Passively modelocked 832 nm vertical-external-cavity surface-emitting semiconductor laser producing 15.3 ps pulses at 1.9 GHz repetition rate

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A passively modelocked 832 nm vertical-external-cavity surface-emitting laser, producing pulses of a duration of 15.3 ps at a repetition rate of 1.9 GHz, has been demonstrated. A fast surface-recombination semiconductor saturable absorber mirror, with a bi-temporal absorption recovery characteristic, consisting of fast and slow time constants of 1.5 and 200 ps, respectively, was used to form the pulses.

Introduction: Optically pumped vertical-external-cavity surface-emitting semiconductor lasers (OP-VECSEL) are a distinct class of semiconductor laser, which utilise optical pumping to allow the optical properties of the device, as well as the thin disc nature, to be fully exploited for applications such as high-power operation, intracavity frequency doubling and modelocking, with no compromises made for electrical properties, such as is necessary in electrically pumped VCSELs [1]. Passively modelocked OP-VECSELs have generated near-transform-limited pulses of 260 fs duration using the optical Stark effect [2], and have been operated at repetition rates in the 1–50 GHz range [2, 3] at wavelengths around 1 μm. Passively modelocked picosecond-pulse OP-VECSELs have also been demonstrated around 1550 nm [4] and 1.3 μm [5]. At 850 nm an actively modelocked OP-VECSEL producing pulses of ~100 ps duration has been reported [6]. We report the first demonstration of a passively modelocked OP-VECSEL operating at 832 nm, producing pulses of a duration of 15.3 ps.

OP-VECSELs are low-gain lasers and hence all cavity elements must be designed to have a low insertion loss. Semiconductor saturable absorber mirrors (SESAMs) used to modelock OP-VECSELs must be designed with this in mind. One previously demonstrated design is the fast surface recombination SESAM. A single quantum well is placed 2 nm from the air interface of a structure grown under optimal growth conditions. The presence of a high concentration of trap sites owing to As at the air interface provides fast recombination, and therefore a surface recombination SESAM can be designed to have a significant modulation depth and fast recovery time whilst minimising non-saturable losses. This type of SESAM design has previously been demonstrated to be capable of producing stable modelocking at operating wavelengths near 1040 nm [2].

Experiment: A Z-shaped laser cavity with a fundamental pulse repetition frequency of 1.9 GHz was used in this work, consisting of a 25 mm radius of curvature, 0.7% output coupler, the gain sample acting as a folding mirror, a second cavity folding mirror with a radius of curvature of 20 mm and the SESAM as the second end mirror. The mode radii on the SESAM and the gain structure were calculated to be 11.2 and 40 μm, respectively, ensuring that the intra-cavity pulse saturated the SESAM faster than the gain, leading to stable modelocking.

The laser gain structure contains 15 6 nm-thick $GaAs/Al_{0.2}Ga_{0.8}As$ quantum wells positioned at the antinodes of an anti-resonant microcavity formed between a 30-pair Bragg reflector and the air surface. The $Al_{0.2}Ga_{0.8}As$ barriers also act as pump absorber layers. A similar structure has been used with an intracavity heat-spreading plate to demonstrate 0.5 W of continuous-wave power at 850 nm, optically pumped with 2.9 W of 670 nm power [7]. In this demonstration we dispensed with the heat-spreading plate to avoid intracavity etalon effects and pumped the unprocessed wafer with up to 2 W of light from a pair of commercial 670 nm diodes, focused into an optical spot with dimensions of 100 × 200 μm.

The SESAM consisted of an $AlAs/Al_{0.2}Ga_{0.8}As$ DBR, a spacer layer of $GaAs_{0.75}P_{0.25}$, a 4.8 nm GaAs quantum well and a 2 nm-thick capping layer of $GaAs_{0.79}P_{0.21}$. A schematic of the SESAM structure is shown in Fig. 1. The spacer layer thickness was chosen so that the quantum well was located 0.68.λ/4 from the interface with the DBR. The GaAsP capping layer is vital for fast carrier recombination in this quantum well system as it allows a high surface concentration of As defect sites, which are primarily responsible for providing the surface recombination states. Pump probe measurements were performed on the SESAM using a titanium–sapphire laser operating at 855 nm to measure the absorption recovery time. The pump pulses had an incident fluence on the SESAM of 100 μJcm^{-2}. Fig. 2 shows the reflected probe signal against delay, revealing the absorption recovery characteristics of the SESAM. The absorption recovery characteristics are bi-temporal with a fast component with a recovery time of 1.5 ps, corresponding to approximately 2/3 of the total absorption. The slow component of the absorption recovers with a time constant of 200 ps.

