Gain Measurements of Fabry-Pérot InP/InGaAsP Lasers using an Ultra High Resolution Spectrometer

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In this paper we present the use of an ultra-high resolution (20 MHz) spectrometer to measure the gain in a Fabry-Pérot InGaAsP laser from subthreshold ASE spectra. The method is derived from the Hakki-Paoli method. A non-linear least-squares fitting of the observed modes is used to extract the gain from the line shape. Each mode of the measured spectrum is fully resolved and fitted separately. Thus the spectral gain curve is not restricted to a parabolic function. The optical gain spectrum and the differential gain are determined. These parameters will be used in our laser simulations.

Introduction

The optical gain of a semiconductor laser is an important parameter to characterize fabricated lasers and to simulate their behavior. The most common method to measure the gain in Fabry-Pérot cavities is the so called Hakki-Paoli method [1]. This method estimates the gain by the depth of the modulations in the Amplified Emission Spectra (ASE) caused by the Fabry-Pérot resonances of the laser cavity below threshold. Cassidy has first modified the previous method by introducing the ratio between the integral of the mode intensity and the minimum intensity. It makes the method less sensitive to the response of the Optical Spectrum Analyzer (OSA) but both methods are sensitive to the noise. Wang and Cassidy have recently proposed and demonstrated a method which is a non-linear least-squares fitting of the Fabry-Pérot equation [3]. By taking into account all the points of the spectrum, it improves the accuracy as compared to previous methods. However they had to introduce a correction to take into account the finite line-width of the OSA. In this paper measurements have been done using an ultra high resolution OSA (20 MHz). Thus the effect of the response function of the OSA does not need to be compensated. The optical gain spectrum and the differential gain are determined for a InP/InGaAsP laser structure. These parameters will be used in our simulation models.

Gain measurement method

The method is a non-linear least-squares fitting of each mode of the Fabry-Pérot equation in order to extract the gain parameter. The steady-state optical output spectrum of a Fabry-Pérot laser below threshold is described by the following Airy function equation.

$$I(\lambda) = B(\lambda).\frac{(1+R.G)\cdot(1-R)}{(1-R.G)^2 + 4.R.G.\sin^2(\frac{2\pi.n.L}{\lambda})} \quad (1)$$

Where *B (λ)* is the total amount of spontaneous emission represented by an equivalent input flux, *G (λ)* is the single-pass modal gain, *R* is the laser facet reflectivity, *L* is the cavity length and n is the group index of the waveguide. The equation to be fitted for each mode is rewritten and the background level is added (2). No convolution with the OSA response is necessary.

$$I_{fit}(\lambda) = \frac{C}{\left(1-P_{RG}\right)^2 + 4P_{RG}\sin^2\left(2\pi nL\left(\frac{1}{\lambda}-\frac{1}{\lambda_{peak}}\right)\right)} + BKG \qquad (2)$$

Where $C(\lambda) = B(\lambda)\,(1 + P_{RG})\,(1 - R)$, P_{RG} is the product of the laser facet reflectivity R and the single-pass optical gain G, λ_{peak} is the peak wavelength of the individual mode, BKG is the background level. We assume that $C(\lambda)$ and P_{RG} vary linearly with wavelength. Thus, the small asymmetry of the Fabry-Pérot modes due to the change of the gain with wavelength is taken into account.

The fitting is done with Matlab using the weighted non-linear least-squares fitting function *lsqnonlin* from the optimization toolbox. This algorithm is a subspace trust region method and is based on the interior-reflective Newton method. The weight used is defined in equation (3). $I(\lambda)$ is the measured signal intensity and σ_{BKG} the standard deviation of the measured background signal. The parameter ε is chosen in order to minimize the residue of the fit. The result from a test on a typical measured sub-threshold spectrum is plotted in figure 1. The minimum of the residue is for $\varepsilon = 0.14$.

$$weight(\lambda) = \frac{1}{\sqrt{\left(\varepsilon . I(\lambda)\right)^2 + \sigma^2_{BKG}}} \qquad (3)$$

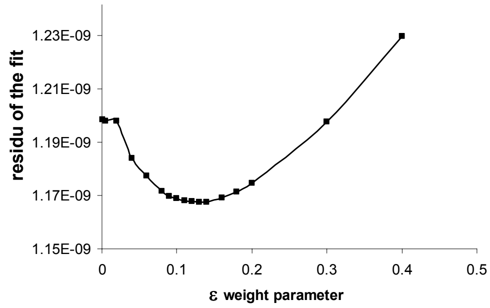


Figure 1: Calculated residue of the fit versus the ε weight parameter.

