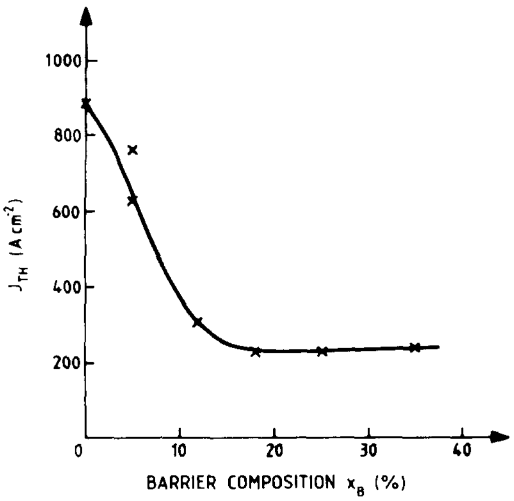

FIG. 3. Variation of J_{th} with the quantum well barrier height.

increased steeply as x_B decreased as shown in Fig. 3.

In conclusion, the variation of emission wavelength with well thickness was best fitted by assuming a well thickness that was 30 Å in excess of the originally estimated value.

In spite of the above problem very low threshold current density laser structures have been achieved and it was shown that low threshold current densities and acceptable T_0 values can be obtained by choosing a suitable form of the aluminium profile. There was no apparent enhancement of T_0 due to size quantization effects and in these single quantum well lasers the maximum value of T_0 was 190 K.

We deduce that the "GRIN" part of the structure behaves as a "funnel" for electrons which enhances confinement as predicted previously.[1] In addition, it increases the probability of electron capture by the quantum well.

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Coupled parallel waveguide semiconductor laser

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The operation of a new type of tunable laser, where the two separately controlled individual lasers are placed vertically in parallel, has been demonstrated. One of the cavities ("control" cavity) is operated below threshold and assists the longitudinal mode selection and tuning of the other laser. With a minor modification, the same device can operate as an independent two-wavelength laser source.

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It is well known that tandem coupled cavity lasers possess a high degree of frequency selectivity compared to single cavity semiconductor lasers.[1–4] This selectivity is due to the additional constraints imposed on the oscillation condition by the added cavity. By (current) control of the optical length of the coupled (extra) cavity, it has been possible to tune the output wavelength of such lasers over significant regions.[2]

It has been demonstrated recently[5,6] that longitudinal mode selectivity can also be achieved by coupling two or more semiconductor laser cavities in *parallel*. As was pointed out,[6] the frequency selectivity in this case involves a control of the phase velocities of the coupled waveguides rather than of resonant frequencies.

In this letter, we report on a new type of parallel-coupled-waveguide (PCW) diode laser, in which the two individually biased active regions are placed one above the other. The output wavelength tuning in this device results from a variation of the gain (and index) of one of the coupled waveguides (the "control" waveguide) by means of current injection through its separate contact.

The PCW laser is illustrated schematically in Fig. 1(a), and its cross section is shown in Fig. 1(b). Fabrication of the device involved a two-step liquid phase epitaxy (LPE) growth on a p^+ (Zn doped) GaAs substrate. In the first LPE step a single n^+-GaAs layer was grown ($\sim 2\,\mu$m; Te doped, $\sim 6\times 10^{18}$ cm^{-3}). Next, 10-μm-wide and ~ 3-μm-deep grooves were etched parallel to $\langle 011\rangle$ direction using a 1:8:8 (H_2SO_4:H_2O:H_2O_2) solution. In the second LPE growth five layers were grown: (1) 0.9 μm p-$Al_{0.4}Ga_{0.6}As$, (2) 0.2 μm n-GaAs (active region of bottom laser; Sn doped, 6×10^{17} cm^{-3}), (3) 1.0 μm n-$Al_{0.25}Ga_{0.75}As$ (optical coupling layer),

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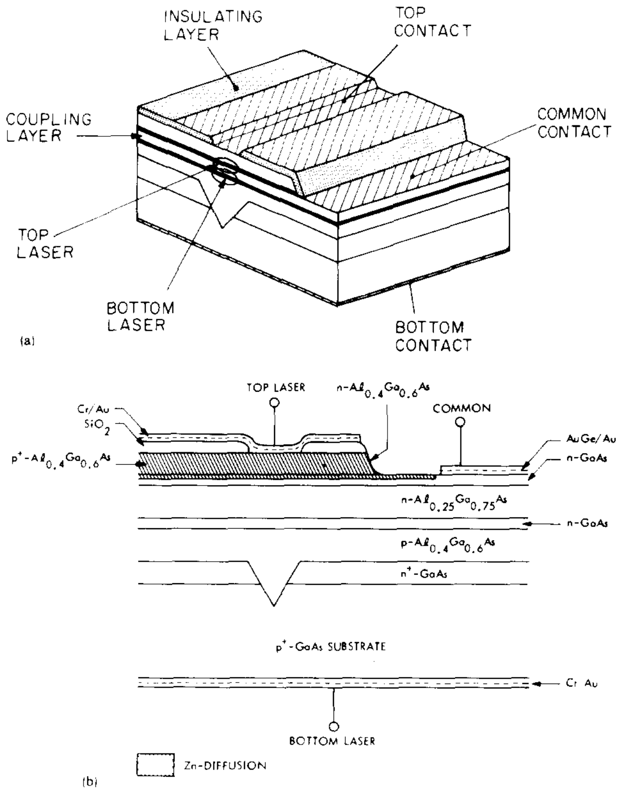

FIG. 1. (a) Schematic illustration of the coupled-parallel-waveguide laser. (b) Schematic cross section of the device.