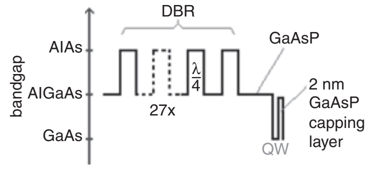

Fig. 1 *Schematic of SESAM layer structure*

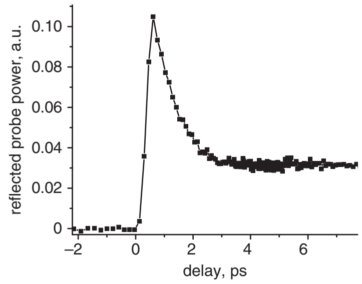

Fig. 2 *Pump probe measurement of reflected probe beam intensity, showing fast recovery time of 1.5 ps; slow component recovers with characteristic time of 200 ps*

The modelocked pulse train from the OP-VECSEL was characterised using an optical spectrum analyser, autocorrelator and RF spectrum analyser. An optical spectrum and second harmonic intensity autocorrelation of the output pulse train are shown in Fig. 3. The optical spectrum is centred at 832.4 nm and has a width of 0.63 nm FWHM. The autocorrelation gives a pulse duration of 15.3 ps assuming a Lorentzian pulse shape. The pulses are approximately 20 times transform limited, showing that these pulses are highly chirped. The average output power of the laser was measured to be 5 mW, with an incident pump power of 1.1 W.

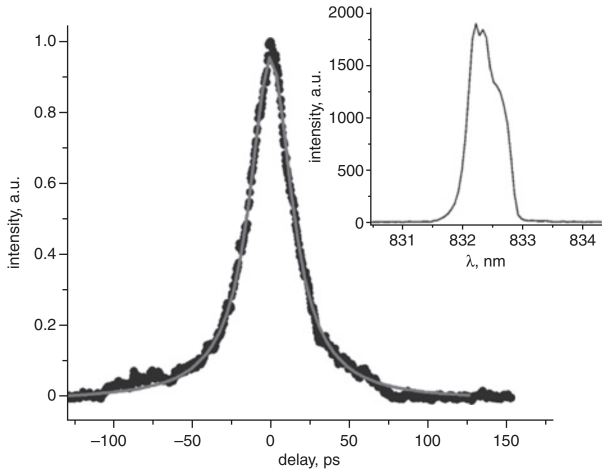

Fig. 3 *Intensity autocorrelation of laser output, at average power of 5 mW, showing measured pulse (circles) and Lorentzian fit (solid line) corresponding to 15.3 ps FWHM duration*
Inset: optical spectrum, with FWHM bandwidth of 0.67 nm

The low T_0 of GaAs/AlGaAs quantum well systems leads to a high degree of temperature sensitivity and reduced tolerance of temperature increases in the pumped region. The local heating caused by the absorbed pump light in this demonstration was non-optimal owing to the mismatch between the pump spot and the laser mode, which impairs efficiency. Experimentally, the sample mount was temperature controlled to $-33^{\circ}C$ to improve efficiency and provide optimal output power. As a result of the low operating temperature, the gain structure, designed to be anti-resonant at $20^{\circ}C$, was in fact operating near a micro-cavity resonance. This introduces a large amount of higher order dispersion, leading to the long highly chirped pulses that were observed.

Conclusions: We report the first demonstration of a passively mode-locked OP-VECSEL operating at a wavelength of 832.5 nm. We also report the design and characteristics of a fast surface recombination SESAM for use in modelocked VECSELs at this wavelength, based on a GaAs quantum well located 2 nm from the air interface, surrounded by GaAsP barriers. Pulses of a duration of 15.3 ps were produced, with an optical bandwidth of 0.63 nm FWHM. The pulses were 20 times transform limited. In future work we will use a thin antireflection coated diamond heat-spreader to improve the heat removal from the active region, increasing efficiency and increasing the operating temperature. This will lead to higher average powers and shorter pulse durations.

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