HIGH POWER 1.55 µm LASER DIODE SOURCES WITH HIGH TRANSVERSE BEAM QUALITY

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Abstract

Through the use of quantum well intermixing technology, significant improvements have been demonstrated in the transverse beam quality of high power laser diodes operating at 1.55 µm. This has been accomplished through the monolithic integration of intra-cavity spatial mode filters which suppress the oscillation of higher order modes, leading to considerable reduction in divergence of the transverse far-field. A theoretical model has been developed to simulate the operation of these devices and to establish the relationship between device performance and device design parameters. This has been used along with previous experimental results to design an experimental wafer which will be used to provide an empirical correlation between the device design and performance attributes, enabling further refinement of the theoretical model and subsequent optimization of device design.

Keywords: InP, laser array, segmented gain section laser (SGSL), extended cavity laser (ECL), all-active laser (AAL), quantum well intermixing (QWI), sputtering.

INTRODUCTION

High power semiconductor diode lasers emitting at the eye-safe wavelength of 1.55 µm have uses in a wide range of applications including range finding, LIDAR, burst illumination and chemical sensing. In order to achieve high optical powers such lasers often employ a broad area configuration, in which the emission aperture is relatively wide (10-100µm) compared to index guided devices. The broad area configuration reduces the likelihood of gain saturation and thermal effects which may limit output power. In addition, the simple fabrication process typically employed for such devices facilitates high volume, high yield manufacturing.

However a major disadvantage of such a diode laser configuration is the tendency of the device to operate in higher order modes due to non-linear effects, which occur due to the strong interaction between the injected carrier density and the propagating optical mode, leading to coupled changes in the refractive index profile which cause self-focussing of the propagating beam. This leads to a process known as filamentation, in which the optical mode fragments into a number of subsidiary beamlets, producing a highly inhomogeneous and time-varying near-field, which in turn leads to a multi-lobed and relatively broad far-field. This effectively limits the use of these devices in many applications where a high beam quality is required.

Several approaches have been investigated in order to inhibit the filamentation process and to improve the beam quality of high power lasers. These have included tapered lasers, such as master-oscillator power amplifiers (MOPAs) Donnelly, et al. (i) and Selmic et al. (ii), the use of patterned contacts, Salet et al. (iii), to increase the carrier density in areas most susceptible to spatial hole burning, while cavity spoiling grooves (1,2), laterally profiled output facet reflectivity Stryckman et al. (iv) and Shigihara et al. (v), and unstable resonators, Tilton et al. (vi), have been employed to select the fundamental Gaussian mode over higher order modes. However, the design and/or processing requirements for such devices are often complex and difficult to make reliable, and therefore high manufacturing yields are difficult to attain in practice.

Here an alternative and robust approach to improving the beam quality of high power semiconductor laser diodes is described. This approach is demonstrated in lasers emitting at 1.55 µm, but is applicable to most other III-V semiconductor lasers. It involves the incorporation of intra-cavity mode filters to suppress the filamentation process and the oscillation of higher order modes. These mode filters are formed through the monolithic integration of passive slab waveguide sections within the laser cavity. As this process does not require any complex photolithography, etching or coating processes, it should provide a more robust route towards achieving high power, high beam quality laser operation. This approach has previously been demonstrated in a range of material systems covering the wavelength range 630-1550 nm, in a range of cavity geometries. In all cases the monolithic integration of the passive section with the active (gain) section has been achieved using a novel quantum well intermixing process.

These mode filters have been incorporated in two types of laser cavity configuration – the extended cavity laser (ECL), in which there is a single gain section with the mode filtering occurring through integrated passive sections at either end of the gain cavity, and the segmented gain section laser (SGSL), in which additional mode discrimination occurs through the segmentation of the gain section into a number of gain elements each separated by an unguided passive section, each of which provides a mode filtering effect.

In this presentation the basic operating concepts of such devices are described along with a review of previous experimental work in which these concepts have been demonstrated. The ongoing work within this program is then detailed, including a description of the theoretical modelling that has been conducted to simulate device performance and optimize wafer design. This work has culminated in the design and fabrication of an experimental wafer, which will provide experimental verification of the device concepts and, through refinement of the theoretical model, enable optimization of the device design.

DEVICE THEORY

The operation of segmented gain section lasers is demonstrated in Figure 1. This shows a laser with several guided sections, in which the propagating mode is laterally confined within the waveguide. However the guided gain regions are separated by unguided sections in which the propagating mode is free to diffract horizontally.

