increases with wavelength, due to the fact that the phase mismatch between the guided mode and the whispering gallery mode decreases with wavelength.[2] At 1550 nm the efficiency for some fibres for radii >4 mm exceeds 70%, whereas for tighter bends it is 20%. This reduction is due to the lower reflectivity of the buffer/cladding interface at higher angles of incidence.

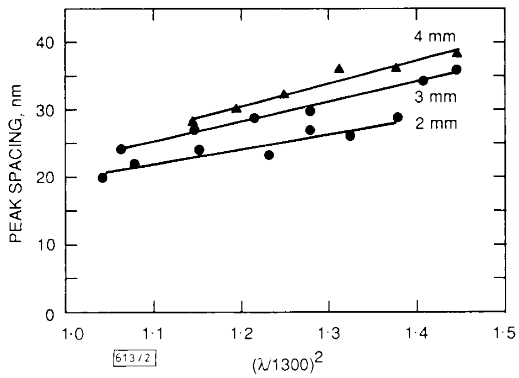

Fig. 2 *Measured peak spacing plotted against $(\lambda/1300)^2$ for three bend radii*

The loss peaks occur when the condition of zero net back-coupling is met. Thus, the peaks in loss represent the true bend loss measured at the peak wavelength. Therefore, an interpolation between the resonance peaks will provide an accurate estimate of the bend loss for all wavelengths. The interpolation is also shown in Fig. 1, along with the values obtained at 1550 nm.

We measured the losses for four fibres obtained from different manufacturers, the fibre had been developed as bend resistant. The 1550 nm results, obtained by the interpolation scheme, are shown in Fig. 3. Fibres A and B are dispersion shifted fibres, C is designed for 1300 nm operation (cutoff at 1240 nm) and D is designed for 1500 nm operation (cutoff at 1430 nm). The mode field diameters were measured using the standard offset technique. The mode field diameters at 1550 nm are $A = 9{\cdot}1$, $B = 8{\cdot}4$, $C = 7{\cdot}5$ and $D = 7{\cdot}3$ microns.[3] The bend loss decreases exponentially with radius, as predicted by theory,[4] in fact, the fit to an exponential dependence is very good for the interpolated data. The loss also depends strongly on the degree of confinement, as measured by the mode field diameter. We verified that the transition loss contributed to the total measured loss is small, by determining the bend loss at 1550 nm as a function of bend angle

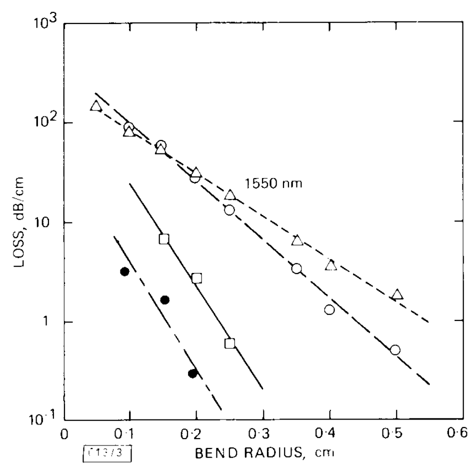

Fig. 3 *Bend losses at 1500 nm obtained by interpolation scheme, for four single mode fibres (shown in the inset are corresponding mode field diameters measured at 1550 nm)*

A ------ 9·1 μm B —— 8·4 μm
C ——— 7·5 μm D — — — 7·3 μm

$(60 \le \theta \le 180°)$ for a fixed radius. The transition loss, as measured by the projected zero angle loss was <0·2 dB at small radii. For fibres C and D the losses are 1·9 dB/cm and 0·3 dB/cm, respectively, at 2 mm radius.

It is clear from the measurements that for a 60 degree bend (which roughly emulates the peel point profile during payout) the loss for fibres C and D will be less than 0·5 dB, which is considerably less than the losses for fibres A and B. Fibres with 7–7·5 micron mode field diameters at 1550 nm are satisfactory designs for payout applications.

