Measurement of optical gain, effective group index and linewidth enhancement factor in 1.3µm dilute nitride double quantum well lasers

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Abstract
The net modal gain, effective group index and linewidth enhancement factor in edge-emitting InGaAsN/GaAs lasers have been determined as a function of both temperature and injection current from experimental amplified spontaneous emission spectra. The shift of the peak gain with temperature was found to be 0.49nm/K. Values of effective group index between 3.52-3.59 were measured, suggesting a relatively high refractive index of 3.75 for the dilute nitride quantum well. Linewidth enhancement factor values between 1.87-2.84 were measured.

1. Introduction
In recent years, the InGaAsN/GaAs material system has shown great promise as a potential low-cost replacement for the traditional directly-modulated 1.3µm InP-based devices used in access networks. The high band offset results in a large $T_0$ (181-266K [1]) and a small variation of lasing wavelength with temperature (typically less than 0.5nm/K [2]). As a result,
active cooling of such devices is not required, thereby reducing the total unit complexity and cost.

Several groups have reported on lasers based on this material system with performances that are now approaching that of their InP counterparts [1]-[4]. For example, Gustavsson et. al. [4] have achieved a 3dB modulation bandwidth of 17GHz at 298K and are capable of direct modulation up to 10Gb/s at a heatsink temperature of 383K.

In order to realize the full potential of these dilute nitride devices, further optimisation is required. This can best be achieved through the use of accurate and predictive simulation tools. These tools require accurate material parameters such as mobilities, effective masses and thermal conductivities to name but a few. Many of these parameters are available in the literature, but others which allow more detailed validation and calibration of the simulation tool can only be obtained from accurate device characterization. This work is concerned with the experimental determination of net gain, effective group index, shift in effective modal index and linewidth enhancement factor. The linewidth enhancement factor (LWEF) $\alpha$, often called the alpha or Henry factor, is defined as [5]

$$\alpha = -2k \frac{d n_{\text{eff}} / dn}{d g_{\text{eff}} / dn} = -2k \frac{A n_{\text{eff}}}{A g_{\text{eff}}},$$

where $n_{\text{eff}}$, $n$, $g_{\text{eff}}$ and $k$, are the effective index, carrier density, modal gain and free space wave-vector, respectively. The magnitude of the alpha factor is a measure of how dependent the effective index is upon the gain and as such is a measure of chirp [5]. The alpha factor is particularly important when modulating laser diodes – the larger the alpha factor, the larger the lasing frequency shift when directly modulated.

In this work, amplified spontaneous emission (ASE) spectra have been measured at the front facet of a series of 1.3µm dilute nitride lasers [6]. The below threshold ASE spectra have been used to extract the net modal gain, effective group index and shift in effective index all as a function of temperature and injection current. From these parameters, we then extract the linewidth enhancement factor using equation 1.

2. Device structure

The devices investigated are edge-emitting double quantum well lasers with 7nm $\text{Ga}_{0.613}\text{In}_{0.387}\text{N}_{0.012}\text{As}$ quantum wells (QWs), separated by 20nm of GaAs. The confinement regions on ether side of the QWs are 20nm thick and are surrounded by 160nm
graded Al\textsubscript{1-x}Ga\textsubscript{x}As cladding layers. The Al composition in the cladding layers is graded from 20 to 50\% [6]. The cap layer is 100nm of p\textsuperscript{+}-GaAs. The measured ridge width is 3.2\,\mu m and was formed by a 1.3\,\mu m deep etch. The facets were uncoated and were therefore assumed to have a reflectivity of \(R=0.32\) [7]. Two cavity lengths (500\,\mu m, 1000\,\mu m) were investigated.

3. Experimental method

A schematic diagram showing the key components of the measurement system is shown in Figure 1. The laser itself is mounted on a temperature controlled stage and current is applied via a computer controlled current source. The ASE is coupled into a single mode fibre connected to an optical spectrum analyser (OSA). The fibre is mounted on a three-axis stage with computer controlled piezo-electric actuators, allowing the collection efficiency to be automatically optimised. It was found necessary to automatically align the fibre before each measurement because of the thermal expansion of the equipment over the range of measurement temperatures.

Measurements were performed for each device at 300K, 320K, 340K, 360K and 380K, using the system shown in figure 1. Approximately ten bias currents per temperature were measured in 1mA steps, starting far below threshold and finishing slightly above. Spectra were measured over 80nm using 5000 sample points, the OSA had a resolution (FWHM) of 0.05nm and an optical reception sensitivity of –90 dBm.

