for the detection function at data rates up to 900 Mbit/s, as limited by the differential carrier lifetime, and with a fibre-to-fibre amplification of around 10 dB. (For the simultaneously amplified signals, these bit error rates can be achieved at multi-Gbit/s rates; we experimentally demonstrated 2 Gbit/s.) The mode of operation of the amplifier device we report here significantly increases the utility of laser amplifiers in photonic transmission and switching systems.

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ROOM-TEMPERATURE CONTINUOUS-WAVE VERTICAL-CAVITY SINGLE-QUANTUM-WELL MICROLASER DIODES

Indexing terms: Semiconductor lasers, Quantum optics, LEDs

Room-temperature continuous and pulsed lasing of vertical-cavity, single-quantum-well, surface-emitting microlasers is achieved at ~983 nm. The active $Ga_{0.8}In_{0.2}As$ single quantum well is 100 Å thick. These microlasers have the smallest gain medium volumes among lasers ever built. The entire laser structure is grown by molecular beam epitaxy and the microlasers are formed by chemically assisted ion-beam etching. The microlasers are 3–50-μm across. The minimum threshold currents are 1·1 mA (pulsed) and 1·5 mA (CW).

Vertical-cavity, surface-emitting lasers[1–4] have many potential advantages over conventional edge-emitting lasers owing to their inherent two-dimensional nature and very short cavity lengths. The previous results of the optically pumped lasers[5] and electrically pumped microlasers[6] implied very low threshold current for a single-quantum-well (SQW) microlaser with proper current injection into an active gain medium.

We made various sizes (3–100 μm) of electrically driven vertical cavity microlasers with a 100 Å-thick GaInAs SQW gain medium. The basic structure is a vertical *pin* junction where electrical current is injected through the bottom and top mirrors. The sample is grown on an Si-doped n^+ GaAs substrate by molecular beam epitaxy. The bottom (output) mirror has 23·5 pairs of AlAs/GaAs quarter-wave stack and is Si-doped $3 \times 10^{18}\,cm^{-3}$. The calculated reflectivity for the bottom mirror is 99·87% at 980 nm. The top mirror consists of 15 pairs of AlAs/GaAs quarter-wave stack Be-doped $5 \times 10^{18}\,cm^{-3}$, phase matching superlattices of GaAs/AlAs, 30 Å of delta-doped (Be, $1 \times 10^{13}\,cm^{-2}$) GaAs for *p*-type ohmic contact, and a 1500 Å thick gold film. The calculated reflectivity for the top mirror is 99·96% at 980 nm. The spacer region consists of a SQW of 100 Å $Ga_{0.8}In_{0.2}As$ active gain region surrounded by a pair of graded $Al_xGa_{1-x}As$ ($x = 0{\cdot}2$–$0{\cdot}5$) and $Al_{0.5}Ga_{0.5}As$ layers so that the combined optical thickness is a full wave. The resultant microresonator should have very high finesse (> 1000) to balance the very small gain from 100 Å-thick $Ga_{0.8}In_{0.2}As$; otherwise, the lasing would not be observed. Mesas of diameter 1, 1·5, 2, 3, 4 and 5 μm (Fig. 1), and 5, 10, 25, 50, 100 and 200 μm square are defined by chemically assisted ion-beam etching. A ~1500 Å-thick Ni layer is patterned on top of the gold film for etch mask. The mesas are etched about 4–6 μm deep through the gold film.

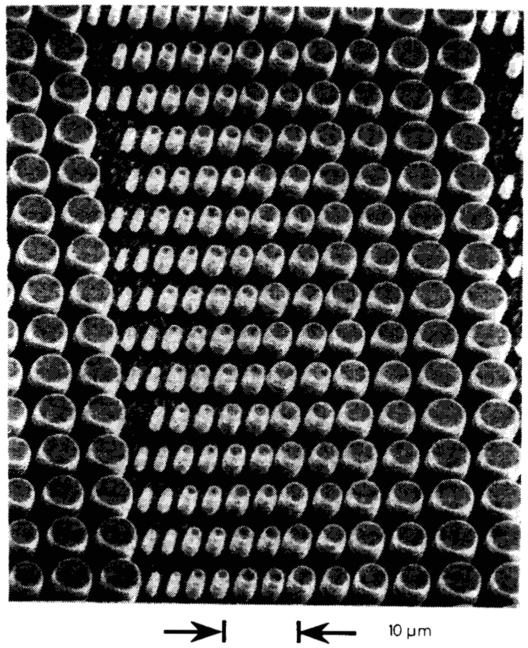

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Fig. 1 *Very small portion of vertical cavity microlasers of diameter 1–5 μm*

Fig. 2 shows a CW laser output characteristic for a 5 μm square microlaser with 1·5 mA threshold at room temperature. The laser light is linearly polarised above threshold. The 983 nm output passes through the polished GaAs substrate with only small loss. Room-temperature continuous lasing is observed for 5, 10 and 25 μm microresonators with 1·5, 3·0 and 13·0 mA thresholds with no heat sinking applied. Continuous lasing is observed with up to 1·5–2·0 times the threshold current. For larger CW current, heating seems to red-shift the gain region out of the Fabry–Perot resonance and the microlaser stops lasing. Reduction of the current will again produce lasing at the same power levels as before. If the current is raised greatly above this point, however, the microlasers are permanently damaged.