Increasing the degree of confinement does have its drawbacks, namely, increased Rayleigh scattering and increased splicing and connector loss. Fibre C exhibits high Rayleigh scattering with the loss at 1300 nm and 1550 nm being 0·9 and 0·6 dB/km, respectively. In contrast the loss for fibre D is 0·28 dB/km at 1550 nm, indicating that better control of fibre doping process and/or fibre drawing has reduced the scattering loss penalty. The smaller mode field diameters used here are not too small to make splicing and connector loss a significant problem.

In conclusion, we have measured the losses at 1 to 5 mm bend radii of some bend resistant fibre designs. The effective mode field diameter clearly determines the bend sensitivity. An interpolation scheme was used to measure the bend loss at all wavelengths, avoiding the complications of fixed wavelength measurements. This technique avoids the difficulties in fixed wavelength measurements which are caused by resonant coupling to whispering gallery modes. Loss values for small mode field diameter fibres are less than 2 dB/cm at 2 mm radius. The peel point loss can be less than 0·5 dB for the tight confinement designs, with low Rayleigh scattering or splice loss penalty.

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OPTIMISED FABRY–PEROT (AlGa)As QUANTUM-WELL LASERS TUNABLE OVER 105 nm

Indexing terms: Semiconductor lasers, Quantum optics

Uncoated, Fabry–Perot (AlGa)As semiconductor lasers are tuned over 105 nm in a grating-coupled external cavity. Broadband tunability is achieved by optimising the resonator loss so as to invoke lasing from both the first and second quantised states of the single quantum well active region.

Semiconductor lasers can provide broadband tunable, single-frequency, narrow line-width sources of radiation when coupled to an external cavity containing a frequency-selective tuning element. Experiments performed with antireflection coated lasers tuned with a diffraction grating have demonstrated tuning ranges of 50–60 nm at 0·8 μm[1,2] and 55 nm at

$1{\cdot}5\,\mu$m,[3] with the latter measuring linewidths of the order of 10 kHz. Similarly, $1{\cdot}3\,\mu$m lasers coupled to single-mode fibre evanescent grating reflective filters were tuned over 66 nm with linewidths less than 50 kHz.[4] Recently, quantum well (QW) semiconductor lasers were shown theoretically and experimentally to possess very wide, flat gain spectra near the onset of second quantised state ($n = 2$) lasing.[5,6] The spectral width of these 'gain-flattened' regions scales as the separation between the $n = 1$ and $n = 2$ carrier states in the QW. By optimising the laser resonator losses so as to include second quantised state lasing, and narrowing the QW to broaden the tuning range, we demonstrate grating-tuning over a range of 105 nm in $0{\cdot}8\,\mu$m (AlGa)As uncoated single QW lasers.

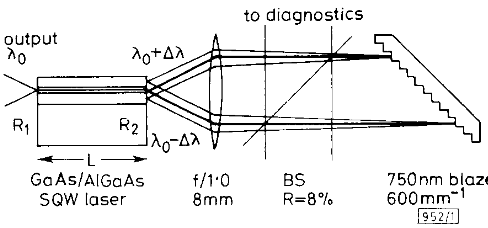

Fig. 1 *Schematic diagram of grating-coupled external cavity configuration*

Light emitted from rear facet of laser is dispersed by grating so that spectrum is imaged back onto facet, providing feedback at tuned wavelength

The experimental apparatus is illustrated schematically in Fig. 1. The external cavity consists of a collimating lens and a diffraction grating which together image a spectrally-resolved, spatially inverted nearfield back onto the rear facet of the semiconductor laser. The spectrum is dispersed perpendicular to the plane of the epitaxial layers and is imaged with 2·2 Å of resolution. This is enough to enforce single-longitudinal mode operation of Fabry–Perot resonators cleaved shorter than approximately $400\,\mu$m. The spectra in the near and far fields were monitored by intercepting the collimated beam with an $R = 8\%$ beamsplitter, while the power output was measured at the front facet of the laser.

