increases with wavelength, due to the fact that the phase mismatch between the guided mode and the whispering gallery mode decreases with wavelength. 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 (λ/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 interpoint 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 1900 nm operation (cutoff at 1430 nm). The field diameters were measured using the standard offset technique. The field diameters at 1550 nm are A = 9.1 μm, B = 8.4 μm, C = 7.5 μm and D = 7.3 μm. The bend loss decreases exponentially with radius, as predicted by theory, 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 effective area and bend radius. This indicates that 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 0.6 dB/cm, respectively, at 2 mm radius.

It is clear from the measurements that for a 60 degree bend radius, the transition loss so as to invoke lasing from both the first and second quantised states of the single quantum well active region.

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 diameters fibres are less than 2 dB/cm at 2 mm radius. The peak point loss can be less than 0.5 dB for the tight confinement designs, with low Rayleigh scattering or splice loss penalty.

References


Fig. 3 Bend losses at 1550 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.

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

Indexing terms: Semiconductor lasers, Quantum optics

Uncoated, Fabry-Perot (AIGa)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, 1.5 and 55 nm at 1.3 and 1.55 μm, respectively. The measured tuning range is limited by the grating efficiency, and further tuning is expected by use of more efficient gratings.
1.5 μm,3 with the latter measuring linewidths of the order of 10 kHz. Similarly, 1.3 μm 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 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 0.8 μm (AlGa)As uncoated single QW lasers.

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 400 μm. The spectra in the near and far fields were monitored by intercepting the collimated beam with an R = 98% beamsplitter, while the power output was measured at the front facet of the laser.

The Al0.4Ga0.6As 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 = 0.2 up to x = 0.4 over a distance of 2000 Å per side. The Al0.4Ga0.6As cladding layers were nominally 1.5 μm 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 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 under low duty cycle, pulsed (200 ns, 1 kHz) conditions.

Fig. 2 illustrates tuning data measured for devices cleaved to three different lengths: L1 = 400 μm, L2 = 240 μm and L3 = 160 μm. For devices of intermediate length L2, stepwise tuning was achieved at over 300 continuous 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 μm wide lasers was 130 mA, and corresponded to emission at 770 nm. This short wavelength and high current density (< several kA/cm²) 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 μm wide devices. As Fig. 2 indicates, however, devices cleaved significantly longer or shorter than 240 μm 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.

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 cavity is facilitated by the selective feedback to a single longitudinal mode and is imaged with 2.2 Å of resolution. This loss reduction could be increased by finite population inversion, but increased by contributions from the electron–heavy hole transition. Thus, γ2 is a reasonable approximation for γ0, available from first quantised state transitions to the modal losses \( \gamma' \), as follows:

\[ \gamma' = \gamma_0 + \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right) = \frac{2nm^2}{W_{mode}} - \gamma_0 \]
MULTIPLE QUANTUM WELL-TUNED GaAs/AlGaAs LASER

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 bias and current 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. 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 and InP/GaInAsP 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.

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. (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 x 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 x 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

\[ \Delta l \approx \frac{\lambda_0}{2n_k} \]  

where \( \lambda_0 \) is the optical length of the semiconductor laser cavity, \( l_0 \) that of the external cavity for \( k = 0 \) (i.e., \( l_0 \)), \( \lambda_0 \) the emission wavelength for \( k = 0 \), and \( n \) the largest integer less than \( k l_0/\lambda_0 \). Optimum tuning sensitivity occurs when \( l_0 \) is close to an integral multiple of \( l_0 \), the minimum value being set by the onset of multimode operation. In the experiment, \( l_0 \) was optimised by placing the tuning element on a micropositioning stage.

Since it is hard to measure the ratio \( l_0/\lambda_0 \) with high accuracy, \( \Delta l \) was measured by first adjusting \( l_0 \) to give low mode selection sensitivity and biasing the laser close to threshold so that the laser cavity modes were broadened. \( \Delta l \) could then be determined from the optical frequency shift \( \Delta f \) produced by tuning the external cavity by an amount insufficient to produce a laser cavity mode change:

\[ \Delta l = \Delta f \lambda_0 c \]  

where \( c \) is the velocity of light in vacuo.

References