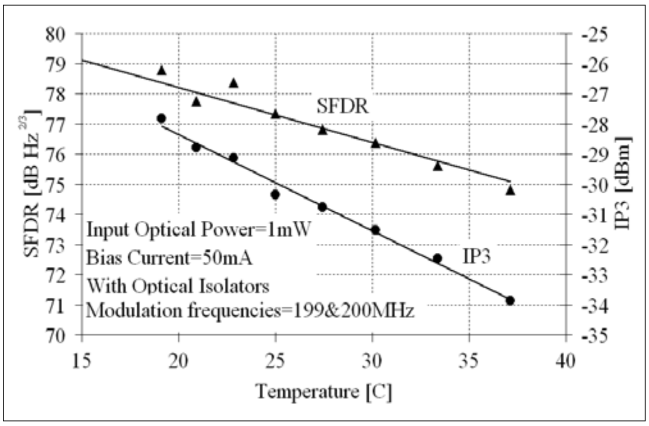


Figure 8. Nonlinearity depends on the Temperature

The noise effect and the nonlinear distortion products are more significant in case of strong optical reflection level, i.e. without optical isolators. The system will be more instable in case of strong optical reflection, and larger SFDR degradation can be observed as seen in *Figure 9 (on the next page).* The change of the SFDR is caused by two different effects. First the noise level of the device increases as a function of the bias point, the degradation is more significant without optical isolator *(Figure 10).* On the other hand the level of the nonlinear product will fluctuate in case of strong optical reflection *(Figure 11).*

4. Chirp investigation

Frequency chirping, that is the change in the instantaneous frequency of the optical signal, is produced by semiconductor devices under pulsed or modulated operating conditions

In the direct modulation of a semiconductor laser, the frequency chirping is caused by the refractive index change of the active layer due to the carrier density modulation. The change of the optical cavity modifies the frequency of the generated optical signal. In case of SOA-modulator the fluctuation of the bias current modifies the value of the carrier density (and the refractive index) and changes the transmission speed. Therefore, it causes phase variation of transmitted light through the modulator together with intensity modulation.

The refractive index can be modeled using the chirp parameter (Linewidth Enhancement Factor = LEF = Henry factor = α factor) approximation. The LEF was originally defined as the ratio of the changes of the real to the imaginary part of the material refractive index [11].

In case of small signal modulation, assuming that the carrier density change (ΔN) is uniform in SOA, for a pure

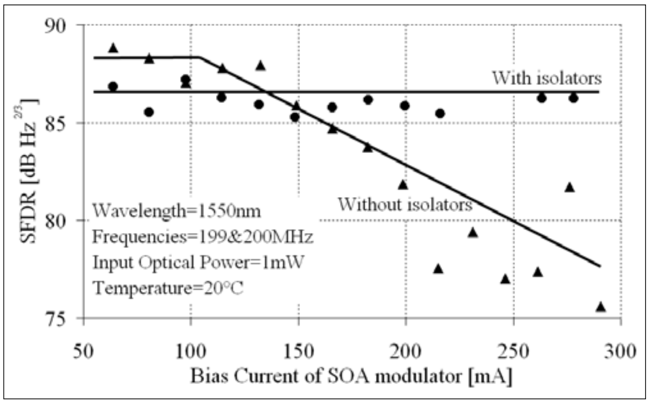


Figure 9. SFDR depends on the optical reflection

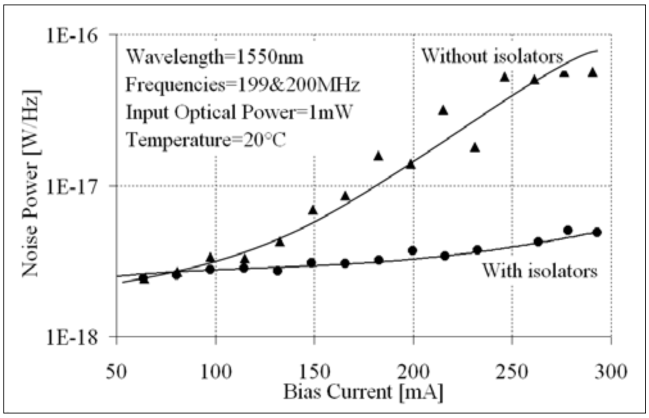


Figure 10. Noise level depends on the optical reflection

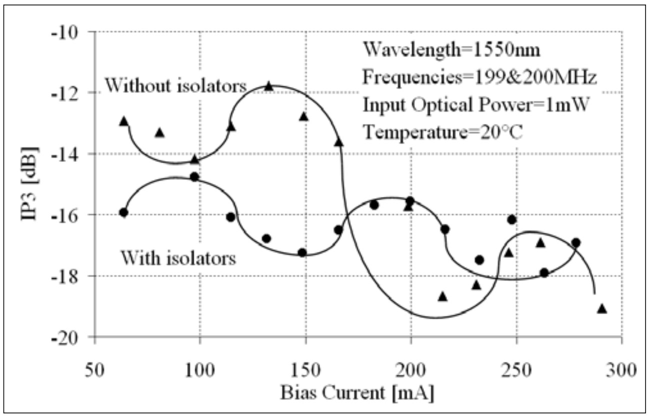


Figure 11. Nonlinearity depends on the optical reflection

traveling-wave amplifier (the facet reflectivity is ignored) the relative AM response becomes independent of LEF, the PM response becomes proportional to LEF, and the ratio of PM to AM reduces to LEF /2 [12].