The $Al_xGa_{1-x}As$ semiconductor lasers used in the experiment were fabricated from graded-index separate-confinement heterostructure single quantum well (GRINSCH-SQW) wafers grown by metal-organic chemical vapour deposition (MOCVD). The thickness of the GaAs QW was estimated to be 75 Å. Outside the QW, the Al content was graded linearly from a value of $x = 0{\cdot}2$ up to $x = 0{\cdot}4$ over a distance of $\simeq 2000$ Å per side. The $Al_{0\cdot4}Ga_{0\cdot6}As$ cladding layers were nominally $1{\cdot}5\,\mu$m thick. For the tuning experiment, oxide-isolated stripe contact lasers were fabricated and coupled to the external cavity without antireflection coating of the cleaved facets. To determine the effect of the uncoupled resonator loss on the tuning characteristics, lasers of various lengths up to $400\,\mu$m were tested. The grating was tuned to successive longitudinal modes of each Fabry–Perot laser, and the threshold current measured as a function of wavelength for operation under low duty cycle, pulsed (200 ns, 1 kHz) conditions.

Fig. 2 illustrates tuning data measured for devices cleaved to three different lengths: $L_1 = 400\,\mu$m, $L_2 = 240\,\mu$m and $L_3 = 160\,\mu$m. For devices of intermediate length L_2, stepwise tuning was achieved at over 300 contiguous longitudinal modes of the Fabry–Perot laser, spanning the wavelength range 750 nm to 855 nm. This 105 nm span, representing a tuning range of 13·1% about the centre wavelength of 800 nm, is the largest value yet published for a semiconductor laser. The threshold current in free-running operation (i.e. with the grating blocked) for $10\,\mu$m wide lasers was 130 mA, and corresponded to emission at 770 nm. This short wavelength and high current density ($\simeq$ several kA/cm^2) is consistent with lasing from the second quantised state of the quantum well.[5] The threshold in grating-tuned operation was thus reduced below the free-running threshold over 90 nm of the 105 nm tuning range. Within this 90 nm range, lasing was observed in a single longitudinal mode at power levels up to 75 mW for the $10\,\mu$m wide devices. As Fig. 2 indicates, however, devices cleaved significantly longer or shorter than $240\,\mu$m did not exhibit such broad effective tuning characteristics. Moreover, experiments performed on similarly optimised devices with wider quantum wells, of dimension 120 Å, exhibited tuning ranges of only 50 nm. This reduction in tuning range was expected due to the diminished energy separation between the $n = 1$ and $n = 2$ carrier states in the wider QW.

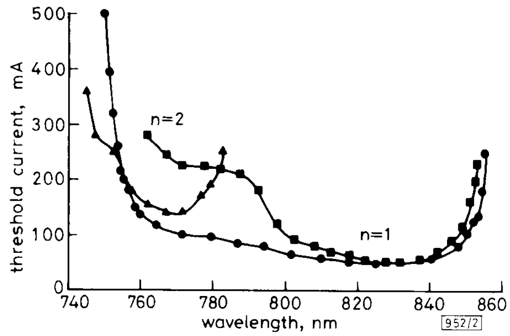

Fig. 2 *Threshold current measured as function of grating-tuned wavelength for lasers cleaved to three different lengths*

Free-running threshold currents are 90, 130 and 140 mA for devices of length 400, 240 and $160\,\mu$m, respectively. Intermediate length of $L_2 = 240\,\mu$m is optimised for broadband tuning from below first ($n = 1$) to above second ($n = 2$) quantised states of single quantum well active region.

