Modal gain measurements in quantum dot amplifiers in the 1600nm-1800nm wavelength range

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We present results on modal gain measurements in InAs/InGaAsP/InP(100) quantum dot amplifiers in the 1600nm to 1800nm wavelength range. A modified gain measurement technique was used to determine the gain at different injection current densities. The modal gain is determined by measuring the amplified spontaneous emission (ASE) power from a series of two-section Fabry-Perot ridge waveguides with variable amplifier section lengths. The results show that this material can be used for tunable lasers with a tuning range of at least 100nm.

Introduction

In one of our projects we want to have a InAs/InGaAsP/InP(100) quantum dot optical amplifiers in the 1600nm to 1800nm wavelength range for the realization of an integrated tunable ring laser for a biophotonics application. These optical amplifiers should be suitable for use in InP based photonic integrated circuits (PICs) with active/passive integration [1] such as a modelocked ring laser [2] or an integrated multiwavelength laser [3]. For the design of a PIC with amplifier sections, detailed knowledge of the characteristics of the gain material is essential. Knowledge of the optical (modal) gain G as a function of wavelength and injection current is essential for the design of tunable lasers.

The optical gain is often determined with the well known Hakki-Paoli technique [4, 5] In the Hakki-Paoli method the optical gain is derived from the contrast ratio or shape of the modulations in the spectrum of the ASE caused by the resonances of the laser cavity operating below threshold. A drawback of this technique is that the spectral measurements have to be done with a high resolution spectrometer in order to resolve the spectral modes and not to distort the observed contrast ratio and/or linewidth of the modes. This is particularly an issue for amplifier sections of several millimeters, which are often required in case of a quantum dot amplifiers due to the relatively low modal gain of the quantum dot gain material. The Hakki-Paoli method is therefore not suitable anymore due to the small mode spacing. Another well-known class of techniques is to extract the gain from the ASE from multisection devices [6, 7]. The measurement technique on which we are reporting here is based on one of these techniques described by Thomson et al [7]. This technique uses a single multisection device. The gain can be calculated from the ASE spectra which are measured under different current injection densities in the several sections of the device.

In this paper we first briefly introduce the measurement technique from Thomson et al and explain which changes were made for our measurements. Secondly we will explain the design and fabrication of our devices and the experimental results.

Gain measurement technique

When no optical feedback takes place and no gain saturation, the net modal gain G of a semiconductor optical amplifier (SOA) can be related to its ASE output power *P* according to [7]:

$$P = \frac{P_{sp}}{G}\left(e^{GL} - 1\right) \quad (1)$$

Where P_{sp} is the spontaneous emission (SE) power (per unit length) and *L* is the SOA length. Note that the modal gain *G* relates to the material gain *g* according to: $G = \Gamma g - \alpha_i$ .Where *Γ* is the optical confinement factor and α_i is the internal loss. Note that this loss value is generally quite high for SOAs, in the order of 15 cm^{-1} to 20 cm^{-1}. When two SOAs of length *L* and 2*L* are compared an analytical expression for G can be found:

$$G = \frac{1}{L}\left[\ln\left(\frac{P_{2L}}{P_L} - 1\right)\right] \quad (2)$$

In practice this means that by comparing the ASE spectra (at the same current densities) of two amplifier sections (without feedback) the gain spectrum can be calculated. A drawback of this technique is that due to a small error in one of the measurements, which can be caused by misalignment or another reason, the resulting gain parameter can change easily.

Another way, which we have used, is to extract the gain by comparing the ASE spectra from a series of amplifiers of different lengths and fit equation (1) on the data at each wavelength to extract the parameters *G* and P_{sp}. This fitting has several advantages over using equation (2) to extract the gain. First of all, the different ASE spectra always contain noise or small deviations in comparison to the ideal situation described by equation 1. These deviations will be averaged out by the fitting over multiple devices. Secondly, large deviations in measurement results due to misalignment or fabrication errors can easily be detected and neglected or the measurement can be redone.

