RF drive frequency from an actively modelocked fibre ring laser without controlling the modulator bias. In general, whenever the RF drive frequency is detuned by an amount equal to $f_{CAV}/2$, from the frequency where stable pulses are found, the laser would produce pulses at repetition rate two times the RF drive frequency. Similarly, when detuning is $\sim f_{CAV}/3$, then the repetition rate of output pulses can be tripled.

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High-frequency modulation of oxide-confined vertical cavity surface emitting lasers

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Indexing terms: Vertical cavity surface emitting lasers, Semiconductor junction lasers, Optical modulation

High-speed studies of packaged, submilliampere threshold, oxide-confined vertical cavity surface emitting lasers show modulation bandwidths > 16GHz. Very high modulation current efficiency factors occur at low bias but decrease as the modulation bandwidth and frequency of the relative intensity noise peak saturate at higher currents.

Fundamentally, the high finesse and small volume of vertical cavity surface emitting laser (VCSEL) resonators promotes high photon densities without excessive photon lifetimes and hence the potential for high speed operation [1]. Experiments have established 71GHz relaxation oscillation frequencies [2]. However, the practical high frequency, electrical modulation of these lasers has lagged due to large electrical resistance, heating [3, 4], and modal confinement constraints. Implant defined, 780nm VCSELs have shown 14GHz 3dB bandwidths [5]. Although small index-guided devices with better transverse optical confinement and improved gain-mode overlap should offer higher bandwidths, they have thus far been limited to 9.3GHz [6] 3dB frequencies, presumably due to resistance and thermal limitations. Here we report 3dB modulation bandwidths up to 16.3GHz for VCSELs with oxide-based index guiding [7]. The all-epitaxial oxide-confined structure [8] offers low electrical and moderate thermal resistance and high efficiency [9] leading to reduced heating.

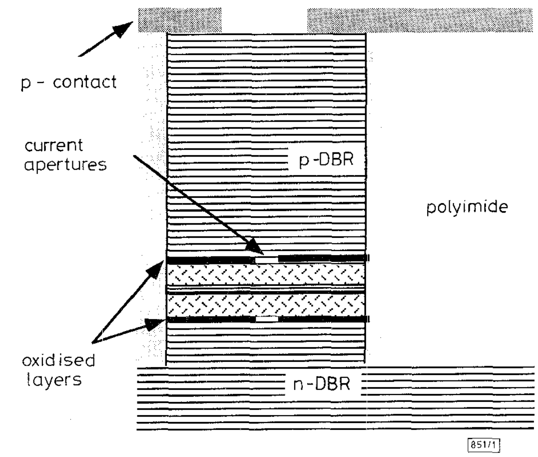

Fig. 1 *Schematic cross-section of an oxide confined VCSEL structure with low capacitance bondpads on polyimide*

The device was fabricated by selective oxidation of a sample from a metalorganic vapour phase epitaxy wafer. The nominally 970nm VCSEL layer structure used an active region of three 8nm InGaAs quantum wells in a graded AlGaAs one-wavelength cavity between a 38-period Si-doped lower mirror and an 18-period C-doped upper quarterwave mirror stack. The maximum aluminum alloy content of the mirror was $x = 0.92$, except in the upper and lower mirror periods immediately adjacent to the cavity, where it was increased to $x = 0.98$ in order to enhance the oxidation rate of these layers. Individual devices with two aligned oxide apertures as illustrated in Fig. 1 were formed in square mesas by selective oxidation as previously described [8]. Approximately 5μm-thick polyimide was used to planarise the surface and to reduce the capacitance of the $75 \times 120\mu m^2$ metal bondpad to an estimated 0.04pF. The measurements reported here were performed at room temperature on a laser with a $\sim 3 \times 3\mu m^2$ aperture in the oxide.

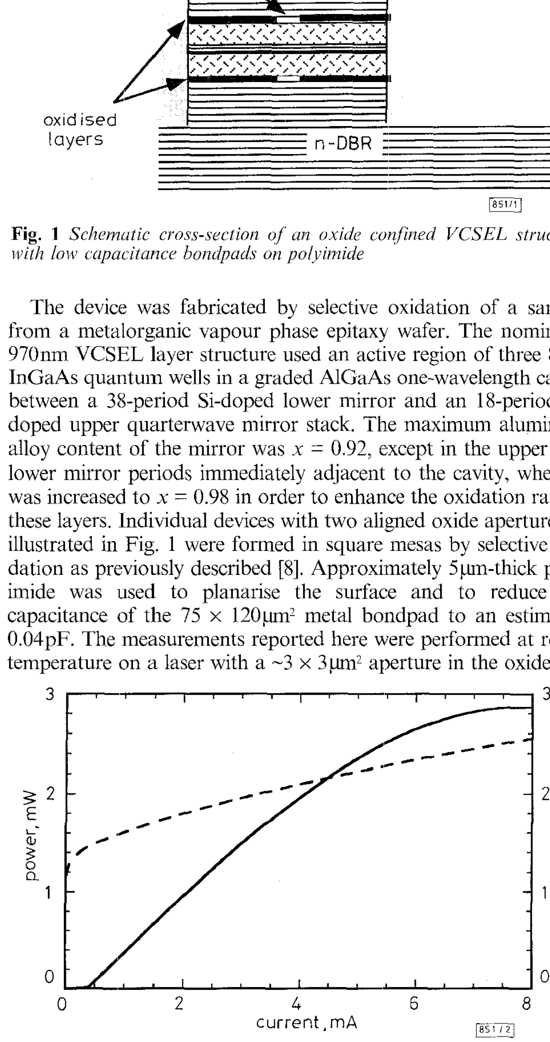

Fig. 2 *Room temperature, continuous wave output power and voltage against current characteristics of a VCSEL exhibiting 16.3GHz modulation bandwidth*