(4) 0.2 μm n-GaAs (active region of top laser; Sn doped, 6×10^{17} cm^{-3}), (5) 2 μm n-$Al_{0.4}Ga_{0.6}As$. The two top layers were then converted into p^+-type regions by Zn diffusion, and oxide stripe contacts ($\sim$8 μm wide) were fabricated above the V grooves, to form one contact of the top laser [see Fig. 1(b)]. One one side of the stripe contact, the wafer was etched down to the top active region, and AuGe/Au contact was evaporated on the etched region. Finally, the wafer was lapped and Cr/Au contact was evaporated on the substrate side.

The PCW laser described here consists of two gain-guided stripe lasers which are coupled optically and whose currents can be controlled independently. The top laser is a conventional oxide stripe laser, whereas the current confinement in the bottom one is accomplished by the n^+-GaAs blocking layer[7] [see Fig. 1(b)]. These lasers were operated under low duty cycle pulsed conditions and threshold current of each individual laser was, typically, 100 mA. The mode structure of these lasers was investigated by observing their spectrally resolved near fields. These were obtained by imaging the near fields on the entrance slit of a spectrometer, using a 20× objective lens, and displaying the output on a monitor using a silicon-vidicon TV camera. The spectrum of each laser could then be obtained by scanning a selected line of the video signal.

The spectrum of the top laser was found to be shifted toward longer wavelengths by $\sim$50 Å. This shift occurred because of the smaller band gap of the top active region, which was p doped due to the Zn diffusion. When the top laser was operated by itself, its spectrum was considerably narrower than the spectral width of conventional gain-guided lasers. An example of such a spectrum is shown in Fig. 2(a). By biasing the bottom laser *below* threshold, it was possible to obtain even narrower spectral envelopes of the top laser. Figure 2(b) shows essentially single longitudinal mode operation of the top, *gain-guided* laser, which is assisted by the control current in the coupled bottom laser. At still higher currents through the bottom laser, this laser attained threshold, and the two coupled lasers operated independently, as shown in Fig. 2(c).

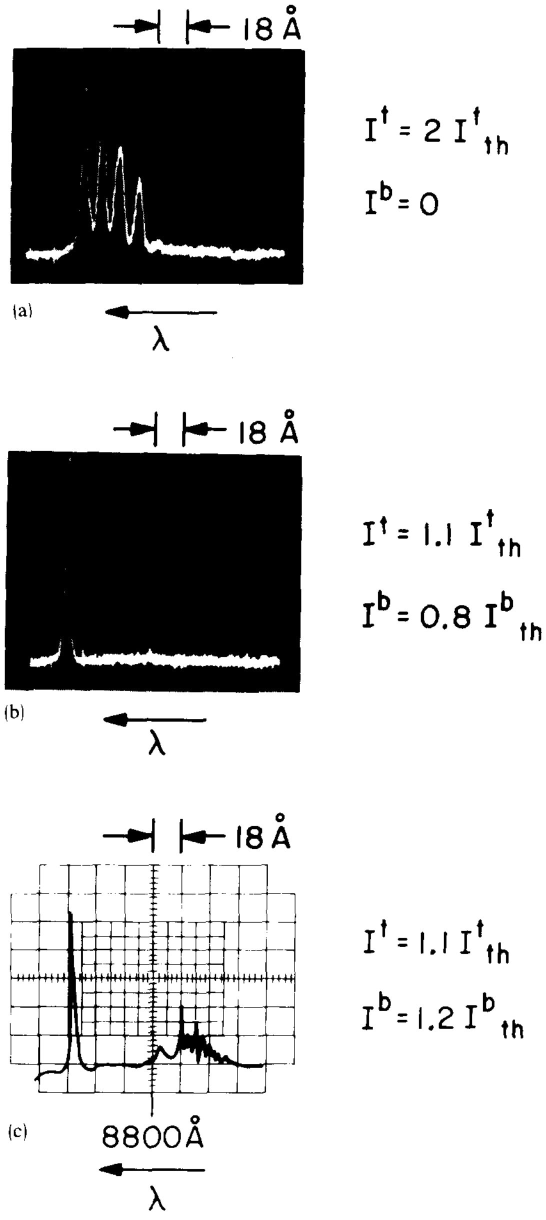

FIG. 2. Output wavelength control with the coupled-parallel-waveguide laser. (a) Top laser operating alone. (b) Top laser is operated above threshold, bottom laser is operated below threshold. (c) Both lasers are operated above threshold. The currents of top and bottom lasers, I^t and I^b, are indicated in the figure for each case.

