Experimental characterisation and analysis of the static behaviour of twin-ridge AlGaInAs laterally coupled diode lasers

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ABSTRACT

Laterally coupled diode lasers emitting at 1.3 $\mu$m are presented. Devices were fabricated with distances between ridges varying from 2.76 $\mu$m to 8.32 $\mu$m. Electronic coupling effects are investigated by individually varying the currents in each ridge while monitoring output power. It is observed that for devices with 8.32 $\mu$m separation between ridges there is minimal current sharing, whereas for 2.76 $\mu$m separation there is considerable current sharing. Optical coupling is measured via the far-field, where most devices show out-of-phase locking, although in-phase locking is observed in a minority of cases. Devices therefore show conditions necessary for the observation of high speed dynamics.

1. INTRODUCTION

Coupled cavity semiconductor lasers show many interesting effects, such as bistability, cavity phase coherence, mode selectivity, etc., and have been studied since the early 1980’s\textsuperscript{1,2,3}. It was later appreciated theoretically that modulation rates beyond the relaxation oscillation frequency could be achieved by coupled cavities that have asymmetric current injection\textsuperscript{4,5,6}. Many novel coupled cavities have been fabricated, including cross-coupled\textsuperscript{7} and Y coupled laser\textsuperscript{8}, but very little experimental work has been done aiming to achieve ultra high (>20GHz) modulation rates using a monolithic coupled cavity approach.

Our aim is to implement monolithic laterally coupled diode lasers (LCDL) to achieve ultra-fast dynamics, with a view to harnessing these dynamics for ultra-high speed telecommunications. To this end we have developed several theoretical treatments\textsuperscript{9,10}, and now present the first preliminary experimental results. According to some theoretical work\textsuperscript{5,10}, to achieve high-speed behaviour, laterally coupled devices should have either in-phase or out-of-phase optical coupling between stripes, and the stripes should be separately addressable in order to modulate the gain of each cavity independently. We have fabricated devices that achieve these primary aims, and present a set of measurements that will allow us to extract the device parameters. These results will then be used to compare with modelling results to obtain a better understanding of the dynamics of these devices.

We therefore start this paper with a brief description of the devices, before describing a selection of their measured electrical and optical properties. These properties show that the devices have separately addressable ridges with good static power-current, current-voltage and temperature characteristics\textsuperscript{11}, with predominantly out-of-phase optical coupling between ridges. Hence we conclude that the devices show promise for exhibiting high speed dynamics, which will be the subject of future work.

2. STRUCTURAL CHARACTERISTICS

The value of the cavity coupling parameter depends on both the length and separation of the ridges\textsuperscript{10}, hence a set of samples were designed to have lengths of 300 or 500 $\mu$m, and ridge separations ranging from 2 to 8 $\mu$m. Ridge widths were designed to be 4 $\mu$m for single transverse mode output. The samples were grown using solid source molecular beam epitaxy and processed at the Optoelectronics Research Centre, Finland\textsuperscript{12}. Substrate material was n-type InP. On this were grown waveguide layers, containing five 5 nm thick QWs of AlGaInAs/InP composition, emitting at a wavelength around 1.325 $\mu$m. The layers have an
overall p-i-n doping profile, the QWs being undoped. Twin ridges are defined by plasma etching. The top surface is coated with a layer of SiO₂, openings in which are etched on top of the ridges, and metal contacts are defined on top of the ridges. P-type contacts are made on the top side of the wafer, the n-contact being made to a gold contact on the substrate. Ridge separations were measured by scanning electron microscopy (SEM) to be 2.76, 3.72, 4.78, 6.81 and 8.32 µm. Ridge widths were measured by SEM to be the same within experimental error for any particular device, but varied from 3.6 µm for the 2.76 µm separation, to 4.1 µm for the 8.32 µm separated devices. The wafer was diced into sets of individual laser chips of approximately 300 or 500 µm lengths, the exact length for any particular chip being measured under a standard optical microscope. Facets were left as-cleaved. However, it was noticed by visual inspection that the quality of cleave varied somewhat from device to device, and even from ridge to ridge, so the precise value of facet reflectivity is slightly uncertain. That this has an effect is born out in power-current curves, where the threshold current density for lasing was generally in the region of 350 ±10 A/cm²/QW for the 500 µm length lasers, but increased to ∼460 in some cases. A similar variation was noted for the 300 µm length devices. Further structure information can be found in ref. 12.

