organic vapour phase epitaxy (MOVPE) in a low-pressure reactor (AIX200) using the precursors TMGa, TMAl, TMIn and arsine. The first epitaxy ends with the *p*-GaAs waveguide layer (see Fig. 1*a*). In this waveguide the gratings are prepared by holographic lithography using a wavelength of 266nm. The light source is a frequency quadrupled Nd:YVO$_4$ laser that allows a minimum grating period of ~133nm instead of the 163nm possible with an HeCd laser. So in the GaAs waveguide layer, a first-order grating is prepared with a period of 157nm and a depth of 65nm. In the second growth step the *p*-cladding layer and the *p*-contact layer are grown.

During the heating-up step of the second epitaxy, mass-transport can lead to a flattening or even vanishing of these gratings [5]. Therefore, the overgrowth process is started with 100nm $Al_{0.25}Ga_{0.75}As$ grown at a low temperature to preserve the grating shape. The system is then heated up to the usual growth temperature 770°C before the AlGaAs-overgrowth is continued. This leads to a remaining grating depth of 35 nm (Fig. 1*b*). After the second epitaxy the heterostructure is processed into 2mm long ridge waveguide DBR laser diodes. A mesa width of 5μm is used for lateral mode confinement. The layout of the evaporated *p*-metallisation allows electrically separated contacts for the gain, phaseshift and DBR sections. The epitaxial structure for these sections is the same and the active layer extends over the whole length. The front and back facets are coated to 10 and < 1%, respectively. The devices are mounted *p*-side up on AlN submounts and housed in TO-3 headers for characterisation under CW conditions.

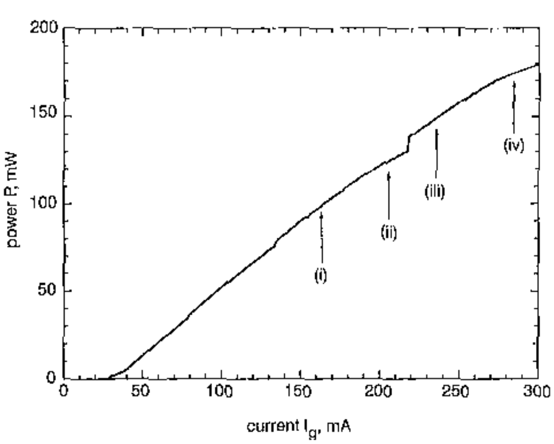

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Fig. 2 *P-I_g characteristic at 25°C of 2000μm long three section DBR laser with ridge width of 5μm*

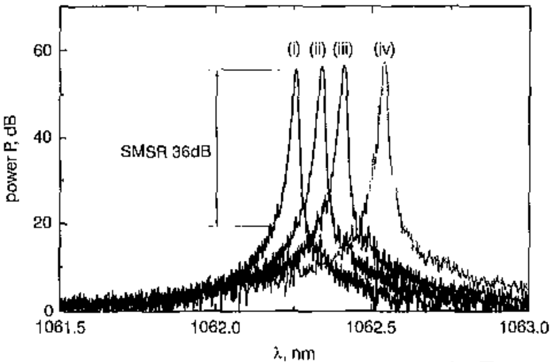

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Fig. 3 *Longitudinal mode spectra at 25°C of DBR laser at different CW output powers*

(i) 100mW
(ii) 125mW
(iii) 150mW
(iv) 175mW

Results: For the measurement of the CW power-current characteristic only the gain section is pumped. Fig. 2 shows a typical P-I_g characteristic of the developed DBR lasers. The laser threshold is reached at 28mA and an output power of 180mW at I_g = 300mA is observed. The averaged slope is η = 0.74W/A. The kinks in the P-I_g characteristic are due to longitudinal mode hopping caused by thermally induced detuning between the Fabry-Perot mode and the reflectivity maximum of the DBR section. In Fig. 2 the output powers of 100, 125, 150 and 175mW are marked by labels (i) – (iv). At these values the longitudinal mode spectra are measured using a 1.2m grating monochromator with a resolution of 0.005 nm. The corresponding spectra are shown in Fig. 3. At all powers the sidemode suppression ratio between the lasing mode and the neighbouring mode is > 35dB and the linewidth is < 5MHz. In conclusion, with first-order DBR lasers we have achieved a higher monomode output power than with second-order gratings as in [4].

Summary: The realisation of DBR lasers emitting at 1062nm with a first-order grating in GaAs prepared by holographic lithography is presented for the first time. After embedding the grating in AlGaAs at low temperature the overgrowth is continued at 770°C. This results in excellent laser characteristics with single frequency operation at high output powers. The sidemode suppression ratio is better than 35dB up to an output power of 175mW.