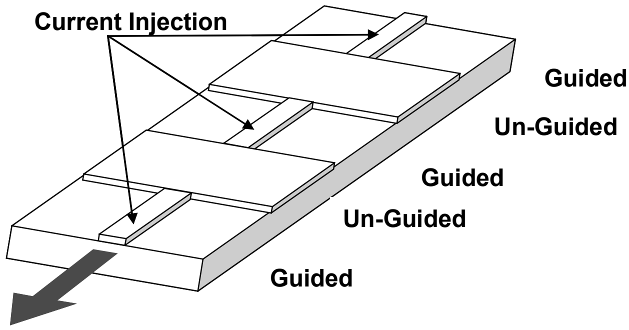


Figure 1. Schematic of segmented gain section laser.

The degree of diffraction that occurs within the unguided region will be determined by the effective emission aperture of the waveguide, and therefore higher order modes which will present a smaller emission aperture will exhibit a greater degree of diffraction than the fundamental mode, as shown in Figure 2.

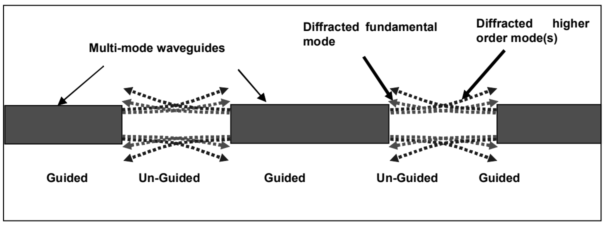


Figure 2. Illustration of diffraction occurring within unguided regions and its mode dependence.

Thus, for a round-trip pass the higher order modes will undergo a greater degree of diffraction and will therefore experience higher losses than the fundamental mode, leading to an effective suppression of their oscillation. This is further demonstrated below, through theoretical simulation.

EXPERIMENTAL DEMONSTRATION

The use of monolithically integrated intra-cavity mode filters in the form of ECLs and SGSLs has previously been demonstrated in a range of material systems. Previous demonstrations in material emitting at 1550 nm have utilised ECL devices, Qiu et al. (vii), in which a single broad-area laser is integrated with two passive slab waveguides on either side, as illustrated in Figure 3.

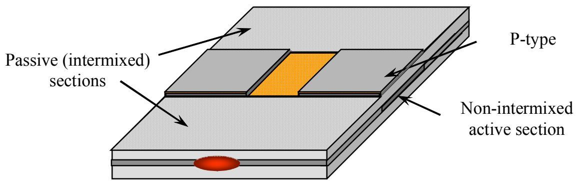


Figure 3: Schematic of an extended cavity broad area laser.

This device geometry was found to exhibit considerable improvement in beam quality as illustrated in Figure 4, which shows the far-field obtained for such a device with a 600 µm long active section and two 300 µm long passive sections. This is compared against a 600 µm long all active laser (AAL). While the AAL exhibits a relatively broad (FWHM ~ 10º), multi-lobed far-field, the far-field obtained for the ECL device is single-lobed and much narrower (FWHM ~ 2º).

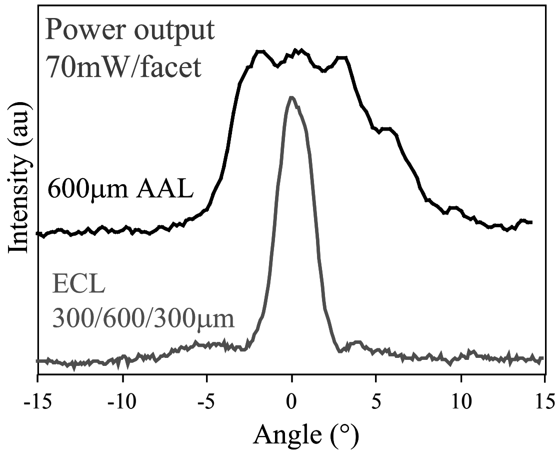


Figure 4: Far-Field improvement using an extended cavity design (ECL) compared to a conventional (AAL) laser cavity.

SGSL devices incorporating multiple gain sections have also been demonstrated to yield significant improvements in beam quality. SGSL have been demonstrated in both broad area, Marsh and Kim (viii), and ridge wave-guide, Kim et al. (ix) configurations in material emitting at 670 nm, and have again shown significant improvements in beam quality over AAL of the same configuration.