3. POWER-CURRENT-VOLTAGE CHARACTERISTICS

For high-speed operation utilising coupled cavity effects, the two ridges need to be separately addressable in order to independently modulate the gain of each cavity⁵,¹⁰. For our devices, it was estimated from depth-profile measurements after

![Figure 1. SEM picture of cleaved facets showing gold contacts on top of the ridges, and ridge dimensions of 3.65 µm width, and 4.77 µm separation.](image)

![Figure 2. Current-Voltage curves for individual ridges of (a) 8.32 (b) 4.77 and (c) 2.76 µm separated devices. Device lengths are 450, 520 and 470 µm respectively. The dotted lines show the I-V curves for each individual ridge when the other ridge is open circuit, whereas the continuous lines show the I-V curves when the other ridge is connected to ground. Straight lines show a linear fit to the lower sections of data corresponding to (a) 131.7 Ω, (b) 47.4 Ω and (c) 37.3 Ω.](image)
etching that some p-type conductive material remained, which would electrically connect the ridges. To check the effect of this electrical interconnection, the current-voltage (I-V) and power-current (P-I) characteristics of the ridges were measured by varying the bias on one ridge, when the other ridge is either disconnected or connected to ground. The I-V results are illustrated in Figure 2, and the P-I results in Figure 3. With the second ridge unconnected, shown as dashed lines in figures 2 and 3, the lasers show good fundamental properties\textsuperscript{11}, as each ridge has an I-V turn-on voltage of around 0.95V corresponding well with an emission of 1.325 \( \mu \)m, a low series resistance and a lasing threshold around 31-35 mA. The curves change significantly when the second ridge is connected to ground. The resulting curves, shown by solid line in figures 2 and 3, can be analysed in two sections, the first section where the IV curve is linear, indicating a simple resistance, and the P-I curve has practically no emission, and the second section where the diode characteristics and the normal laser operation are recovered. From this we infer that by connecting one ridge to ground, carriers are drawn from one ridge to the other, without the carriers entering the QWs. The interconnection between ridges thus acts as a resistance with measured values varying from 131.7 \( \Omega \) for the 8 \( \mu \)m separated 450 \( \mu \)m length laser, to 37.3 \( \Omega \) for the 2 \( \mu \)m separated 470 \( \mu \)m length laser. These figures yield a value for connecting sheet resistance of approximately 6.8 \( k\Omega \) per square, which is significant at low bias voltage, where the diode has a high impedance, but is much less significant at higher biases where the devices will be operated.

In order to determine the strength of coupling between ridges, a constant current, \( I_{DC} \), was injected in one ridge, while the current \( I_{bias} \) in the second ridge was varied, figure 4. In each plot of fig. 4, values of \( I_{DC} \) are different for each curve, varying from 0.5 mA to 45 mA. \( I_{bias} \) is plotted on the X-axis, and the total output power collected from both ridges is plotted on the Y-axis. Several features can be noticed. In the 8 \( \mu \)m separated device, the threshold current of one ridge increases as \( I_{DC} \) is

![Figure 3](image-url)

Figure 3. Power-Current curves corresponding to the I-V curves of figure 2, for the same devices under the same bias conditions. The power axes for the 4.77 and 2.76 \( \mu \)m devices are expanded to show that no light is emitted up to 20 and 28 mA respectively when the unbiased ridge is connected to ground, corresponding to the linear sections in figure 2.

![Figure 4](image-url)

Figure 4. Power-Current curves taken as the current \( I_{bias} \) in one ridge is varied, while the current \( I_{DC} \) in the other ridge is held constant. (a) 8 \( \mu \)m ridge separation, (b) 4 \( \mu \)m and (c) 2 \( \mu \)m. Traces in each figure are taken at \( I_{DC} = 0.5, 10, 20, 30, 35, 40, 45 \) mA. An integrating sphere is used to collect the total emission from both ridges together.
increased in the other. Given the fact that if there was significant optoelectronic coupling, the threshold should decrease as more electrons are injected into the system, we conclude that the coupling does not play a significant role in this case. We also conclude that the higher currents act to heat the device, as spectral measurements show that the peak of emission moves to longer wavelength, and temperature measurements show that the threshold increases with increasing temperature. In contrast, the threshold for the 2 µm separated device clearly goes to lower currents as I_{DC} is increased. This is evidence of significant optoelectronic coupling. A second effect observable in the data is the roll-off of emitted power in all cases as I_{bias} approaches threshold, generally in the region of I_{bias} between 10 and 30 mA. This is due to current induced heating, confirmed in spectral measurements as above.