The separate current control of each active region makes it possible to modify the complex dielectric constant of the lower resonator by varying the current applied to it, while the upper laser is biased above threshold. This current variation, in turn, is expected to change the resonance condition of the combined cavity, which can result in wavelength tuning. Such tuning is demonstrated in Fig. 3, where the output wavelength of the top laser is shown to tune toward

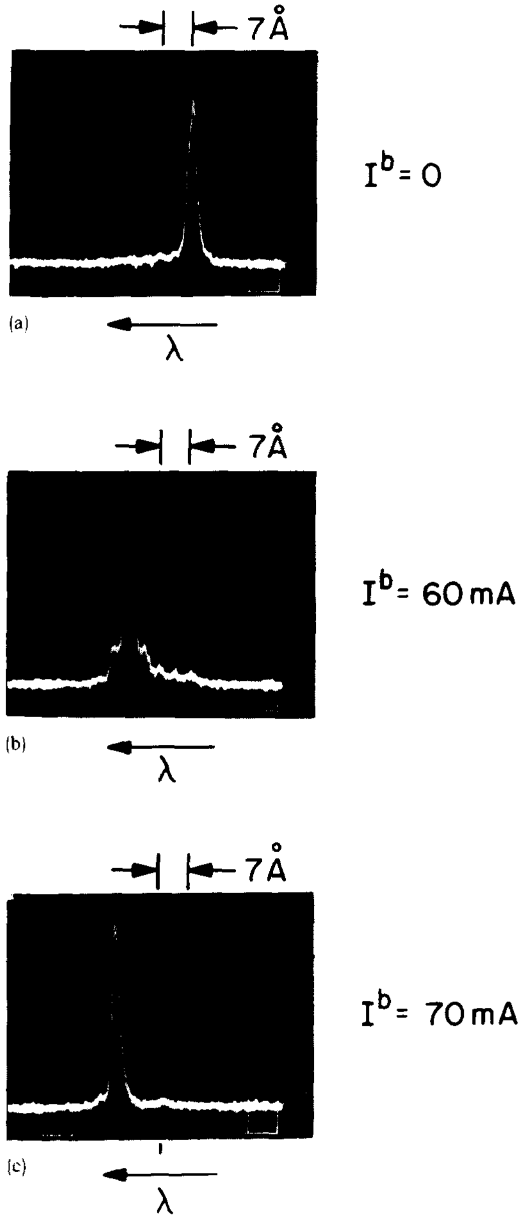

FIG. 3. Output wavelength tuning with the coupled-parallel-waveguide laser, for fixed current of the top laser, $I^t \cong 1.1 I^t_{th}$, and for various currents I^b of the bottom laser. (a) $I^b = 0$, (b) $I^b = 60$ mA, (c) $I^b = 70$ mA. The wavelength is about 8800 Å.

longer wavelengths by mode hopping, as the control current through the lower cavity was increased. Tuning ranges up to 30 Å were achieved in such cases.

The explanation of the frequency control mechanism observed in our PCW laser involves the concept of the eigenmodes ("supermodes") of a two (parallel) coupled waveguide configuration. It is well known[6,8] that near the phase velocity matching point of the two waveguides, the spatial profile of the supermode is a sensitive function of the difference in the phase velocities, and, hence, of the wavelength. It follows that for a given set of input currents (I_1, I_2) into the two coupled waveguides, the laser will "choose" to operate at the wavelength where the corresponding modal profile best "milks" the gain, i.e., where the modal gain is a maximum. This extra agility, i.e., the dependence of mode profile on λ is the basis for the tuning mechanism. Since even small differences in modal gain can lead to large tuning, the changes in profile attendant on tuning can be made very small and unobjectionable. A more detailed analysis of this frequency control mechanism will be given elsewhere.

Frequency stability was demonstrated also by the double active region lasers reported by Tsang *et al.*,[5] in which, however, the two active regions could not be biased separately. From the results presented in the present work, it is clear that the incorporation of separate contacts for the coupled waveguides is essential, particularly if output wavelength tuning is desirable. It should also be noted that by increasing the thickness of the coupling layer (see Fig. 1), one could obtain a two-wavelength laser source. Multiwavelength diode lasers that have been demonstrated previously either did not have the separate control of each wavelength,[9-10] or incorporated two sources in a lateral configuration.[11]

In conclusion, we have reported on the fabrication and operation of an integrated device which incorporates two parallel coupled laser cavities, each controlled separately, in a vertical configuration. Under the current device parameters, one of the cavities is operated below threshold and serves the longitudinal mode selection and tunability of the other laser. In particular, it is demonstrated that by coupling a parallel waveguide to a gain-guided laser, it is possible to obtain a *single* longitudinal mode operation of this, usually multimode, laser. With a minor modification, the same device operates as a two-wavelength laser source.

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