Picosecond surface-emitting semiconductor laser with > 200 mW average power

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A passively modelocked diode-pumped surface-emitting semiconductor laser at 950 nm with a 2 GHz repetition rate is reported. Compared to the first device of this kind, which the authors recently reported, a greatly improved average output power of 213 mW and a reduced pulse duration of 3.2 ps are achieved. The device consists of an optically pumped semiconductor gain structure and a semiconductor saturable absorber mirror (SESAM) in an external cavity.

Introduction: Pulsed laser sources with multi-GHz repetition rates and average powers > 100 mW are required for applications such as optical clocking of integrated circuits, optical testing of semiconductor electronics and telecommunication components, particle accelerators, and analogue-to-digital conversion. Edge-emitting semiconductor lasers have been passively modelocked for quite some time [1] and ultra-short pulses [2] and extremely high repetition rates [3] have been reported. The average and peak power is limited in these devices, because stable modelocking requires fundamental transverse mode operation, which restricts the size of the facet. With optically pumped vertical-external-cavity surface-emitting semiconductor lasers (VECSELs [4]) these constraints are eliminated, and much higher powers are possible with accordingly increased mode areas, while diffraction-limited output is enforced by the external cavity. Pulsed operation has been achieved with synchronous pumping [5, 6] and with active modelocking [7]. Recently [8], we demonstrated the first VECSEL which is continuously pumped and passively modelocked with a semiconductor saturable absorber mirror (SESAM [9, 10]). With a new gain structure optimised for a low thermal impedance and a smooth gain spectrum we have obtained ten times more average power and six times shorter pulse duration.

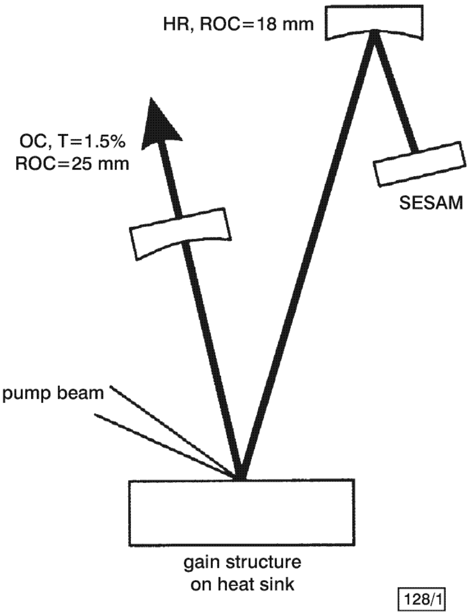

Fig. 1 *Laser setup*

HR: high reflector, OC: output coupler, ROC: radius of curvature, T: transmittance, SESAM: semiconductor saturable absorber mirror
Cavity length is ~7.5 cm

Gain structure: In the previously described gain structure [8], the generated heat is removed through the GaAs substrate, which introduces a significant thermal impedance. We have eliminated this problem by fabricating a structure where the active region is separated from the copper heat sink only by a semiconductor Bragg mirror. This is achieved by epitaxial lift-off (ELO): first, we grew the gain structure in reverse order on a GaAs substrate with three intermediate etch-stop layers. We used a fluxless indium soldering process similar to the one published by So *et al.* [11] to solder a dice to a copper heat sink and finally removed the GaAs substrate by etching.

The additional effort of the epitaxial lift-off is justified by two important improvements. First, the reduced thickness of the semiconductor material leads to a greatly reduced thermal impedance, and the nearly one-dimensional heat flow into the heat sink makes the device power-scalable: the output power can, for example, be doubled by applying twice the pump power to twice the mode area without raising the temperature of the gain structure, as long as the heat sink is able to remove the additional power. The second improvement is that we eliminate the previously observed etalon effect from the interference of reflected waves from the Bragg mirror and the soldered surface. This effect limited the bandwidth and disturbed the modelocking in the previous device.

The gain structure consists of a bottom mirror, an active region, and an anti-reflective section grown by metal-organic chemical vapour deposition (MOCVD). For the bottom mirror we used seven pairs of GaAs/AlAs and 23 pairs of $Al_{0.2}Ga_{0.8}As/AlAs$ in a numerically optimised sequence to achieve 99.8% reflectivity for the laser wavelength (950 nm) and 98% reflectivity for the pump wavelength (805 nm) under 60° angle of incidence, allowing us to double pass the pump light. The anti-reflective section has < 1% reflectivity for the laser wavelength under normal incidence and ~20% reflectivity for the pump wavelength at an angle of incidence of 60°. It contains $Al_{0.2}Ga_{0.8}As$ and AlAs layers apart from a 10 nm thick GaAs cap layer. A total of nine $In_{0.15}Ga_{0.85}As$ quantum wells with 8.2 nm well width are distributed three-by-three in the anti-nodes of the standing wave pattern. The spacer layers are made of GaAs and serve as an efficient absorber for the pump light. The exited carriers in the spacer layers are then trapped in the quantum wells.