$$AM = \frac{\Delta G}{G} = \frac{dg}{dN} \cdot L \cdot \Delta N$$

$$PM = \Delta\Phi = -\frac{dk}{dN} \cdot L \cdot \Delta N = \frac{LEF}{2} \cdot \frac{dg}{dN} \cdot L \cdot \Delta N \tag{3}$$

$$LEF = -2 \cdot \frac{2 \cdot \pi}{\lambda_{in}} \cdot \left(\frac{dn}{dN}\right) \Big/ \left(\frac{dg}{dN}\right)$$

where G, ΔG, $\Delta\Phi$, L, g, N, n, λ_{in} and k are the optical gain, the perturbation of the optical gain, the perturbation of the output phase, the length, the material gain per unit, the carrier density, the refractive index, the wavelength of the input optical signal and the wave number, respectively.

Measurements of LEF can be found in the literature and show that LEF is not a constant factor but it is for instance a function of bias current, wavelength and input optical power. To obtain the total phase variation of the beam in a long SOA, we have to take the longitudinal variation of LEF into account. To solve it we can divide the active region into a large number of short sections. It means a quasi ideal situation: constant carrier density along the active region of the section length. The total amplitude and phase modulation can be calculated from the modulation product of the sections.

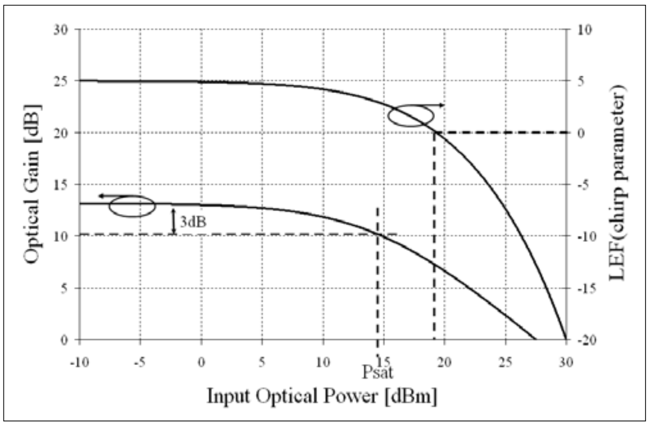
In the unsaturated region the LEF value ranges from 2 to 7 for GaAs and GaInAsP conventional lasers and from 1.5 to 2 for quantum well lasers [13]. However, as the optical input power increases, carrier depletion occurs in SOA and this induces gain saturation. In optical amplifiers under saturation conditions, an increasing input intensity causes a decrease in the amplifier gain ($dG/dP_{in}<0$). In this case LEF can be calculated from the unsaturated *LEF* value *(LEF_{unsat})*:

$$LEF = LEF_{unsat} \cdot \frac{dG}{dP_{out}} = LEF_{unsat} \cdot \frac{dG / dP_{in}}{1 + (dP_{out} / dP_{in})} \tag{4}$$

Due to this reason, the chirping parameter which is positive for light sources and unsaturated optical amplifiers is negative for saturated amplifiers [14].

Figure 12 represents the optical gain saturation and the LEF dependence on the optical power. When the input power becomes larger than the saturation value, the chirp parameter of the SOA rapidly falls to a negative value.

Figure 12. Optical gain saturation and the calculated chirp parameter



The amplitude and phase modulation indices are presented in *Figure 13*. Based on these results the modulation of the laser amplifier can also be made in such a way that, the PM response is suppressed. Beside frequency modulation, this method does also reduce the amplitude of intensity modulation of the SOA. Thus, near-pure AM can be obtained.

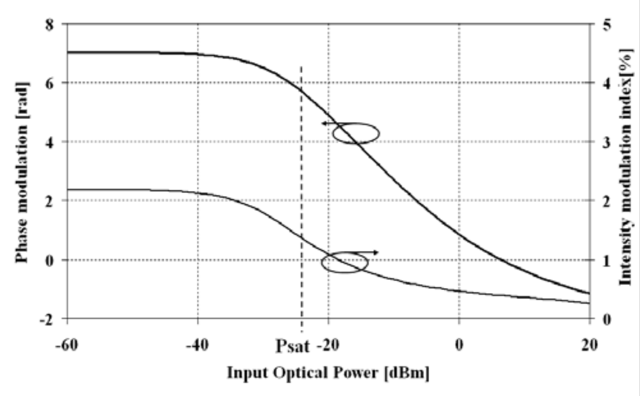


Figure 13.
Phase modulation and intensity modulation indices

5. Conclusion

The numerical simulation and experimental results show that SOA provides acceptable nonlinear distortion and the frequency chirp can be eliminated.

Applying the nonlinear carrier recombination rate, the simulation describes the frequency dependence of the modulation and the harmonic products, and the effects of the bias current and the input optical power. The model can take the mismatch between the light and the electrical signal into consideration, then the modulation bandwidth decreases. From the measurements it is clear that the dynamic range is temperature and optical reflection sensitive.

The modulation efficiency decreases and the nonlinearity can be improved when the input optical power increases, because of the saturation effect. The unwanted phase modulation decreases, because the line enhancement factor falls to the negative value.

The optimal operating point must be selected cautiously. The SOA is efficiently used as an external modulator in optical SCM systems.

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