■—■ $L = 400\,\mu$m ●—● $L = 240\,\mu$m ▲—▲ $L = 160\,\mu$m

To achieve optimum tuning, the uncoupled resonator is designed to have a loss slightly exceeding the peak gain at the onset of second quantised state lasing. At the pump level required to overcome this loss, the gain spectrum is very flat,[5,6] so that only a modest amount of external feedback is required for grating-tuning from below the $n = 1$ to above the $n = 2$ transition in the QW. The resonator requirement for broadband tuning can then be expressed by equating the maximum modal gain γ_0, available from first quantised state transitions[7] to the modal losses $\mathscr{L}$, as follows:

$$\mathscr{L} = \alpha + \frac{1}{2L}\ln\frac{1}{R_1 R_2} \simeq \frac{2\pi\mu^2 m_r}{\lambda_0 \varepsilon_0 n_0 \hbar^2 W_{mode}} = \gamma_0 \qquad (1)$$

where α is the distributed guided mode loss, L is the length of the Fabry–Perot resonator, and $R_{1,2}$ are the front and rear facet reflectivities, respectively. γ_0 is determined primarily by the design of the GRINSCH-SQW transverse laser structure. In eqn. 1 W_{mode} is the effective width of the transverse optical mode, μ^2 and m_r are the matrix element and reduced effective mass of the electron-heavy hole ($n = 1$) transition, respectively, ε_0 is the permittivity of free space and n_0 is the nonresonant refractive index. In actual fact, the gain at the onset of second quantised state lasing γ_0', is reduced from γ_0 by finite population inversion, but increased by contributions from the electron-light hole ($n = 1$) transition. Thus, γ_0 is a reasonable approximation for γ_0'. Typically $\gamma_0 \simeq 60$–$125\,\text{cm}^{-1}$, for our wafer we estimate $W_{mode} \simeq 3500$ Å and as a result $\gamma_0 \simeq 80\,\text{cm}^{-1}$. In this work, lasers were simply cleaved short enough to achieve this elevated loss level. The loss near the tuned wavelength, i.e. the wavelength which is retroreflected by the grating, is then reduced by the selective feedback to a level approximately $15\,\text{cm}^{-1}$ (for $L = L_2$) below that of all other wavelengths. This loss reduction could be increased by antireflection coating of the rear laser facet, but the flatness of the gain spectrum makes it unnecessary. Hence, no antireflection coating was applied. The reason for designing the loss $\mathscr{L}$, to be slightly above γ_0' (rather than slightly below) is evident from comparison of the tuning data for the two cases of $L_2 = 240\,\mu$m and $L_1 = 400\,\mu$m. Only for the $240\,\mu$m length was single longitudinal mode lasing achieved over most (90 of 105 nm) of the broad tuning range with a minimum variation in threshold current.

In conclusion, we have demonstrated stepwise tuning of Fabry–Perot single QW semiconductor lasers over ranges approaching those of dye lasers. Tuning in an external grating-tuned cavity over 105 nm under pulsed conditions has been achieved with stripe contact single QW lasers grown by MOCVD. The uncoupled resonator loss has been optimised to access a flattened gain spectrum, and a corresponding requirement for broadband tunability was given. Preliminary experiments indicate that tuning ranges in excess of 10% can be achieved under room temperature CW operation with improved contact quality. It now appears perfectly feasible that commercial QW semiconductor lasers based on GaInP, AlGaAs and GaInAsP will provide compact tunable solid-state sources of radiation in the wavelength region 650–1500 nm. At moderate output power, and reduced linewidths, these devices could replace dye lasers in many applications.

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MULTIPLE QUANTUM WELL-TUNED GaAs/AlGaAs LASER

Indexing terms: Semiconductor lasers, Quantum optics, Optical communications

The electrorefractive effect in a *pin* multiple-quantum-well (MQW) modulator has been used in a novel, electronically tuned, external-cavity GaAs/AlGaAs laser system. Mode selection over a frequency range of 600 GHz (1·4 nm in wavelength) has been demonstrated for a 6 V change in MQW modulator bias, with less than 0·6 dB variation in laser output power.