ONGOING WORK

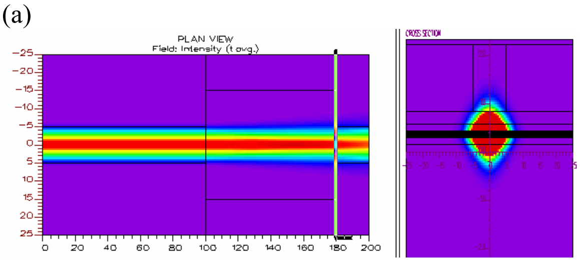
The initial work conducted as part of this program has involved a review of previous experimental work, the development of a theoretical model to simulate device performance work, and the design of an epi-layer structure suitable for high power laser emission at 1.55 µm. As a result of this work, a new epi-wafer design has been grown and assessed and an experimental mask has been designed to enable the fabrication of a series of ECL and SGSL chips which will provide a large source of data to enable the relationship between chip performance and device design to be established. This will facilitate development of the theoretical model and subsequent optimisation of the chip design.

Theoretical Modelling

It is a primary aim of this program to develop a theoretical model suitable for the simulation of SGSL and ECL devices.

Initial work conducted towards this objective has involved theoretical simulation of the diffraction occurring within a singe unguided passive section of the device. The results of such a simulation are shown in Figure 5 for a forward propagating beam within a single diffractive segment consisting of two 10 µm waveguides, separated by an 80µm long unguided passive section, within which lateral diffraction can occur. The simulation shows the diffraction that occurs for the fundamental mode and the first order mode.

(a)



(b)

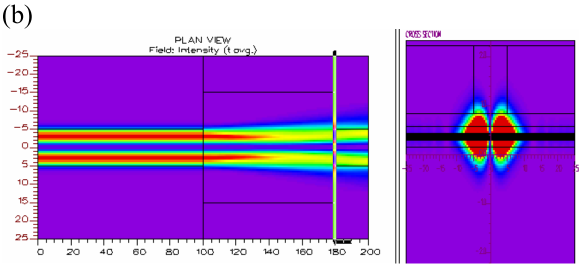


Figure 5. Simulation of diffraction occurring for fundamental and first order mode within an unguided passive section.

This illustrates that the higher order modes will experience higher diffraction loss within the passive section than the fundamental mode, the degree of which is dependent upon the width of the waveguide and the length of the passive section.

This is further illustrated in Figure 6 which shows the calculated transmission coefficient through an unguided passive section as a function of passive section length for both the fundamental and first order modes. The calculation is performed for a single section and then extrapolated to a ten section SGSL. The predicted losses are illustrated for a 10 µm wide waveguide.

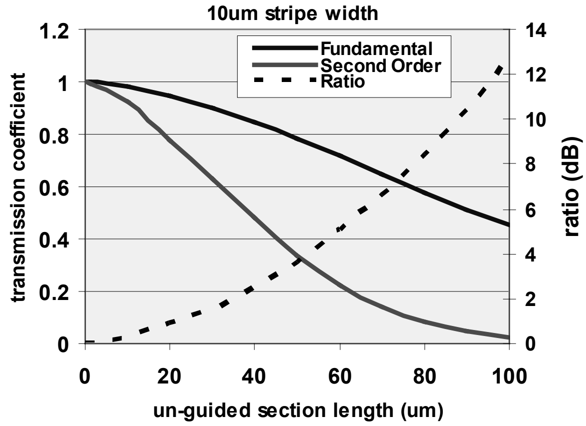


Figure 6: Transmission coefficients for the fundamental and second order modes as a function of unguided section length for a 10 µm wide waveguide.

Figure 6 shows that as the length of the passive sections is increased, the transmission coefficient for the fundamental mode decreases and hence longer gain sections have to be used to overcome the loss. This results in increased threshold currents and lower efficiencies. There is a similar dependence upon the number of passive sections (and therefore the number of gain sections) - as the number of passive sections is increased, the suppression of higher order modes is improved, but with an associated increase in loss associated with the fundamental mode. All sources of loss have to be accounted for when designing the laser chip in order to ensure optimum performance.

Simulations so far carried out have been used as an input into the design of an experimental wafer which comprises a range of different device configurations as further below. Fabrication and test of this wafer will subsequently be used to iterate and refine the theoretical model thereby facilitating device design optimisation.

Further development of the theoretical

model will take place during quarter 1 and 2 of year 2.

Epi-Layer Design

In order to obtain high power laser operation at 1550 nm, it is vital that the epi-wafer design is optimized to yield raw material with low threshold current and high slope efficiency, leading to maximized operating power.

The material used in this program has utilized InAlGaAs QWs, which typically provides improved high power and high temperature performance compared to InGaAsP material, due largely to the larger conduction band offset of this material.

Wafer design work has endeavoured to minimize loss by optimizing the number of quantum wells, N, their composition and well width, d for a particular device configuration.