Gain curve measurements

The measurements were performed on Fabry-Pérot InP/InGaAsP ridge waveguide lasers. The SOA consists of a 120 nm thick λ = 1.5 µm bulk InGaAsP layer between two 190nm thick λ = 1.25 µm InGaAsP layers. The structure is clad by a 1500-nm thick p-InP layer with gradual doping levels and a 50 nm p-InGaAs contact layer. The cavity is 1985 µm long and the waveguide 2 µm wide.

The chip is fixed on a copper mount and the temperature of the chip is automatically regulated by a TEC (Thermo Electric Controller). Light is coupled out through a lensed fiber and led to an isolator and the high resolution OSA (APEX AP2041A). The OSA is based on an interferometer principle which enables the achievement of a resolution of 0.16 pm (20 MHz) and a wavelength accuracy of ± 3pm. Measurements of the spectra were done by windows of 5 nm (20.000 points). 5 or 6 windows were needed to rebuild an entire output laser spectrum. In order to obtain the gain as a function of the carrier density, measurements have been done for ten current values. All the measurements were performed below the lasing threshold, which is around 106 mA at 15°C and around 113 mA at 20°C. Typical measured and fitted spectra are plotted in figures 2 and 3. The spectrometer fully resolves the modes which are easily fitted with an appropriate weighing of the data.

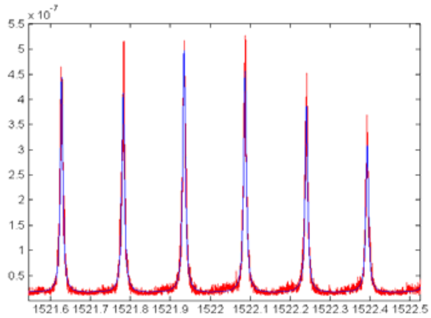


Figure 2: part of the measured and fitted spectra I=103.5mA T=15°C

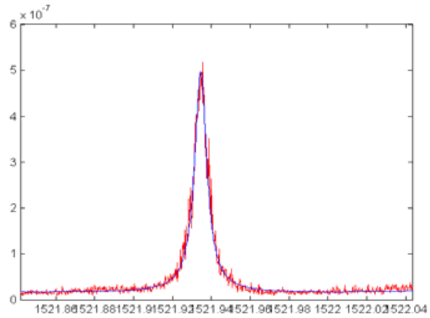
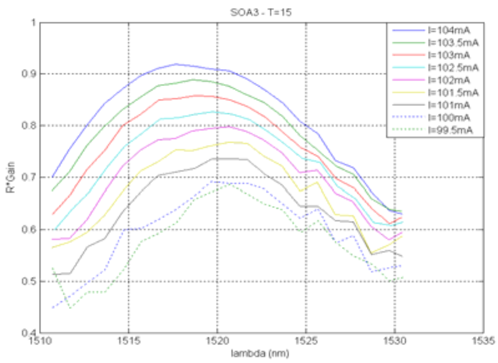
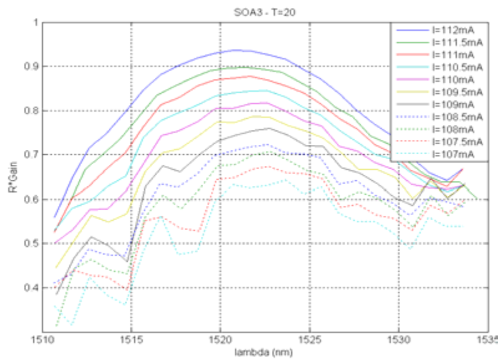