——— output power
– – – – voltage

The continuous-wave laser characteristics shown in Fig. 2 indicate an extended range of operation. The maximum power of 2.86mW before thermal rollover is reached at a bias of 7.8 mA, 21 times the 0.37mA extrapolated threshold current. The differential quantum efficiency is 45% just above threshold. Higher mirror reflectivity could be used to obtain lower threshold current and higher photon densities to enhance the modulation bandwidth at the expense of decreased slope efficiency. An approximate effective slope resistance of 160Ω in the 1–4mA range and extrapolated zero current diode voltage from this region of 1.47V result in low operating voltages. The good slope efficiency and low voltage reduce waste heat generation which leads to thermal limitations. The device's resistive component dominates the input impedance although it results in virtually no electrical limitation to the modulation response as the *RC* time constant of the pad capacitance and series resistance corresponds to a 3dB electrical frequency > 100GHz. The device is predominantly singlemode up to ten times threshold, although the strong optical confinement supports a large number of higher order transverse modes [7]. One higher order mode reaches threshold at 2.5mA, but it remains suppressed to 10dB below the fundamental until 4.0mA. The singlemode operation is important for maintaining increasing photon density in the mode with increasing current and thus maximising modulation bandwidth.

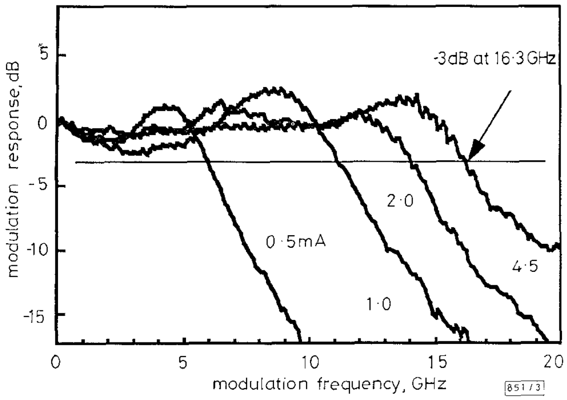

Fig. 3 *Modulation responses at different bias currents*

Small signal frequency response measurements using an HP 8510C vector network analyser indicated a maximum 3dB modulation bandwidth of 16.3GHz. The sample was die-attached to an RF circuit package containing an APC 3.5mm coaxial connector and 50Ω stripline launch circuit. A 4 mil wide bonding ribbon was used to bond the lasers in the interest of minimising bondwire inductance. The laser emission was focused by an antireflection-coated lens into a multimode optical fibre coupled into a 25GHz New Focus model 1434 photodetector. The modulation responses at various currents are shown in Fig. 3. The bandwidth increases rapidly at low currents, reaching 11.2GHz at a bias current of only 1mA. A response peak of a second mode, at 6.5GHz, is apparent when the bias reaches 4.5mA. The bandwidth reaches a maximum of 16.3GHz at this current.

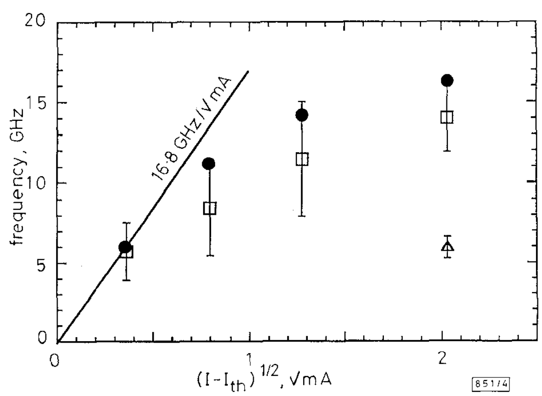

Fig. 4 *Modulation 3dB bandwidth and RIN peak frequencies of fundamental and higher order modes*

Error bars on RIN symbols denote approximate full-width at half-maximum (3dB) points. Initial point has a 16.8GHz/√mA modulation current efficiency factor
● 3dB bandwidth
□ fundamental mode
△ higher order mode

As seen in Fig. 4, the dependence of the maximum bandwidth and laser relative intensity noise (RIN) peak on the square root of the current above threshold both show a sublinear dependence. This gradual saturation of frequency contrasts with the expected linear dependence on the abscissa, with the slope being defined as the modulation current efficiency factor (MCEF) [10]. Assuming a linear dependence below the lowest plotted current of 0.5mA, the MCEF there would be 16.8GHz/√mA, well above the 9.5GHz/√mA previously reported as the highest [11]. The RIN peaks observed for this laser were relatively broad, with the FWHM indicated by the error bars in Fig. 4, and the maximum was typically only 4–8dB above the noise floor. The RIN peak frequency tracks below the 3dB frequency at the higher currents, suggesting that the frequency response is not principally limited by circuit parasitics. The presence of a second well defined RIN peak at 4.5mA also confirms the interpretation of the modulation response curve in Fig. 3 at that bias point. The gradual frequency saturation in the present laser may be associated with the higher order transverse mode competition or decreased differential gain due to increasing temperature.

In conclusion, record modulation bandwidths have been observed for VCSELs based on an oxide confined structure which offers enhanced optical confinement in conjunction with excellent electrical and thermal properties. Singlemode operation is important for minimising gain competition between multitransverse modes in such structures. Future work will address the saturation of the frequency at higher currents.

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