Worst case dynamic range of the system is in excess of 13 dB; as shown in Fig. 4. The output pulse quality is generally significantly better than this, much of the observed lower amplitude signal structure being present on the input pulse and replicating directly to the output. The measured system insertion loss of 0·85 dB represents the losses arising in the four tunable couplers, determined by direct comparison with a comparable length of monomode fibre to be below the limit of characterisation and thus better than 0·004 dB, together with the two FC/PC connectors interfacing the code generator system to the external test system.

Table 2 PULSE WIDTH CHARACTERISTICS

Bit	Mean (ps)	Standard deviation (ps)
bit1	113·9	0·36
bit2	111·8	0·56
bit3	117·1	0·16
bit4	118·4	0·31
Overall	115·4	0·45

Hysteresis in the mechanical coupler units prevented absolute calibration of coupling strength against tuning scale reading. It is operationally preferable to set the output pulse levels by direct reference to the generated waveform. Fig. 4 confirms the validity of this approach for setting uniform pulse intensities, with pulse height deviation of less than 0·13 dB being readily achieved.

Conclusions: We have demonstrated the feasibility of the manufacture of monolithic arrays of evanescent wave coupler elements in a single length of fibre with uniform coupling characteristics and repeatable coupler separation. This is suitable for the assembly of splice-free multi-stage optical fibre lattice signal processing systems, confirming that multi-element arrays of high precision couplers can be fabricated on a single fibre length at separations considerably less than the mechanical dimensions of an individual mechanical assembly. Although an output pulse repetition rate of 2 GHz has been demonstrated, based on an incremental fibre delay length of 103 mm, this dimension is obviously capable of significant further reduction. Given current technology, it appears perfectly feasible to reduce the incremental delay by a factor of 10, to the order of 10 mm, giving an output pulse repetition rate of 20 GHz.

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BROADBAND TUNING (170 nm) OF InGaAs QUANTUM WELL LASERS

Indexing terms: Semiconductor lasers, Tuning

The wavelength tuning properties of strained InGaAs quantum well lasers using an external grating for feedback is reported. Tunable laser oscillation has been observed over a range of 170 nm, between 840 and 1010 nm, under pulsed current excitation. The optimal conditions for broadband tunability for the InGaAs lasers are different from GaAs lasers, which is attributed to a difference in spectral gain curves. Together with an optimised GaAs quantum well laser the entire region between 740 and 1010 nm is spanned.

Semiconductor lasers exhibit broadband gain and can emit radiation over a wide spectrum under proper operating conditions. Quantum well lasers, in particular single quantum well lasers, can make better advantage of this bandwidth than bulk double heterostructure lasers because of their small active region volume and larger band filling at the same current density. This large bandwidth can be useful in creating short mode locked pulses,[1] and for applications where broadband tunability is desired.[2] The use of InGaAs for the active region of the laser permits the lasing to be extended beyond 1 μm and includes the 980 nm wavelength which is of current interest for pumping Er^{+} doped fibre amplifiers. We report on the broadband tuning properties of strained InGaAs quantum well lasers and compare them with GaAs quantum well lasers optimised for this purpose. The InGaAs lasers have been tuned over a wider range, 170 nm, than previous reports[3] and we observe a difference in the tuning characteristics compared with GaAs lasers.

An optimal laser for tunability has a perfectly flat gain spectrum so that a wavelength dependent loss mechanism can select the desired lasing wavelength without a large increase in bias current. GaAs single quantum well lasers have been shown to have a step-like gain curve, with the separation between steps corresponding to the separation of the $n = 1$ and $n = 2$ quantised levels in the well.[4] To optimise the tuning range of these devices, the energy separation between the two states is made as large as possible, which is limited by the difference in the band gap of the barrier and well materials. The laser is then operated under conditions where most of the states between these levels are populated with carriers, and lasing can then occur at any of these energies given the proper feedback. Our optimised GaAs lasers have a 60 Å quantum well with $Al_xGa_{1-x}As$ ($x = 0{\cdot}4$–$0{\cdot}7$) graded barriers, and are cleaved just short enough to lase free running (without feedback) in the $n = 2$ state.[5] With a diffraction grating to provide feedback in an external cavity configuration these lasers are then tuned to the filled lower energy states and oscillate at the corresponding wavelengths. The wavelength range over which we can tune the GaAs laser is 125 nm.