Using 90 ns pulses, the threshold currents are the same (1·1 mA) for the microlasers of diameter 3–5 μm, and 1·1, 2·3, 12 and 45 mA for the microlasers 5, 10, 25 and 50 μm square.

The measured single-facet differential quantum efficiency is about 8–10%. The threshold currents are marginally lower than in the previous three-quantum-well microlasers,[6] not three times better. For the larger devices ($> 5\,\mu m$), the threshold current density stays almost constant at $1{\cdot}8\,kA/cm^2$. This value is still much larger than the theoretical[7] minimum threshold current density ($60\,A/cm^2$). For the smaller devices ($< 5\,\mu m$), the threshold current density increases with the reduction in size, which we believe is due mainly to surface recombination of carriers.

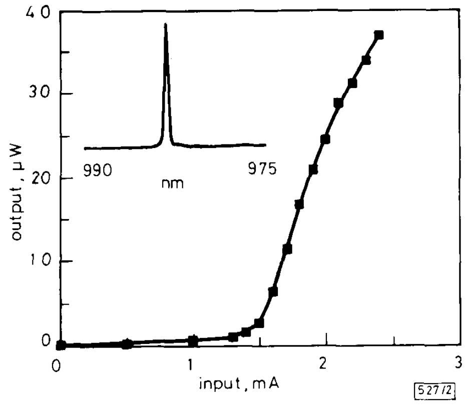

Fig. 2 *Output against current for 5 μm-square microlaser operating CW at room temperature without heat-sinking*

Inset shows spectrum at 1·8 mA. Spectral line width is 3·5 Å, the resolution limit of spectrometer

Since the maximum possible gain per pass from a SQW is of the order of 10^{-3}, any small loss of this magnitude can be critical for the lasing action. Possible sources for the loss are band-tail and/or free carrier absorption by highly doped impurities, a slight mismatch between the gain maximum and the peak reflectivity of the mirrors, and scattering. The electrical resistance through the heterostructure mirrors is rather high (between 50–5000 Ω depending on the sizes). This high resistance and high current density are the main problems preventing continuous operation at high driving currents. Reduction of the resistance and better heat sinking should make more efficient room-temperature continuous microlasers.

In summary, we have demonstrated single-quantum-well (100 Å-thick GaInAs), surface-emitting microlasers with minimum thresholds of 1·1 mA (pulsed) and 1·5 mA (CW) at room temperature. These microlasers have the smallest gain medium volumes of any lasers ever built. Even though the microlasers are not optimised in the present form, the threshold current is low enough to consider driving arrays of microlasers simultaneously. We can expect another order-of-magnitude reduction in the threshold current (less than $100\,\mu A$ with a 2–3 V source) with proper improvement of design and processes involved. Arrays of very low threshold microlasers will be critical components for optical computing, chip-to-chip communication, and photonic switching.

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FABRICATION AND GAIN MEASUREMENTS FOR BURIED FACET OPTICAL AMPLIFIER

Indexing terms: Optoelectronics, Integrated optics, Optical communications

The paper reports the fabrication and gain measurements of buried facet optical amplifiers. Chip gain of 25 dB, gain ripple of < 1 dB and gain difference of < 1 dB for TE and TM-polarised light are observed. The gain is found to decrease rapidly with increasing temperature. This behaviour is explained using a model calculation of the radiative and non-radiative recombination rates in the active region of the amplifier.

Optical amplifiers are currently of interest for applications in optical communication systems.[1,2] Two important criteria for the performance of the optical amplifiers are (i) absence of any gain ripple, i.e. the modulation of the optical gain at residual cavity mode wavelengths be negligible, and (ii) the optical gain must be independent of the polarisation of the input light. This letter reports the fabrication and optical gain measurements of buried facet amplifiers[3,4] which exhibit very low gain ripple (< 1 dB) and low polarisation dependence of gain (< 1 dB).

The buried facet configuration (Fig. 1) is useful for two reasons, (*a*) it provides a polarisation-independent reduction in reflectivity (by a factor of 50–100) over a cleaved facet, and (*b*) it allows one to achieve effective reflectivities of 10^{-4} or less reproducibly simply by putting a conventional anti-reflection coating ($\sim 10^{-2}$) on the facet.[4]

The fabrication of the device involves the following steps. The epitaxial layers consisting of the *n*-InP buffer layer, undoped GaInAsP ($\lambda \sim 1{\cdot}55\,\mu m$) active layer, *p*-GaInAsP ($\lambda \sim 1{\cdot}3\,\mu m$) antimeltback layer, *p*-InP cladding layer and *p*-GaInAsP ($\lambda \sim 1{\cdot}3\,\mu m$) contact layer are grown on a (100)-oriented *n*-InP substrate by the liquid-phase epitaxy growth technique. Mesas are then etched on the wafer along (110)

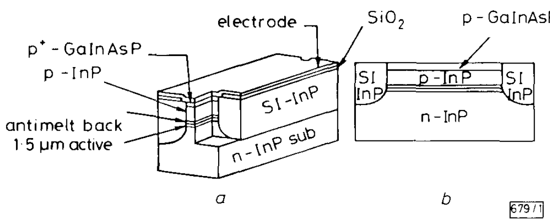

Fig. 1 *Schematic diagram of buried facet amplifier structure*