3.1 Gain

The net gain was extracted from the ASE spectra using Cassidy’s method [8], an improvement on the Hakki-Paoli technique [9]. Cassidy’s method relies upon the ratio of the integral of a single Fabry-Perot mode to the mode minima whereas the Hakki-Paoli technique relies on the ratio of the mode peak to the mode valley. Cassidy’s method has two advantages over the Hakki-Paoli technique. Firstly, the mode sum is not affected by the spectral response of the system, so that the gain is less likely to be underestimated [8]. Secondly, the noise immunity is improved because the integral averages over \(N\) sampling points thereby reducing the noise by a factor of \(\sqrt{N}\). Cassidy’s method uses equation 2 to calculate the net modal gain

\[
g_{\text{net}} = \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right) + \frac{1}{L} \ln \left( \frac{\gamma_i - 1}{\gamma_i + 1} \right) \quad (2)
\]

where
\[ \gamma_i = \frac{\sum I(\lambda_i)}{N_{\text{min}} \cdot N}, \]  

(3)

is the ratio of the mode sum to the mode minimum. \( N \) is the number of sample points in the mode, \( I \) is a data point in the ASE spectra, \( R_1 \) and \( R_2 \) are the mirror losses and \( L \) is the device length. In order to evaluate equation 3, the position of the minima throughout the spectra must be found, they are identified by determining the points within the spectra at which the spectral gradient goes through zero.

Although Cassidy’s method has been shown to have a good immunity to system response, it is nevertheless known to slightly underestimate the gain [10]. Therefore the impact of the spectral response of the OSA on the measured gain spectra was investigated. An in-house simulation tool was used to simulate the ASE spectra expected at the front facet. The simulated spectra were then convolved with the measured system response. Using Cassidy’s method, gain spectra were extracted from both the convolved and unconvolved ASE spectra, which were compared to estimate the error that the OSA response introduces into the measurements.

The simulation tool used a 4x4 band \( \text{k.p} \) model [11] for the valance bands and a band anti-crossing model for the conduction band structure. The stimulated and spontaneous emission rates were calculated from the band structure using Fermi-Dirac statistics and Fermi’s golden rule [11]. The rates were then used to calculate the single pass ASE. Finally, a Fox-Li iteration scheme was used to model the full cavity. An accurate estimate of the OSA’s response was obtained by measuring the spectra of a DFB laser. A series of simulations were performed for different electron densities and different cavity lengths. From these comparisons, it was found that the worst-case error was 1.0cm\(^{-1}\) for the modal gain and 1.6cm\(^{-1}\) for the net gain.

### 3.2 Refractive indices

The effective group index, \( n_g \), was calculated using equation 4 [12]-[13]

\[ n_g = \frac{\lambda^2}{2L\Delta\lambda} \]  

(4)

where \( \lambda \) is the wavelength, \( \Delta\lambda \) is the mode spacing and the effective group index [13] is defined as
To calculate the LW EF the change in effective index as a function of bias current is needed. This can be calculated using equation 4 [12]-[14]

\[ \Delta n_{\text{eff}} = \frac{\lambda \Delta \lambda_s}{2L\Delta \lambda_m}, \]

where \( \Delta n_{\text{eff}} \) is the shift in effective index, \( \Delta \lambda_s \) is the mode spacing and \( \Delta \lambda_m \) is the shift in wavelength of the mode. To use equations 4 and 6 one needs to accurately find the position of the peaks in the ASE spectra. Due to the finite resolution of the OSA, there is often no data point exactly on the modal maxima, this produces uncertainty in its exact position. It is common to fit an analytical function to the data points within the mode and calculate the position of the maxima from the fit. However, any noise in the spectra can be problematic for the fitting algorithm, often producing a poor fit and false peak position. It was found that by using a weighted mean over each mode the peak position could be accurately and robustly extracted. The calculation used for this weighted mean is given by equation 7

\[ \lambda_{\text{peak}} = \frac{\sum N I(\lambda)\lambda}{\sum N I(\lambda)}. \]

The shift in refractive index as a function of bias current is obtained using equations 6 and 7.

Below threshold, changes in the effective index are dominated by changes in the gain. However, temperature induced effects also play a large role. For the calculation of the alpha factor, one is interested in the change of the effective index due to the changes in gain. In this, work, we follow Gerhard [15] to separate the two effects below threshold by recognizing that the gain clamps at threshold, so any changes in the effective index above threshold can be primarily attributed to thermal effects. The shift in effective index above threshold is then used to eliminate the thermally induced shift in effective index below threshold, so that only the gain induced change index change remains. This method assumes that the temperature rise due to current injection is the same above and below threshold. It was found experimentally that for the 500\( \mu \)m device the effective index increased above threshold at a rate of \( \frac{dn_{\text{eff}}}{dI} = 2.55 \times 10^{-2} \text{A}^{-1} \) at 300K and at a rate of \( \frac{dn_{\text{eff}}}{dI} = 2.8376 \times 10^{-2} \text{A}^{-1} \) at 320K.
These values were used to correct the effective index shift below threshold when calculating the alpha factor.