Laser setup: The modelocked laser setup is shown in Fig. 1. We used up to 7.4 W of pump light from a fibre-coupled diode array emitting at 805 nm, focused to a spot with a diameter of ~260 µm on the VECSEL. The heat sink was cooled with a Peltier element to –4°C, while dry N_2 prevented moisture precipitating on the gain structure. The SESAM was of a low-finesse anti-resonant design, consisting of a Bragg mirror with 25 pairs of GaAs/AlAs and a single quantum well absorber, embedded in a GaAs spacer layer of $\lambda/2$ thickness. The absorber was a low-temperature (350°C), 8 nm thick $In_{0.15}Ga_{0.85}As$ quantum well grown by molecular beam epitaxy (MBE). The cavity design had two focal points, one on the gain structure and the other one on the SESAM. The beam diameter on the gain structure was ~200 µm while it was significantly smaller (~18 µm) on the SESAM. The output coupler had a transmission of 1.5%.

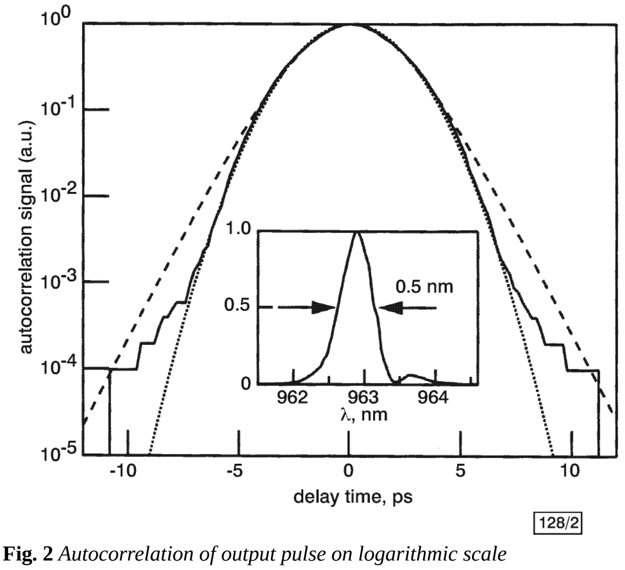

Fig. 2 *Autocorrelation of output pulse on logarithmic scale*

——— measured data
·········· fit assuming Gaussian shaped pulse, 3.2 ps full width at half maximum duration
– – – – fit assuming $sech^2$ shaped pulse, 2.8 ps full width at half maximum duration
Inset: Optical spectrum taken with resolution of 0.1 nm

Results: A slowly scanning autocorrelator with lock-in amplification was used to measure the pulse shape (Fig. 2). The autocorrelation was recorded for a maximum output power of 213 mW, showing that the pulses have a Gaussian shape and are free of any pedestals down to –30 dBc. The optical bandwidth (inset of Fig. 2) was ~0.5 nm, close to the transform limit for Gaussian pulses. The peak power was 30 W. The pulse duration as well as the stability of the modelocking was strongly dependent on the cavity setup. We observed that the pulses became shorter when the mode size on the SESAM was reduced, while the mode size on the gain structure was kept constant [12].

With photoluminescence microscopy we detected dark line defects in the gain structure. This might explain the low efficiency of ~10% for continuous wave operation, and its observed degradation: the output power significantly degrades within a few hours. With refined designs (e.g. including strain compensation for the quantum wells) we expect further substantial improvements.

Conclusion: We have demonstrated what is to our knowledge the highest power directly from a passively modelocked semiconductor laser oscillator. It is based on a vertical-external-cavity surface-emitting laser passively modelocked with an SESAM. We obtained 213 mW with 3.2 ps pulses at a repetition rate of 2.06 GHz. The basis for this performance is the gain structure design, which allows for low thermal impedance and a smooth gain spectrum. We believe that such lasers will soon deliver multi-watt average powers at several GHz repetition rates.

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