To extend the tuning range to shorter wavelengths, a higher carrier confinement barrier than is available in $Al_xGa_{1-x}As$ is necessary. To access longer wavelengths, an active region of lower band gap material can be used. The relative barrier heights are now larger, permitting the use of a narrower wells and thereby increasing the energy subband separation and absolute tuning range. $In_yGa_{1-y}As$ ($y > 0$) has a lower band gap than GaAs and, when used as the active region in quantum well lasers, has been shown to emit at wavelengths as long as 1·1 μm.[6] Although the $In_yGa_{1-y}As$ is not lattice-matched to the GaAs substrate, high quality devices, i.e., with low threshold currents[7] and high quantum efficiencies,[8] can still be fabricated since the thin wells in these structures are less than the critical layer thickness[9] for this material system. We have examined the tunability of an $In_yGa_{1-y}As$ quantum well structure bounded by a GaAs spacer and an $Al_xGa_{1-x}As$ ($x = 0{\cdot}2$–$0{\cdot}5$) graded region for confinement of the optical mode.

The 50 Å $In_{0\cdot35}Ga_{0\cdot65}As$ single quantum well structure was grown on a GaAs substrate by molecular beam epitaxy (MBE) and has a 40 Å GaAs spacer layer on each side. Details of the growth conditions have been reported elsewhere.[7] From this low threshold current material, 10 μm wide stripe ridge waveguide lasers were fabricated and tested. We cleaved lasers of various lengths and show the measured emission wavelength as a function of cavity length, L, in Fig. 1. A sharp

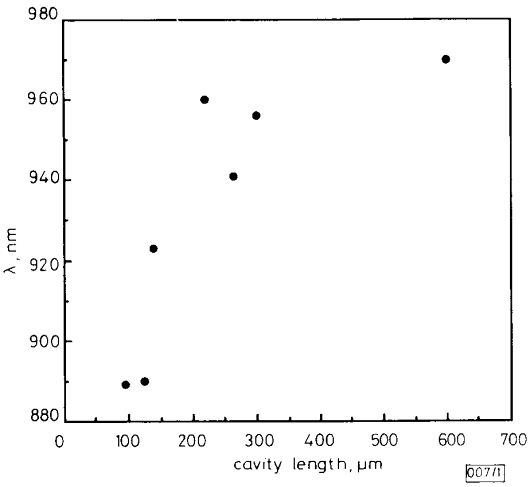

Fig. 1 *Measured lasing wavelength against cavity length*

transition to shorter wavelengths is apparent for $l < 150\,\mu$m, which we attribute to the $n = 2$ lasing state.[4] For the tuning experiments, the lasers were uncoated and operated pulsed at low duty cycle and placed in an external cavity as described elsewhere.[4,5] Results from the tuning measurements are presented in Fig. 2, where we have plotted threshold current as a function of tuned wavelength. As a comparison we also show the tuning characteristic of an optimised GaAs quantum well laser. The InGaAs laser oscillates over 170 nm, which is to be compared with 125 nm for the best GaAs laser. As far as we know these are the widest published tuning ranges for these material systems. The threshold currents are comparable for the two lasers and are low enough to permit CW operation. In agreement with other work[3] we see a continuous tuning curve into GaAs wavelengths.