Figure 3: zoom on a mode of the measured and fitted spectra. I=103.5mA T=15°C

Once all the spectra are fitted, *R.G* products are plotted versus the wavelength and the injected currents. To improve the accuracy of the extracted differential gain per carrier, the curves have been smoothed over 6 modes (~ 1.0 nm). Results for T= 15°C and T=20°C are plotted in figures 4 and 5. The typical gain shape is observed. The gain peak wavelength shifts to the lower wavelengths with an increase in carriers. The bandwidth of the gain is slightly wider (~ 5%) at 20°C. The gain peak shifts over 3.5 nm from 20°C to 15°C. The sensitivity of the OSA is – 70 dBm, which limits the measurements of the *R.G* product below 0.5.





Figures 4 and 5: *RG* product versus the wavelength and current in the SOA for T = 15°C and T = 20°C

Differential gain measurements

The material gain (g_m) per meter for each wavelength is calculated from the previous curves. The total optical losses of the cavity (free carrier absorption within the active region, losses due to scattering and the two cleaved mirrors transmissions) and the confinement factor of the mode within the active layer are needed [1]. The material gain as a function of carrier density is approximated using a linear expression under small signal conditions:

$$g_m = \frac{dg_m}{dN}.(N - N_0) \tag{4}$$

Where dg_m/dN is the differential gain, N is the carrier density and N_0 is the transparency carrier density. In order to extract the differential gain value, a relation between the injected current and the carrier density is required. At subthreshold N could be extracted from the simplified rate equation (5).

$$\frac{N}{\tau} + B.N^2 + C.N^3 = \frac{I}{q \cdot S_{ActiveLayer} \cdot L} \quad (5)$$

Where τ is the carrier lifetime, B is the bimolecular recombination coefficient, C is the Auger recombination coefficient, I is the injected current, q is the charge of the electron, $S_{ActiveLayer}$ is the cross-section surface of the active layer of the SOA and L is the length of the SOA. Figures 6 and 7 show the results of the differential gain at 15°C and 20°C. The differential gain decreases with the wavelength. For T = 20°C the point at 1517.5 nm falls out of the trend. Indeed, P_{RG} values are below 0.5 and are not exact. At the gain peak the differential gain is $2.55.10^{-20}$ m² at 15°C and $2.25.10^{-20}$ m² at 20°C. These values are in good agreement with values reported in the literature for bulk InP/InGaAsP material [4-5].

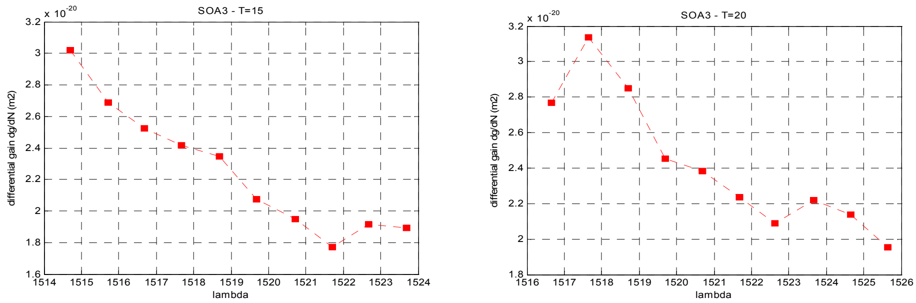


Figure 6 and 7: differential gain ($.10^{-20}$ / m²) versus the wavelength for 15°C and 20°C.

Conclusion

We report in the use of an ultra-high resolution (20 MHz) spectrometer to measure the gain in a Fabry-Pérot InP/InGaAsP laser from subthreshold ASE spectra. The method is based on a non-linear least-squares fitting of the observed modes. The spectrometer fully resolves the modes which could be fitted accurately. The optical gain spectrum and the differential gain have been determined. These parameters will be used in our laser simulation models.

Acknowledgments

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