Design and fabrication

In order to fabricate a series of optical amplifiers from which we can measure the ASE signals without any optical feedback, a series of ridge waveguide amplifiers with two electrical sections were realized on a single chip. The ridges are oriented perpendicular to the cleaving planes. The two-section devices are operated by forward biasing the longer gain section which thus operates as an amplifier and generates the ASE. The shorter gain section is reversely biased which makes the section absorbing the ASE from one side of the amplifier and prevents any feedback from one facet. The reflection from the facet at the amplifier end does not create a problem if the ASE power is well below the saturation power of the amplifier. This condition is easily satisfied in the experiments. The QD laser structure which we have characterized is grown on n-type InP (100) substrates by metal-organic vaporphase epitaxy (MOVPE), as presented in [8]. In the active region five InAs QD layers are stacked. These are placed in the center of a 500 nm InGaAsP optical waveguiding core layer. The QD layers are designed to have a gain spectrum in the 1600nm to 1800nm wavelength region. The bottom cladding of this laser structure is a 500-nm thick n-InP buffer and the top cladding is a 1.5-μm p-InP with a compositionally graded 300-nm p-InGaAs(P) top contact layer.

This layerstack is compatible with a butt-joint active-passive integration process for possible further integration. The ridge waveguides of the two-section FP-type laser devices have a width of 2 μm and are etched 100 nm into the InGaAsP waveguiding layer. To create electrical isolation between the two sections, the most highly doped part of the p-cladding layer is etched away. The waveguide and isolation sections are etched using an optimized CH_4 / H_2 two-step reactive-ion dry etch process. The structures are planarized using polyimide. Two evaporated and plated metal pads contact the two sections to create two contacts. The backside of the n-InP substrate is metalized to create a common ground contact for the two sections. The structures are cleaved and no coating was applied. The devices are mounted on a copper chuck, p-side up.
In this work we present the results from devices with a total length of 7 mm and with variable amplifier lengths between 4.94mm and 6.48mm.

Experimental results

Measurements were performed at room temperature (288 K) on 7mm devices with a -3V on the short waveguide section to create absorption and to prevent any feedback. The amplifier injection current value for the different devices was such that all had the same injection current density for which we want to know the gain spectrum. Twenty-two different devices with amplifier lengths between 4.94mm and 6.48mm have been used. The ASE from the devices was collected with a lensed fiber and measured with a 0.5nm resolution spectrometer over 300nm in 3000 data points. All devices were measured with injection current densities between 500A/cm^2 and 5000A/cm^2 (with steps of 500A/cm^2). The cases in which the FP devices started lasing due bleaching of the absorber were not used in the analysis. In such cases the measured spectrum is not an ASE spectrum anymore and can not be described by equation (1). A nonlinear least square algorithm fitting algorithm was used to fit the parameters in equation (1) to the data. For each wavelength a fit is made on the recorded power data for one wavelength over several different amplifier lengths. Thus besides the gain parameter also the spontaneous emission power (per unit length) is extracted at each wavelength from the fitting.

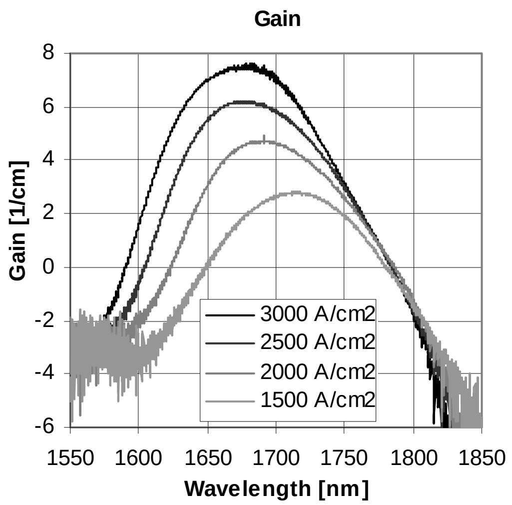

Figure 1a: Calculated gain spectra for a range of injection current densities.

