Gain spectra and saturation power measurements in a two-section InGaAsP/InP semiconductor optical amplifier at 1.3 um

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We present a characterization method for on-chip gain and optical saturation measurements of 1300 nm band semiconductor optical amplifiers (SOA) integrated on InP. The SOA is divided into two electrically insulated sections each with a separate electrode using a 20 µm long isolation section in between. By changing the injection current density on one SOA segment and measuring the photocurrent in the second SOA segment, the gain spectra, the optical saturation power and the noise figure are determined.

Keywords: *Semiconductor optical amplifiers, Gain Saturation, InP, Bandwidth.*

1. Introduction

Semiconductor optical amplifiers (SOAs) are a critical component for many kinds of photonic integrated circuits (PICs). SOAs are often used to increase output power and to maintain sufficiently high signal levels as the signal propagates throughout many optical components [1]. Important parameters which describe the SOA are optical power gain and gain saturation power [2]. In separately packaged devices these parameters are also dependent on input and output coupling loss since they lower the fiber-to-fiber gain [3]. In this paper, we present a technique to measure on-chip the unsaturated gain and the optical saturation of a two-section InGaAsP/InP SOA with four quantum wells. In these devices one section is used as amplifier, and the other acts as a photodetector to collect the amplified photocurrent at different current densities and for several wavelengths inside the 1300 nm range.

2. Theory

A steady state model can describe the behavior of the SOA for amplification in one direction in terms of both a carrier and a photon density. The amount of photons inside the amplifier as function of time can be described locally at each position in the amplifier as [2]:

$$\frac{dP(x,t)}{dt} = v_g g(x,t) P(x,t) \quad (1)$$

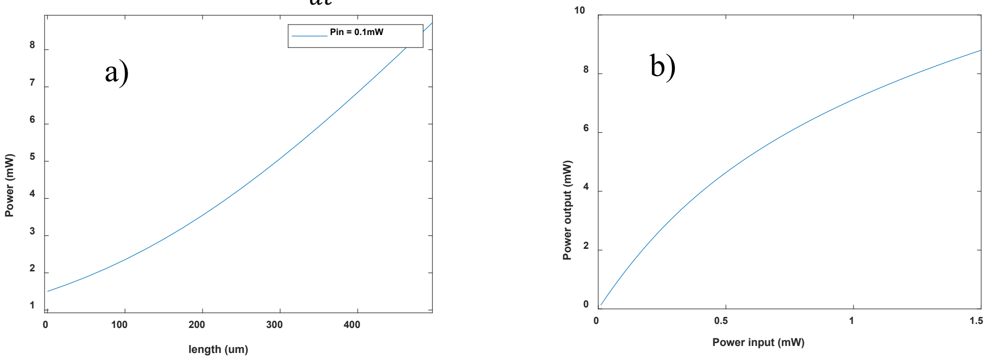

Figure 1: SOA output power as function of a) amplifier length and b) input optical power, for a current density J= 4kA/cm^2 and $\lambda = 1300$ nm.

where v_g is the group velocity and g is the net modal gain, which is dependent on the carrier density and the photon energy. In figure 1 a) and 1 b) numerical simulation results are presented of the output power of an optical amplifier, for a specific injected current density J=4 kA/cm^2, as function of its length and as function of input power. We can use a simple travelling-wave base model neglecting the amplified spontaneous emission (ASE), to model an optical amplifier under the condition of constant current density and free carrier absorption loss [4]. The material gain is described as a linear function of the carrier density and from the analysis of the carrier density rate equation at steady state it is possible to link the optical gain and the optical power as:

$$g = \frac{g_0}{1+P/P_s} \tag{2}$$

where g_0 is the unsaturated gain, function of the current density, and P_s is the saturation power which depends on the photon energy and the mode cross section and it is inversely proportional to the carrier lifetime and the differential gain [4]. As shown in Fig. 1b, the gain decreases below its small signal gain value as function of the external laser power. This happens when, for a sufficiently high input power P, the conduction band electron depletion inside the active region, due to the stimulated recombination with valence band holes, becomes significant at the back section of the SOA and saturates the optical gain, decreasing from the g_0 value. From a first order approximation of the photon density rate equation it is possible to get the gain factor G = P_{out}/P_{in} at the wavelength of maximum optical gain, as function of input light P [5]:

$$G \approx G_0 \frac{1 + P/P_s}{1 + G_0 P/P_s} \tag{3}$$

where $G_0 = \exp(g_0 L)$.
For P>>P_s the amplifier becomes transparent, and we can link $P_{in,s}$, which is the input power level at which the gain reduces to half of its unsaturated value, to P_s as:

$$P_{in,s} = \frac{P_s}{G_0 - 2}. \tag{4}$$

Equation 3 will be used in this paper to fit the experimental measurements and obtain the input saturation power of our amplifier for different current densities and wavelengths.

3. Device experimental setup

The active region of the SOA under test is grown on an n-doped InP substrate. It presents four compressively strained 5 nm wide quantum wells within an InGaAsP waveguide core with a 1.1 µm energy bandgap (Q-value). Both the material composition and the amount of strain were chosen to exploit gain at 1300 nm and make this active layer stack suitable for an active passive integration scheme with a low loss passive waveguide [6].
The device under test consists of two SOA segments that are electrically insulated from each other by different split electrodes; both the segments share the same active region and are separated by a 20 µm section where 1 µm of highest p doped InP is removed to ensure electrical isolation between the two amplifiers. The end facets of the chip are coated with an anti-reflection coating to increase the light transmission at the input and avoid the effect of back reflected ASE.

In Figure 2, a diagram of the experimental setup used to characterize the amplifier is shown. We inject light from an external laser and measure on chip the amplification as the input power is varied. Since the isolation section resistance is varying as function of both the input light and current due to carrier leaking between the two sections, the external laser is modulated at low frequency and a lock-in amplifier (LIA) is used to measure the photocurrent to increase the sensitivity of our measurements. Those measurements are referenced with respect to the photocurrent produced when the two sections are shorted, and the same reverse bias voltage is applied to both. An optical circulator is added at the input for connecting a power detector to perform fiber automated alignment routines [7] from the output power of the first section SOA.

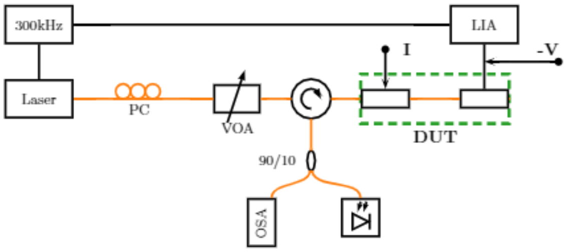

Figure 2: Schematic diagram of the experimental setup

4. Results

The amplifier behavior is observed using the photocurrent measured in the second amplifier segment as a function of the input current density on the first section. The photocurrent is then detected by the LIA, as voltage, after passing through a resistance in series. Figure 3 a) and b) show an example of the output signal together with the calculated net modal gain for input power levels between -15 and 5 dBm. The measurements presented in Figures 3 are obtained for an amplifier length of 620 um and at a wavelength of 1310 nm. In figure 3 a) we can notice a sudden change in the