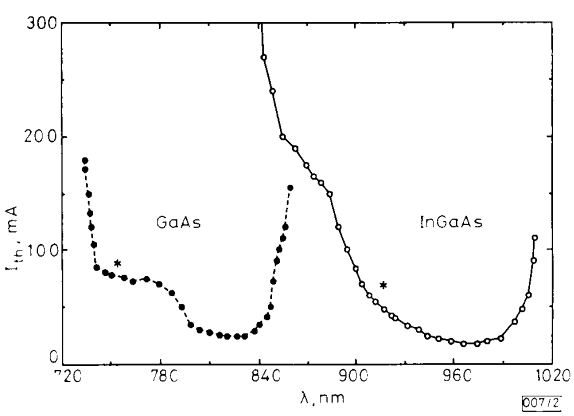

Fig. 2 *Threshold current at grating selected wavelength*

Free running values of I_{th} and λ are indicated by an asterisk

Our measurements indicate that the tuning characteristics of the InGaAs lasers are qualitatively different from the GaAs lasers. For GaAs lasers we have seen, from calculations of gain spectra and previous tuning measurements, that the spectral gain saturates at high current injection, and is relatively flat just at the onset of the second quantised state lasing, in agreement with the simple theory.[4] When the gain requirement of the resonator is set too high, an abrupt reduction in the tuning range is observed since the $n = 1$ transistions are no longer accessible.[5] For InGaAs lasers we observe a gradual loss of tuning on the long wavelength side on increasing the gain requirement. We measured the tunability of InGaAs lasers of various cavity lengths, shown in Fig. 3, and found

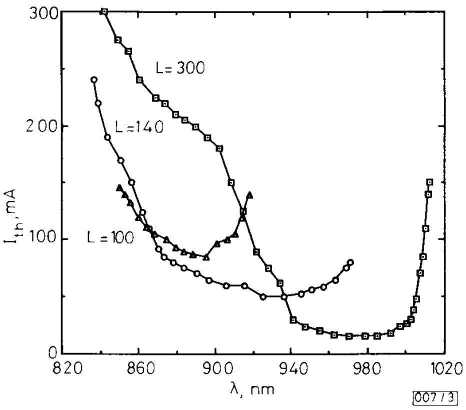

Fig. 3 *Tuning curves for InGaAs laser*

that as the cavity length is shortened the tuning range on the long wavelength side decreased. This indicates that the maximum available gain from the $n = 1$ transitions in the strained lasers is not as flat as for unstrained GaAs quantum well lasers. The results suggest that the maximum gain, from $n = 1$ transitions, is significantly lower at the longer wavelengths and the feedback from the grating is not sufficient to overcome the losses. Our experimental results, in particular the difference in tuning characteristics of InGaAs and GaAs, can be explained by considering a simple model for the maximum achievable gain. When operating at high current densities the gain at a given wavelength reaches a maximum value and, to a first approximation, follows the spectral distribution of the density of interband transitions. From energy band calculations by Suemune *et al.*,[10] the valence band density of states (DOS) is an increasing function of hole energy in strained InGaAs quantum wells and can increase by as much as a factor of three in the first quantised state. Since the reduced DOS is given by

$$\rho_r = \frac{\rho_v}{1 + \dfrac{\rho_v}{\rho_c}} \qquad (1)$$

we see that the maximum gain is increased by a factor of 1·5 when ρ_v/ρ_c increases from a value near unity at the first sub-band edge compared with its value of near three just below the second sub-band. If we scale the gain constant of GaAs with effective mass we see that the absolute gain difference is in the order of 35 cm^{-1}, which can explain our observations. A more detailed calculation of the modal gain constant as a function of wavelength is shown in Fig. 4. Here we have used the data published by Suemune *et al.*,[10] for the valence band DOS, assumed a constant electron effective mass, and a matrix element equal to that of GaAs. These calculations suggest that the modal gain at 1000 nm is limited to 50 cm^{-1} no matter how strong the pumping. The maximum available gain at 900 nm is more than 1·5 times larger. Consequently, the gradual loss in tuning at long wavelengths can be attributed to the nonparabolicity in the valence band.

In conclusion we have tuned InGaAs quantum well lasers over 170 nm and, together with an optimised GaAs laser operated in the same external cavity, we see that the entire region between 740 nm and 1010 nm can be spanned. In the course of these measurements a different behaviour between the strained and unstrained lasers corresponding to a different shape of spectral gain curves for the two types of lasers can be detected. A possible explanation is an energy dependent valence band effective mass in the strained laser.