This has been performed by solving the basic threshold gain equation:

$$G(d,n)\Gamma(N)N=\alpha_b+\alpha_{qIVBA}+\alpha_{cIVBA}+\alpha_p L_p/L_a-\ln(R_1R_2)/2L_p \quad (1)$$

whilst simultaneously solving the following expression for threshold current, I_{th}, as a function of carrier density:

$$Ith=\eta(An+Bn^2+Cn^3)L_aWd \quad (2)$$

Where L_a is the length of the active section, L_p is the length of the passive section, W is the stripe width, n is the carrier concentration, α is a loss term, with the subscript b referring to background loss, qIVBA and cIVBA referring to free-carrier loss in the QW and cladding layers respectively. C_{IVBA} is intervalence band absorption coefficient. Table 1 lists the parameters used in the modelling.

This is then used to determine the free-carrier loss within the QW layer.

$$\alpha_{qIVBA}=\Gamma(N)C_{IVBA}N\ n \quad (3)$$

where C_{IVBA} is intervalence band absorption coefficient.

From this it is possible to determine the carrier density at threshold for a given QW design, and then determine the corresponding loss and threshold current. This then enables the loss to be minimised to produce a design which should enable high output power and low threshold current. In addition, the p-type doping profile has been optimized in order that the free carrier absorption loss is minimized whilst maintaining the structure's electrical and optical properties.

Growth and assessment of this optimized epi-wafer design has been completed.

Assessment of the material has been performed by fabricating a series of broad area lasers which were subsequently tested under pulsed conditions to determine the threshold current and slope efficiency as a function of cavity length.

Typical light-current characteristics for a 1000 µm long BAL are shown in Figure 7. The threshold current and slope efficiency obtained for this cavity length is 250 mA and 0.14 W/A respectively, comparable with state-of-the-art literature values.

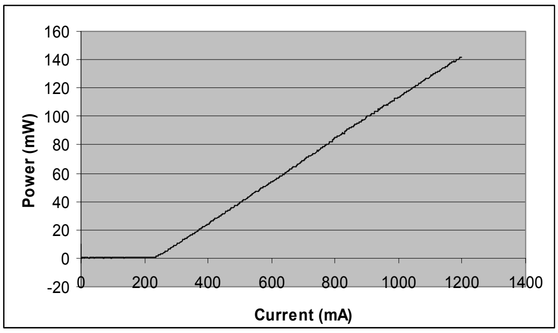


Figure 7: Light-current characteristics obtained for a 1000µm long BAL from new high power wafer.

Device Design

An experimental wafer has been designed based on a review of previous experimental work and the results of the theoretical modelling described in section 2.

This wafer incorporates a number of device configurations – (a) SGSL with both 2 and 4 sections, (b) ECL devices in which active : passive section ratios of 60:40 and 40:60 are employed, as well as (c) AAL control devices as illustrated in Figure 8. All lasers will use a fixed cavity length to allow a meaningful assessment of the design trade-offs. For each type of cavity configuration, a number of current injection stripe widths will be investigated, including 10, 40 and 75 µm. Narrower stripes should exhibit a greater degree of mode discrimination and therefore should produce more dramatic improvements in beam quality, however they will require greater process tolerance which may offset the potential gains in beam quality.

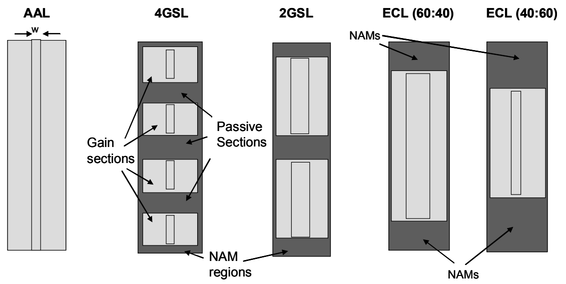


Figure 8: Experimental device configurations to be employed as part of initial development phase. For each configuration, 3 different oxide stripe widths will be investigated: 10, 40 and 75 µm.

Fabrication of this experimental wafer will be completed at the end of DTC year 1, with comprehensive tests taking place in the first 3 months of year 2, to determine the influence of the chip design parameters upon output power and beam quality.

FUTURE WORK

This initial stage of the program will verify the device concept through the manufacture and test of an experimental wafer, the results of which will provide valuable data to facilitate development of the theoretical model.

Following completion of fabrication and test of the experimental wafer, the results obtained will be used to refine the theoretical model so far developed for these devices. This will subsequently be used to optimize the device design through a second stage of device fabrication, taking place in the first half of DTC year 2. This will be followed, in the second half of year 2, by thermal modelling of an uncoupled array of such devices, in order to eventually provide a high power, low coherence 1550 nm laser source with high beam quality.

The manufacture of such an array is planned for year 3 of the program, together with ongoing process development work, in particular investigation of the potential for broadening the output spectrum of such devices in order to further reduce the coherence length.

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