Introduction: The widespread adoption of coherent optical communications systems would be greatly facilitated by the development of simple electronically tunable, single-mode semiconductor lasers. While temperature[1] and bias current[2] tuning are well established approaches, they involve considerable attendant output power variation. Tuning speed is also limited by the thermal time constants of the laser and, for current tuning, by the photon and electron lifetimes. Interesting lasers having separate tuning sections utilising the plasma effect have been reported.[3,4] However, these exhibit considerable output power variation with changes in emission frequency owing to electroabsorption in the tuning section.

Multiple-quantum-well (MQW) material displays a considerable electric field-induced variation in refractive index, which has been studied for both the GaAs/AlGaAs[5] and InP/GaInAsP[6] systems. Variations of over 1% are readily obtainable, a value approximately one hundred times that for bulk material. This letter describes a novel, external cavity, GaAs/AlGaAs laser system which uses electrorefraction in an MQW device to provide electronic frequency tuning.

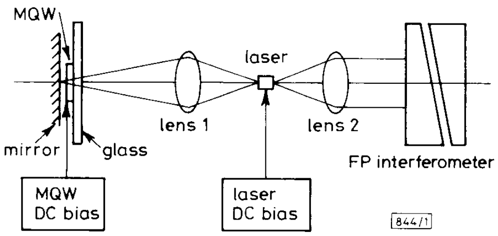

Fig. 1 *MQW tuned semiconductor laser*

Experiment: Fig. 1 shows the experimental arrangement used. The laser was a GaAs/AlGaAs CSP device (Hitachi HLP 1400) emitting at about 830 nm. The MQW tuning element was a GaAs/AlGaAs *pin* structure as described by Whitehead *et al.*[7] (wafer MV246). Growth was by MOVPE to give 75 wells, each of width 4·7 nm, with 6 nm-wide barriers. Devices were defined by mesa etching, and 400 μm × 400 μm windows were etched through the GaAs substrate so that the structure could be illuminated perpendicularly to the junction plane. At a wavelength of 830 nm the change in transmission of the completed devices was less than 2% over the reverse bias range 0–12 V. Devices were mounted on glass slides with a plane mirror behind the device to complete the optical cavity.

One facet of the laser was coupled to the tuning element through a GRIN-rod lens, giving an optical cavity length of 15 mm. The other facet was coupled to a scanning Fabry–Perot interferometer through a ×10/0·17 NA microscope objective, care being taken to minimise optical feedback to the laser.

Neither facet of the laser was antireflection-coated. The system can therefore be analysed as a coupled cavity laser with emission occurring at wavelengths where the two cavity resonances coincide. Because the coupling of the external cavity to the laser is weak, its main effect is to select laser cavity modes. The change in the optical length of the external cavity required to produce a wavelength increase of k modes is

$$\Delta l \simeq \frac{\lambda_0}{2}\left(\frac{kl_l}{l_o} - n\right) \tag{1}$$

where l_o is the optical length of the semiconductor laser cavity, l_l that of the external cavity for $k = 0$ ($l_l > l_o$), λ_0 the emission wavelength for $k = 0$, and n the largest integer less than kl_l/l_o. Optimum tuning sensitivity occurs when l_l is close to an integral multiple of l_o, the minimum value being set by the onset of multimode operation. In the experiment l_l was optimised by placing the tuning element on a micropositioning stage.

Since it is hard to measure the ratio l_l/l_o with high accuracy, Δl was measured by first adjusting l_l to give low mode selection sensitivity and biasing the laser close to threshold so that the laser cavity modes were broadened. Δl could then be determined from the optical frequency shift Δf produced by tuning the external cavity by an amount insufficient to produce a laser cavity mode change:

$$\Delta l = \frac{\Delta f l_l \lambda_0}{c} \tag{2}$$

where c is the velocity of light in vacuo.