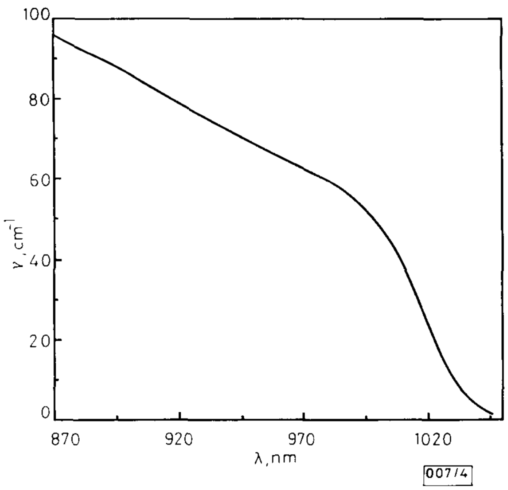

Fig. 4 *Calculated gain spectrum of InGaAs laser*

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HIGH-SPEED FULLY SELF-ALIGNED SINGLE-CRYSTAL CONTACTED SILICON BIPOLAR TRANSISTOR

Indexing terms: Bipolar transistors, High-speed devices, Epitaxial lateral overgrowth, Self-aligned

A novel high-speed self-aligned *npn* bipolar transistor fabrication process is presented. Base contacts are formed by epitaxial lateral overgrowth of single-crystal silicon on silicon-dioxide. Impurity-enhanced oxidation of silicon is used to achieve self-alignment of the emitter. Ultra-low resistance *p*-type base contacts have been fabricated with measured sheet resistances of 19 Ω/□.

Very fast switching speeds in modern bipolar junction transistors (BJT) have been achieved by reducing parasitic components within the device such as the base/collector capacitance, C_{bc}, base/emitter capacitance, C_{be}, and base resistance, r_b.[1] To reduce these parasitics, virtually all high-speed BJT processes use heavily doped polysilicon, polyoxides, and in some cases metal silicides to form small area 'self-aligned' extrinsic base and emitter contacts.[2] As a consequence, the extrinsic base resistance, $r_{b'}$, is dependent on the polysilicon and/or poly-silicide-related processing difficulties such as control of grain size, impurity diffusion, long-term material stability, poly-oxide leakage, and inherent oxide trapping at the poly/substrate interface.

As a major improvement over poly-silicon, we propose a bipolar super self-aligned transistor (SST) utilising all single-crystal silicon base contacts. A unique application of impurity-enhanced oxidation is described in forming ultra-low resistance base contacts with measured sheet resistances of 19 Ω/□. The resulting device, shown in Fig. 1, will significantly lower extrinsic base resistance and thereby increase circuit speed when compared with devices with state-of-the-art poly-silicon contacts having sheet resistances of 50–200 Ω/□.[3] Isolation of the extrinsic base/emitter region with high-quality

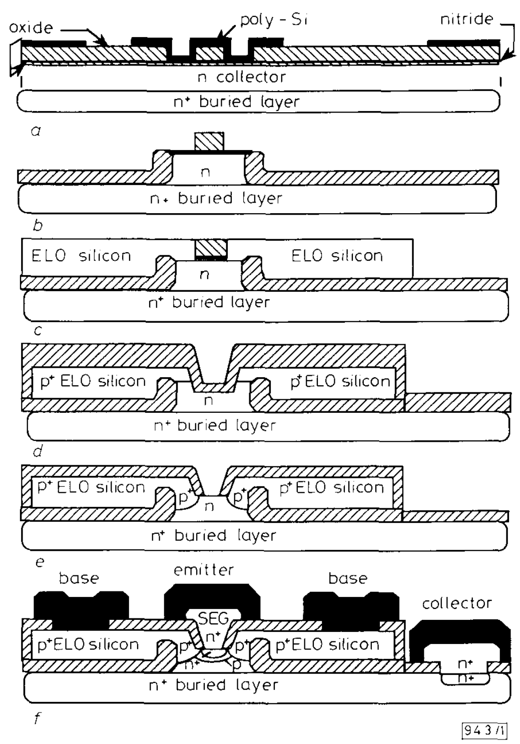

Fig. 1 *Fabrication sequence*

a Via holes
b LOCOS mesa
c ELO-silicon
d Base contact oxidation
e Base contact RIE
f Complete structure