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Determination of external cavity coupling-coefficient for diode laser with phase-conjugate feedback

J.S. Lawrence and D.M. Kane

An experimentally determined coupling coefficient for a singlemode diode laser operated with conventional optical feedback is contrasted with that for phase conjugate feedback. Values are determined to be 0.2 ± 0.05, and 0.7 ± 0.1, respectively. These quantitative measurements indicate the enhancement in coupling efficiency that can be achieved using a phase conjugate reflector.

Over the last 20 years many aspects of semiconductor diode lasers operated with conventional optical feedback (COF) have been theoretically and experimentally examined. Such feedback has been found to induce a variety of effects, either detrimental or advantageous to the diode laser's operating characteristics; depending on the feedback level. These effects include linewidth narrowing or broadening, reduction in threshold gain, and a variety of dynamic states including chaos or coherence collapse. More recently, the operation of diode lasers with phase conjugate feedback (PCF) has attracted attention. PCF is found to induce more complex dynamic behaviour, and to provide better mode coupling for broad area diodes and laser diode arrays.

Crucial to any theoretical model describing feedback behaviour is the amount of feedback that is actually coupled into the diode. This is important for comparisons with experimental data, and while several methods have been applied to estimate the coupling coefficient from system measurables for the case of COF [1 – 3], none of these methods has been reported for the case of PCF. Values used in the literature of the coupling coefficient for a diode laser with COF range from 0.02 to 0.7 [2, 3]. The exact value is dependent on the specific system parameters such as the collimating optic, the external cavity length, and the size, wavelength, structure, and facet reflectivities of the solitary laser diode. For PCF theoretical models, the coupling coefficient is typically considered to be unity [4, 5] owing to the temporal phase reversing nature of the feedback; no experimental data have been previously reported.

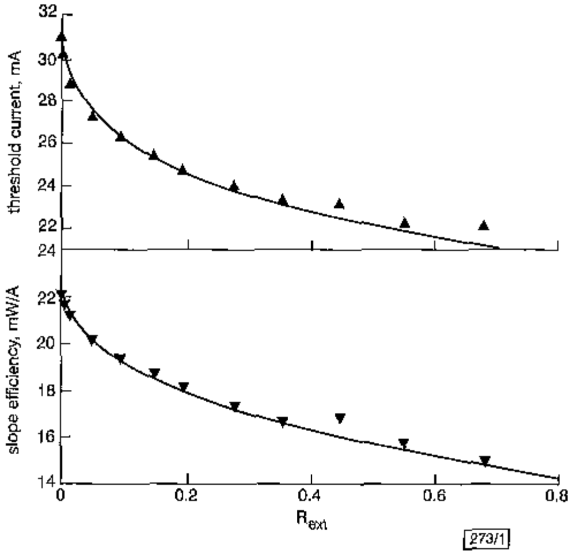

Fig. 1 *Variation of slope efficiency and threshold injection current with feedback ratio for COF*

▲, ▼ experimental data
—— theoretical predictions of eqns. 2 and 3

The experimental apparatus is typical of a diode laser in COF systems (see for example [6]). A singlemode diode laser (50mW STC model LT50-03U, 850nm) is collimated with a GRIN lens and feedback is generated from a plane mirror at a distance of 300mm. For PCF the plane mirror is replaced by a phase conjugate mirror, which is a rhodium-doped barium titanate crystal in a self-pumped internal reflection geometry. An intracavity beamsplitter is used to observe output and feedback powers, and a neutral density attenuator is used to control the amount of feedback.

It is known that the introduction of feedback into a diode laser will decrease both the slope efficiency and the threshold injection current of the system, dependent on the amount of feedback coupled into the diode [7]. The measurement of such a reduction in slope efficiency and threshold can thus be used to determine the coupling coefficient, η_c, for the system. Provided that the feedback is weak, and the external cavity is longer than the coherence length of the diode laser and collimating optic, the effective reflectivity of the diode front facet and the external reflector may be considered as

$$R_{eff} = \left| \frac{r_2 + r_3}{1 + r_2 r_3} \right|^2 \qquad (1)$$

where $r_3 = \sqrt{[\eta_c R_{ext}]}$, and R_{ext} is the ratio of the reflected power to the output power. The external slope efficiency η_2 is derived from the gain equals loss condition for lasing, and is given by

$$\eta_2 = \frac{\ln\left(\frac{1}{R_{eff}}\right)}{2\alpha L + \ln\left(\frac{1}{R_{eff}}\right)} \eta_i \left(\frac{h\nu}{e}\right) B \qquad (2)$$