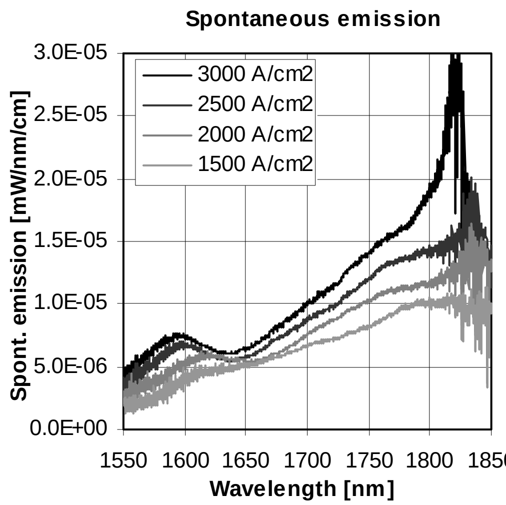

Figure 1b: Calculated spontaneous emission power levels for a range of injection current densities.

The measurements which are performed with an injection current density of 3500A/cm^2 or higher all show a lasing spectrum or at least some feedback phenomena and could therefore not be used. The spectra recorded with the injection current densities of 500A/cm^2 and 1000A/cm^2 could also not be used. The power levels in these cases were too low to fit the exponential function (equation 1) on the data points. In figure 1a the calculated gain spectra are given for 1500A/cm^2, 2000A/cm^2, 2500A/cm^2 and 3000A/cm^2. The gain peak has a 50nm blue shift with increasing injection current densities. Injected carriers prefer to go to the largest quantum dots with the lowest energy state. If these quantum dots are filled, more carriers will go to smaller dots with higher energy states and so give rise to light emission in the shorter wavelength region. As can be seen in figure 1b, the spontaneous emission power appears to increase from the short to the long wavelength side of the spectrum for all the injection current densities. This indicates an increase in dipole transition dipole moment with increasing size of the quantum dots.

Conclusion

A fitting algorithm is used to extract the gain from the ASE spectra of amplifier sections with different lengths. The gain in InAs/InGaAsP/InP(100) quantum dot amplifiers was measured for several injection current densities. The gain peak is at 1700nm and shifts to shorter wavelengths with increasing injection current densities. The gain bandwidth is 200nm at 3000A/cm^2 and can be used to make a tunable laser with a tuning range of at least 100nm. Improvements in the measurements can be made by increasing the relative amplifier length differences of the measured devices to obtain a larger data range to fit the equation (1) to. Furthermore gain measurements can be done with higher injection current densities by decreasing the amplifier length and increasing the absorber length to prevent lasing.

Acknowledgement

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References

[1] H. Wang et al., “Butt joint integrated extended cavity InAs/InP (100) quantum dot laser emitting around 1.55 µm”, IEE Electron. Letters, Vol. 44, No. 8, 522-523, (2008).

[2] Y. Barbarin et al., "Characterization of a 15 GHz Integrated Bulk InGaAsP Passively Modelocked Ring Laser at 1.53µm", Optics Express, Vol. 14, Issue 21, pp. 9716-9727, (2006).

[3] J. H. den Besten et al., “A Compact Digitally Tunable Seven-Channel Ring Laser”, IEEE Photonics Technology Letters, Vol. 14, No. 6, pp. 753-755, (2002).

[4] B. W. Hakki and T. L. Paoli, “Gain spectra in GaAs double−heterostructure injection lasers”, Journal of Applied Physics, Vol. 46, No. 3, pp. 1299-1306, (1975).

[5] Y. Barbarin et al., “Gain Measurements of Fabry-Pérot InP/InGaAsP Lasers using an Ultra High Resolution Spectrometer” Applied Optics, Vol. 45, Issue 35, pp. 9007-9012, (2006).

[6] S.D. McDougall and C.N. Ironside, “Measurements of reverse and forward bias absorption and gain spectra in semiconductor laser material”, Electron. Letters, Vol. 31, No.25, pp. 2179-2181, (1995).

[7] J. D. Thomson et al., “Determination of single-pass optical gain and internal loss using a multisection device”, Applied Physics Letters, Vol. 75, No. 17, pp. 2527-2529, (1999).

[8] S. Anantathanasarn et al., “Lasing of wavelength-tunable (1.55 µm region) InAs/InGaAsP/InP (100) quantum dots grown by metal organic vapor-phase epitaxy”, Appl. Phys. Lett., Vol. 89, 073116, (2006).