output power reached 76 W at 91 A before catastrophic degradation of the device. To the best of our knowledge, this is the highest cw power level reported to date from any monolithic semiconductor lasers of any aperture width. The electrical-to-optical power conversion efficiency was 46% at an output power of 40 to 50 W and was 39% at 76 W.

A similar test was performed on one of the devices with a 20×10 structure at room temperature. The output power reached 55 W. The threshold current and the slope efficiency was 8.5 A and 0.83 W/A, respectively. The electrical-to-optical conversion efficiency was 39% at an output power of 30 W and 34% at 55 W.

To assess operational reliability, constant power life tests at 10 W cw were performed on two of the lasers with 30% packing density at 20° C heatsink temperature. These particular arrays had wavelengths of around 810 nm at 10 W cw. One laser array with the 15×20 structure has been operated for 1,500 hours and the other with the 30×10 structure, for 3,000 hours. These two lasers seem to follow a similar degradation curve. By defining the end of laser life as a 50% increase in the operating current, a projected lifetime of over 5,000 hours is obtained. Ten W cw laser diode arrays are now commercially available (SDL-3490S).

One application of laser diode arrays is for pumping solid state lasers. A TEM_{00} output power of 3.18 W and a slope efficiency of 44% from a Nd:YAG laser was demonstrated when pumped with a 10.9 W from one of our diode arrays with a 20% packing density (10×20 structure).[2]

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Low threshold electrically-pumped vertical-cavity surface-emitting micro-lasers

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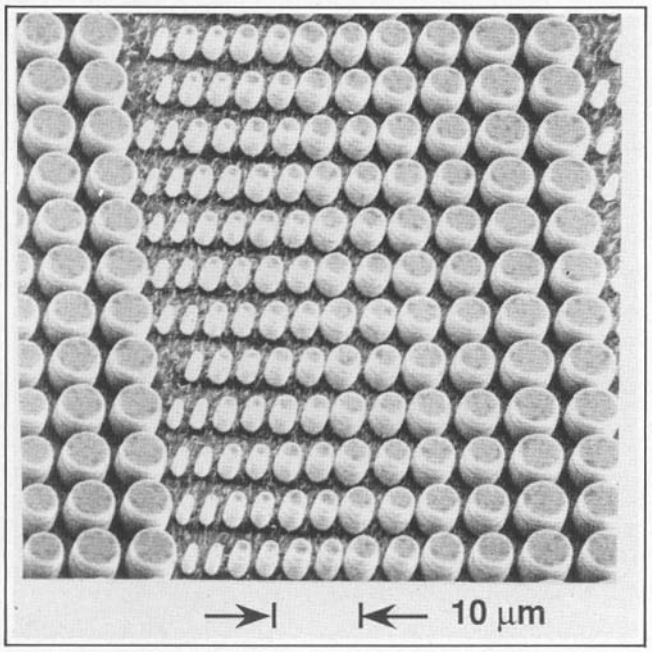
Vertical-cavity surface-emitting lasers[1,2] show promise for a variety of applications. Use of large coherently-coupled arrays could provide high power, cheap laser sources. Smaller arrays could accomplish high-speed communication between electronic chips, overcoming a bottleneck that presently limits the speed of computers. In the longer term, arrays of laser logic gates may be used for photonic switching in communication networks or for general purpose computing. For information processing applications, minimizing the threshold current is essential. The lowest threshold edge-emitting lasers[3] contain a single quantum well and require ~0.55 mA. Minimum thresholds will be attained by minimizing the volume of active material in the laser, which in turn requires high-reflectivity mirrors.

GaAs-AlAs mirrors grown by molecular beam epitaxy have achieved extremely high reflectivity (>99%), high enough to achieve optically-pumped lasing in a vertical cavity with an 80 Å single quantum well active layer[4]. Chemically-assisted ion beam etching can form waveguiding pillars in such heterostructures with micron dimensions, and optically-pumped lasers with 1.5 μm diameters were demonstrated.[5] Use of these technologies is appropriate for fabricating ultra-small, ultra-low threshold micro-lasers.