where η_i is the internal quantum efficiency of the solitary diode, α is the diode internal loss factor, L is the diode length, ν is the diode frequency, and B represents the power coupled out of the cavity from the beamsplitter. The reduced operating threshold current, I_{th}^{ec}, due to the presence of feedback, is given by [1]

$$I_{th}^{ec} = I_{th}^{d} \left(1 + 2 f_d \tau_d \ln\left(r_2 \frac{1 + r_2 r_3}{r_2 + r_3}\right)\right) \qquad (3)$$

where I_{th}^{d} is the solitary diode threshold with no feedback, f_d is the diode longitudinal mode spacing, and τ_d is the photon lifetime, which is a function of the internal loss factor, diode length, and facet coatings. The coupling coefficient can thus be determined from fits of experimental data to eqns. 2 and 3 for different values of R_{ext}. This is shown in Fig. 1; η_c is found to be 0.22 ± 0.05. The large uncertainty arises because the internal loss factor and internal quantum efficiency are also unknown quantities (determined to be $\eta_i = 0.8 \pm 0.2$ and $\alpha = (2000 \pm 200)$ cm^{-1}).

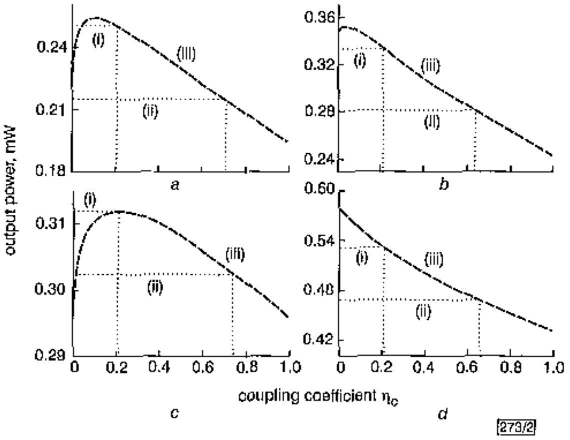

Fig. 2 *Prediction of variation of output power with coupling coefficient from eqn. 4 for fixed feedback ratio and injection current*

a Feedback ratio = 0.20, injection current = 40 mA
b Feedback ratio = 0.20, injection current = 45 mA
c Feedback ratio = 0.05, injection current = 45 mA
d Feedback ratio = 0.10, injection current = 55 mA
(i) COF output power
(ii) PCF output power
(iii) theory

When the feedback is produced by a phase conjugate mirror, the coupling coefficient cannot be determined by the same method as used for COF. This is because the phase conjugate efficiency is not a linear function of the pumping power. It is found that the reflected power is constant over a wide range of incident powers, and thus the efficiency actually decreases with an increase in feedback. Since the reflected power does not increase linearly with current a linear slope efficiency and threshold current are not measurable. However, eqns. 2 and 3 can be combined in order to predict the output power, P_b, at a given current and feedback ratio, as a function of the feedback coefficient. This may be expressed as

$$P_b = (I - I_{th}^{ec})\eta_2 \qquad (4)$$

Fig. 2 shows the output power as a function of the coupling coefficient for a fixed feedback ratio and injection current as determined from eqn. 4. The power is found to decrease with an increase in the coupling coefficient (or feedback ratio) at currents above the solitary diode threshold. This occurs because the slope efficiency and threshold are both decreasing, hence at very low currents the largest η_c (or feedback ratio) will have higher power, but as current is increased the largest η_c (or R_{ext}) will have a lower power. Also in the Figure are lines showing the experimental output power at this current and feedback ratio, for both COF and PCF.

For COF the output power corresponds to a coupling coefficient of ~0.2, which agrees with the earlier determination. For the diode laser with PCF, the output power is significantly lower for the same injection current and feedback level. The coupling coefficient is determined from fits of the experimentally observed output power to the theoretically predicted output power against coupling efficiency. For a number of different injection currents and feedback ratios, the coupling coefficient has been estimated for PCF. For low feedback levels (< 35%) the values predict a coupling efficiency in the range $\eta_c = 0.7 \pm 0.1$. As the feedback is increased the coupling coefficients predicted are outside this range, indicating that the theory, while showing qualitative agreement for all feedback levels (i.e. a decrease in power due to an increased efficiency), is not quantitatively appropriate for high feedback levels.