4. Results

The gain spectra were extracted from the measured ASE spectra using equations 2 and 3. Gain spectra as a function of current have been plotted for two temperatures in Figure 2. As expected, the gain spectra red shift as the temperature is increased due to the decrease of the band gap energy. Also as expected, the peak gain increases with bias current until it clamps at threshold. The peak gain wavelength has been plotted in Figure 3 as function of temperature and current density. A gradual blue shift in the peak gain can be seen due to band filling effects. As the temperature is increased, the peak gain wavelength red shifts at an average of 0.49nm/K as the QW bandgap energy decreases. This value is comparable to those commonly measured in more traditional InP-based devices 0.3-0.5nm/K. [17]

Using equation 4, the effective group index has been extracted as a function of temperature for the 500µm device at a constant current of 20mA. This is plotted in Figure 4, where the shift in effective group index due only to temperature effects can be clearly seen, values between 3.52-3.59 were obtained.

The experimental values of group index were compared to those predicted theoretically by a 2D mode solver. The refractive index values of AlGaAs are well known and were taken from Afromowitz’s work [18]. However, the refractive index of the dilute nitrides is less well known. In order to calculate the refractive index of the QWs, the simulated group index was fit to the experimental group index by varying the refractive index and dispersion (dnqw/dλ) of the dilute nitride QWs. The best fit was found for a refractive index of 3.75 and a dispersion of 3x10^6 m⁻¹. Although no experimental refractive index values for Ga0.613In0.387N0.012As exist, the value obtained by fitting is in line with the trends given in [19]. The calculated value of dispersion is higher than that measured in [19] since dispersion increases rapidly close to the band gap of the QW (the measurement in [19] was not performed close to the band gap). Furthermore, the measurements in [19] were preformed by spectroscopic ellipsometry of an unpumped surface layer, where as our measurements are performed on QWs electrically pumped close to threshold. Jin et.al. have previously reported on the effective group index of InGaAsN lasers [20], obtaining a higher value of 3.65. It has been reported that refractive index increases with nitrogen content [19]. Therefore, the higher nitrogen content of 1.8% in the QW and the introduction of nitrogen into the barriers [21] could be the cause of the higher effective group index reported in [20].

The shift in effective index as a function of bias current was calculated for the 500µm device using equation 6. The results are
shown in Figure 5. The results in Figures 5, 6 and 7 are all calculated relative to 17mA. Two effects can clearly be seen. As the current increases below threshold, the gain increases so that the effective index decreases. Then at 20mA the gain clamps and thermal effects start to dominate thus increasing the refractive index.

The gain and the shift in effective index have been calculated for a range of bias currents and the LWEF was calculated from these using equation 1. The LWEF is plotted in Figure 6 for the 500µm device at 300K. The alpha factors extracted at the peak gain position for two temperatures (300K and 320K) are plotted as a function of current density in Figure 7.

5. Summary
The modulated ASE spectra of a series of double quantum well InGaAsN/GaAs lasers have been measured and the gain extracted using Cassidy's method. The error introduced in the measurement system has been estimated by measuring the spectral response of the OSA used and convolving this with simulated ASE spectra. The resulting estimated worst-case error is 1.0cm⁻¹ for the modal gain and 1.6cm⁻¹ for the net gain. The shift of the peak gain with temperature was found to be 0.49 nm/K. This value is comparable to that of many other InGaAsN devices and is at the acceptability limit for telecommunication systems. Effective group index values between 3.52-3.59 were obtained. The effective group index was extracted and fit with the group index values obtained from a 2D mode solver; we calculate the refractive index of the QW to be 3.75 and the dispersion to be 3x10⁶m⁻¹. The change in effective index has been extracted and the linewidth enhancement factor found to be between 1.87-2.84.

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References


Figure 1: Block diagram of the experimental system.

Figure 2: Gain spectra for the 500µm device at 300K and 380K. At 300K, the lowest curve was produced with an injection current of 15mA. At 380K, the lowest curve was produced with an injection current of 20mA. The spectra are plotted for currents increasing in 1mA steps.
Figure 3: Shift of peak gain wavelength with effective current density and temperature.

Figure 4: Shift of the effective group index with temperature for the 500µm device at a constant bias current of 20mA.
Figure 5: Shift in effective modal index with current for the 500µm device.

Figure 6: Alpha factor for the 500µm device plotted for 300K. The crosses represent the position of the peak gain.
Figure 7: Alpha factor calculated at the position of the peak gain as a function of temperature and current density for the 500µm device.