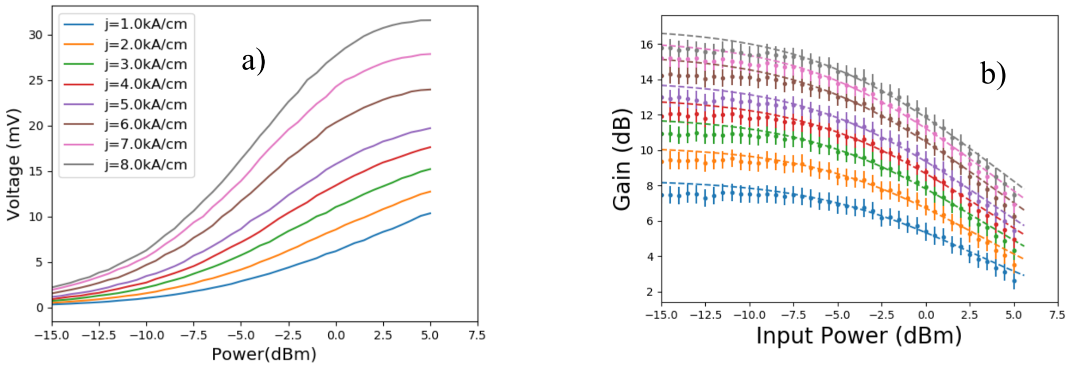

Figure 3: a) Example of the photocurrent signal detected at the lock-in amplifier and b) calculated logarithmic gain for an optical amplifier configuration of L=620 um and W=2.2 um at a wavelength of 1310 nm

exponential behaviour of the output voltage as function of the external light power, which indicates the presence of saturation. Figure 3 b) shows the gain saturation as function of input power in a logarithmic plot. As described in the previous section the saturation power is the input power that reduces the gain of half of its unsaturated value G_0, or of 3 dB in a logarithmic scale. The error bars of ± 0.5 dB represent the measurement error due to the uncertainty on the input coupling loss, on the length of the amplifier, and on the effect of the spontaneous emission noise. In figure 3 b) the dashed lines represent the fit of the experimental data with equation (3), which allows to extract the input saturation power $P_{in,s}$ and the linear amplification at very low input powers G_0. Figure 4 a) presents the 3-dB input saturation power, which decreases with increasing input current density.

When more carriers are injected in the active region, the input light experiences a higher modal gain in the first part of the amplifier which makes that the optical power affects the carrier density in the SOA faster and thus one observes smaller saturation input powers. Figure 4 b) shows the comparison between the small signal gain measured from the ASE in [6] and the unsaturated gain $g_0 = \ln(G_0)/L$, extracted from the saturation measurement fit with equation (2). We can observe that the values are comparable within

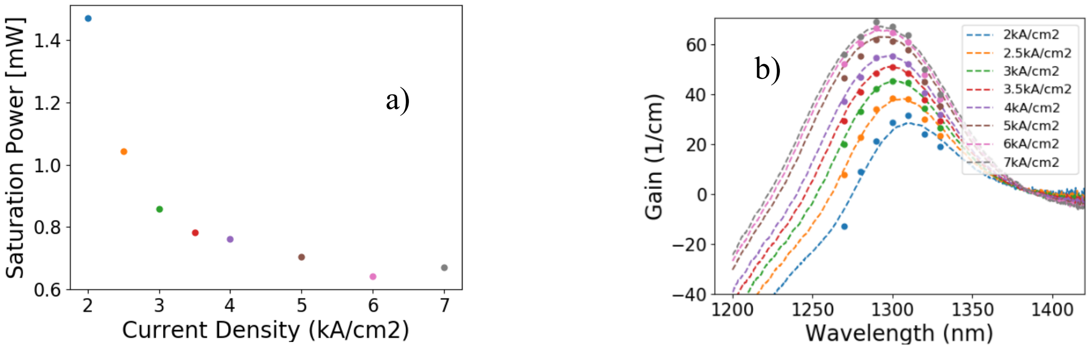

Figure 4 a) Input 3-dB saturation power and b) unsaturated gain spectra with this method (dots), compared with the gain spectra from the ASE measurements

a 5% error due to the different measurement techniques, and the uncertainty over the amplifier length. We suspect that at higher wavelength the error is bigger due to a smaller responsivity of the photodetector in that wavelength region, that has not been considered in the analysis.

5. Conclusions

In this paper we described a method to measure the unsaturated gain and the optical saturation of 1300 nm SOA with both on-chip light amplification and detection. This technique is promising since it can lead to a full on-chip amplifier characterization by having a tunable laser and an absorption modulator, used as an optical attenuator, together with this two sections device on a single photonic integrated circuit.

Acknowledgments

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