In summary, the coupling coefficient for a semiconductor diode laser with conventional optical feedback from a plane mirror is calculated by considering the reduction in slope efficiency and threshold injection current with feedback power. It is found to have a value of 0.22 ± 0.05 for the particular semiconductor laser system used. The plane mirror is then replaced by a phase conjugate mirror and the coupling coefficient is found to be significantly increased to 0.7 ± 0.1. This has important implications for strong feedback external cavity laser systems, which would benefit from the significant increase in coupling efficiency by using phase conjugate feedback rather than conventional mirror feedback. It also allows an improvement in the accuracy of theoretical models describing the effects of phase conjugate feedback on diode laser operation.

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High temperature GaInSbAs/GaAlSbAs quantum well singlemode continuous wave lasers emitting near 2.3μm

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Narrow ridge 5μm-wide GaInSbAs/GaAlSbAs quantum well (QW) lasers emitting in the continuous wave (CW) regime at temperatures up to 130°C have been fabricated. The CW threshold current varied between 20 and 35mA at room temperature (RT). The lasers operated in the fundamental spatial mode and exhibited single longitudinal mode emission over a wide range of CW operation conditions. The emission wavelength increased from 2.26μm at RT up to 2.43μm at 124°C. The CW output optical power reached 45mW/facet at 22°C and exceeded 10mW/facet at 100°C.

The wavelength range between 2.2 and 2.4μm is of great interest for molecular spectroscopy and environmental monitoring. In this spectral region the degree of water vapour absorption is very low while strong absorption lines of some pollutants, such as CO, CH_4, NO_2 and HCOH, are present. Tunable diode laser absorption spectroscopy (TDLAS) is one of the most accurate techniques for gas analysis and, to reduce the cost of the equipment, diode lasers operating in the continuous wave (CW) regime above room temperature (RT) are required.

Continuous wave lasing at room temperature (RT) above 2μm has been achieved using structures grown by molecular beam epitaxy (MBE) on GaSb substrates and employing compressively strained either type-I or type-II GaInSbAs quantum wells (QWs) in the active region. To provide maximum TDLAS performance, singlemode and single frequency lasers are required. Singlemode operation can be obtained in narrow ridge lasers with cleaved Fabry-Perot resonators. Single frequency type-I GaInSbAs/GaAlSbAs QW ridge waveguide lasers emitting near 2.1μm have been reported [1]. Lasers with coated facets have been realised which exhibit a maximum output power of 28mW in the CW regime at RT. Single frequency CW operation at 2.35–2.4μm has been realised in type-II GaInSbAs/GaSb QW narrow ridge lasers [2, 3] with a maximum output optical power of 17mW/facet at 20°C [3]. The near room temperature performances of type-I and type-II lasers is comparable but the lower temperature dependence of the threshold current in type-I devices makes them preferable for use at elevated temperatures. The highest to-date temperature for CW operation obtained to date for lasers emitting beyond 2 μm is 70°C [4], but CW characteristics of the lasers were given only at 15°C. In this Letter we present singlemode GaInSbAs/GaAlSbAs QW lasers operating in the CW regime up to 130°C.

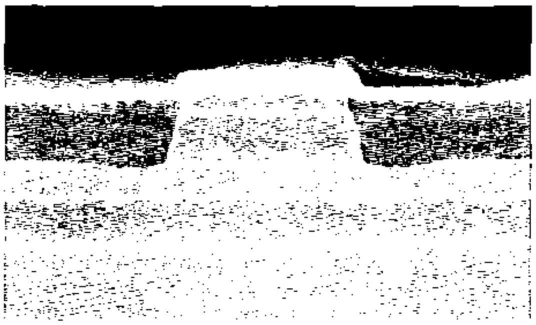

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Fig. 1 *Scanning electron microscope photograph of cleaved facet*

The laser structure, grown on an *n*-GaSb (Te) substrate by molecular beam epitaxy, contains the following layers: *n*-GaSb buffer, 0.1μm-thick *n*-layer graded from GaSb to $Ga_{0.1}Al_{0.9}SbAs$, 1.5μm-thick *n*-$Ga_{0.1}Al_{0.9}SbAs$ cladding, undoped 0.8μm-thick active region consisting of three 10nm-thick $Ga_{0.65}In_{0.35}Sb_{0.84}As_{0.16}$ quantum wells and four 30nm-thick $Ga_{0.65}Al_{0.35}SbAs$ barriers surrounded by $Ga_{0.65}Al_{0.35}SbAs$ spacers, 1.5μm-thick *p*-$Ga_{0.1}Al_{0.9}SbAs$ cladding, 0.1μm-thick *p*-layer graded from $Ga_{0.1}Al_{0.9}SbAs$ to GaSb, and 0.5μm-thick *p*-GaSb contact layer. All the layers are nominally lattice-matched to the substrate, except for the compressively strained wells.