We have constructed more than one million electrically-pumped vertical-cavity surface-emitting semiconductor lasers with dimensions of a few μm (μ-lasers) on a single GaAs chip.[6] Cylindrical μ-lasers have diameters 1, 1.5, 2, 3, 4, and 5 μm with heights about 5.5 μm (see figure). Device density is around two million per square cm with a typical chip size about 7×8 mm. Square devices 5, 10, 25, 50, 100, and 200 μm across were also tested. Two wafers were tested containing active regions of three quantum wells (3QW), each 80 Å thick, and a 100 Å single quantum well (SQW), of $In_{0.2}Ga_{0.8}As$. Lasing wavelengths were typically 960–980 nm. All experiments were performed at room temperature. In most of the 3QW chips tested, the 5-μm in diameter devices have yields around 95–100%. Lasing was observed in 3QW μ-lasers as small as 1.5-μm in diameter. The active material volume was <0.05 μm^3 compared to well over 1 μm^3 for edge emitters and >10 μm^3 for all previous surface emitters.

The 3-μm-diameter 3QW μ-lasers had a typical pulsed threshold about 1.3 mA and the measured single-facet differential quantum efficiency was about 16%, despite some absorption of the laser output in the doped substrate. For 4-μm SQW μ-lasers the thresholds were 1.1 mA with ~7% differential quantum efficiency. In all cases, the light vs. current shows sharp threshold, very low below-threshold output, and linear response above threshold. Room-temperature CW operation was achieved in SQW devices with thresholds as low as 1.5 mA. No heatsinking was applied to any of the devices.

The main heat flow was conduction through the bottom mirror into the substrate. These very low thresholds



Scanning electron micrograph of a small portion of the μ-laser array.

were obtained despite very short carrier lifetimes due to surface recombination on the sidewalls. The highest power obtained so far was 170 m W pulsed (4 mW average) from a 100 μm square region. We have also modulated the SQW 10-μ-square lasers with pseudorandom pulses at 1 Gb/sec yielding $<10^{-10}$ bit error rates. Smaller μ-lasers should be capable of much higher speeds.

This was our first attempt to realize ultra-small microlasers. Reduction of optical absorption in the cavity and suppression of surface recombination should allow further volume reductions to <0.01 μm^3 active material and thresholds less than 10 μA.

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Single and multiple element 4-pass phase conjugate master oscillator power amplifier using diode lasers

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Scaling laser diodes to high optical powers demands large emission apertures. Simple broad-area structures or laser diode arrays suffer from degradation of both the spectral and spatial mode as the emitting aperture increases in size. In addition, when multiple elements are combined, proper phasing is a difficult and sometimes impossible task.

We have demonstrated laser diode based phase conjugate master oscillator power amplifier (PC MOPA) systems as an alternative for power scaling.[1] In a PC MOPA, a relatively low power master oscillator with good beam quality is passed through one or many large area power amplifiers. After optical phase conjugation on the amplified beam(s), any linear aberrations due to either the optical system or the amplifier(s) are corrected by a second pass through the material. A second property of a PC MOPA system is that multiple amplifiers that are physically separated can be phased with no need to provide interferometer path length matching. Provided that the phase conjugation for the different amplifiers takes place in the same nonlinear interaction, all path length differences accumulated on the first pass will be removed on the second pass.

We have demonstrated a new 4-pass PC MOPA geometry that more readily allows for efficient heat sinking of the diode amplifiers than previous work. We also phased three discrete amplifiers yielding a single lobbed diffraction limited output beam with the spectral properties of the master oscillator. In single amplifier experiments, output powers as high as 100 mW have been obtained.

The geometry used in the 4-pass PC MOPA experiments is shown in the figure. The master oscillator (MO) is a commercially available GaAs/GaAlAs buried heterostructure laser that operates in a single spatial and spectral mode. The beam from the MO is split into three beams by a binary phase grating, then reshaped and focused into the amplifiers for the first two passes. After these passes, the polarization is rotated by the half-wave plate and Faraday rotator so that the beam splitter deflects it to the conjugate arm of the system. The conjugate return then passes through the amplifier for passes three and four reforms at the phase grating and exits the system. The polarization on the first two passes is perpendicular to the junction of