The slope efficiency of the 2 µm device, derived from figure 4(c), is shown in figure 5. At low values of I_{DC} the slope efficiency is that of a normal single ridge laser. This shows that small currents in the second ridge do not contribute much to the current injection of the first ridge. As I_{DC} increases close to the threshold of the ridge into which it is injected, there is a 45% increase in the slope efficiency of the total output power. This clearly shows that the carriers are contributing more efficiently to the lasing action when both ridges are close to, or above, threshold, confirming the presence of significant coupling. The strength of the coupling between ridges will be determined from simulation of these results.

Temperature dependent measurements show an average change in peak wavelength of 0.41 nm/K, and a T_0 for threshold in the region of 100 K at 25 °C. This value of T_0 compares well with other devices operating at this wavelength, showing excellent growth quality. The longitudinal mode spacing is found to be 0.50 nm for the 500 µm cavity length and 0.83 nm for the 300 µm cavity length devices, indicating that the effective refractive index for each ridge is approximately 3.513. The average wavelength change with current was 0.12 nm/mA.

4. NEAR AND FAR FIELD MEASUREMENTS

It was determined in the previous section that the ridges have a good degree of independence, but some coupling is present. Optical coupling between ridges is necessary to achieve the desired high frequency regime. If such coupling is occurring, it is expected that the optical fields of each ridge will tend to lock and oscillate either in-phase or out-of-phase. Pure in-phase coupling will produce a far-field pattern with a dominant on-axis lobe, and minor side-lobes, while pure out-of-phase coupling will produce a far-field with minimum emission on-axis, and two off-axis lobes. In the out-of-phase case, the angle at which the off-axis lobes occur depends inversely on inter-ridge separation. Far-fields were measured by rotating the sample on a rotation stage, and using a photodiode detector apertured to collect light from a ±0.5° cone. Several devices have far-fields that show the
distinctive double-peak indicative of out-of-phase coupling, figure 6. However, the peaks are in general closer together and broader than that from simple diffraction theory. A partial explanation of this can be determined from figure 7(b). Figure 7 was taken by imaging the near-field via a x40 lens and a spectrometer onto a CCD camera, and so spectrally resolves the near-field. Fig. 7(b) is the near-field corresponding to fig. 6(c), showing that while the far-field is almost symmetrical, the near-field is very markedly asymmetrical, even under equal biasing of the two ridges. The asymmetry implies that there cannot be complete destructive interference in the far-field, and accounts for the fact that the peaks are broad and the minima do not go to zero.

Besides this, we have also observed that the peak emission wavelength of each ridge could be current-tuned, so that under some bias conditions the longitudinal modes of one ridge would coincide with the longitudinal modes of the other ridge, and the emission would lock to a common wavelength. Under other bias conditions, no modes coincide, and so the peak wavelength

Figure 6. Selected far-field profiles for (a) 8.32 (b) 4.77 and (c) 2.76 µm separated devices. A double lobe feature can be seen in each case, indicating predominant out-of-phase optical coupling between ridges.

Figure 7. Spectrally resolved near-field. (a) CCD image of near-field, as measured at the output of a monochromator. (b) Integrating along the horizontal axis of (a) results in the spectrally integrated near-field intensity. (c) Selecting horizontal sections of (a) corresponding to the position of each ridge, R1 and R2, gives the spectrum of each ridge. Thin line is spectrum for ridge 1 (R1), thick line is for ridge 2 (R2).
from each ridge would be somewhat independent of the other. It was found that the ‘lock’ wavelength could hop to any mode in a window of approximately 10 nm, depending on precise bias conditions. The lock could be maintained within a current tolerance of about ±1.5 mA variation in each ridge.

Finally we note that whereas the above mentioned devices showed two peaks in the far-field, some devices showed single lobed emission with side-lobes, indicating in-phase locking. In all cases, however, due to the presence of some type of coupling, the devices show promise for possible ultra-high speed properties.

5. CONCLUSIONS

We have fabricated and measured the DC properties of sets of laterally coupled diode lasers. The DC properties show clear evidence of significant optoelectronic coupling between the two ridges, which varies in strength from the further separated devices, 8.32 µm, to the closer separated devices, 2.76 µm. Some devices show locked in-phase or locked out-of-phase coupling, but in either case promise to have a range of useful high speed properties. By comparing the measurements with our model, device parameters will be extracted which should then give information as to the optimum biasing conditions needed to obtain useful high speed performance, which shall be the topic of future work.

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REFERENCES