Passively modelocked GaInNAs VECSEL at centre wavelength around 1.3 μm

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A passively modelocked GaInNAs vertical-external-cavity surface-emitting laser (VECSEL) is demonstrated for the first time. The VECSEL was optically pumped using an 808 nm semiconductor diode laser. An intracavity GaInNAs semiconductor saturable absorber mirror was used for stable self-starting modelocking and 57 mW of average output power was obtained at a centre wavelength of 1308 nm with a pulse repetition rate of 6.1 GHz and a pulse duration of 18.7 ps.

Introduction: Broadband optical communication networks need cost-effective pulsed laser sources in the zero-dispersion wavelength regime of 1.3 μm. In addition, laser sources at this wavelength can be used for optical clocking of future generations of microprocessors and RGB projection applications employing frequency doubling to generate red light. Optically pumped VECSELs have potential for both high average output power and near-diffraction limited beam quality. Similarly to diode-pumped solid-state lasers, they have the advantage to efficiently improve spatial mode quality, wavelength tunability and flexibility in mode of operation such as passive modelocking and intracavity frequency doubling. Optically pumped VECSELs were passively modelocked for the first time in 2000 [1]. Since then we have seen tremendous progress in average output power, shorter pulses, high pulse repetition rates and different operation wavelength [2]. However no VECSEL has been passively modelocked at around 1.3 μm until now.

In this Letter we describe the first passively modelocked VECSEL at a centre wavelength of around 1.3 μm. The quaternary alloy GaInNAs can be fabricated to have an emission wavelength of 1.3 μm and has the advantage, compared to other semiconductors with the same electronic bandgap, to be better lattice matched to GaAs substrates [3]. Since the discovery of this material, its development as a gain medium for semiconductor lasers has been hindered by the incorporation of non-radiative defects during the growth process of this dilute nitride material. Post-growth thermal annealing together with optimised growth conditions are essential tools to increase the radiative efficiency and obtain good laser-quality material [4]. Recently, an optically pumped GaInNAs VECSEL at 1.3 μm reached 612 mW of continuous-wave (CW) output power in a fundamental Gaussian mode [5]. Here, we exploit the potential of this material by adopting it not only as the gain medium but also as the absorbing medium in a semiconductor saturable absorber mirror (SESAM) used to obtain self-starting passive modelocking. We have previously used GaInNAs SESAMs to modelock solid-state lasers at 1.3 [6] and 1.5 μm, also obtaining self-starting passive CW modelocking at very high repetition rates. The insertion of a GaInNAs SESAM into a GaInNAs VECSEL cavity allowed us to obtain for the first time self-starting CW modelocking of a 1.3 μm VECSEL at 6.1 GHz with 18.6 ps pulses at an average output power of 57 mW.

Gain and absorber structures: The GaInNAs VECSEL consisted of four parts: an etch-stop structure, the antireflection layers, the active region, and two stacked distributed Bragg reflectors (DBRs) for the laser wavelength and the pump light. The whole structure was grown upside-down on a GaAs (100) undoped substrate to allow for removal of the GaAs substrate after growth. The etch-stop consisted of three layers of the following materials: $Al_{0.85}Ga_{0.15}As$, GaAs and AlAs. The antireflection structure consisted of 10 alternating layers of AlAs and $Al_{0.20}Ga_{0.80}As$ with numerically optimised thicknesses for low reflectivity of both the pump wavelength at 45° of incidence and the laser wavelength of normal incidence. $Al_{0.20}Ga_{0.80}As$ was used in the mirrors instead of pure GaAs to avoid absorption of the pump wavelength outside of the active region. The active region consisted of five 8 nm-thick $Ga_{0.65}In_{0.35}N_{0.018}As_{0.982}$ quantum wells (QWs) separated by 178 nm GaAs barriers to place each QW into the antinodes of the standing wave pattern of the laser electric field. Up to this point the structure was grown by molecular beam epitaxy (MBE). The DBRs were grown by metal organic vapour phase epitaxy (MOVPE). The first mirror consisted of a 32-pair $AlAs/Al_{0.20}Ga_{0.80}As$ DBR centred at the laser wavelength of 1300 nm for normal incidence. The second one was a 10-pair DBR of the same materials composition, designed for high reflectivity of the 808 nm pump wavelength at 45° of incidence. The design of the last few layers of the VECSEL structure can be seen in Fig. 1*a*. After the growth, the structure was metallised and soldered in vacuum to a copper heatsink using indium. The substrate was removed by lapping and wet chemical etching. This upside-down growth process with subsequent substrate removal was applied to minimise the thermal impedance of the VECSEL to allow for high pump power densities [7].

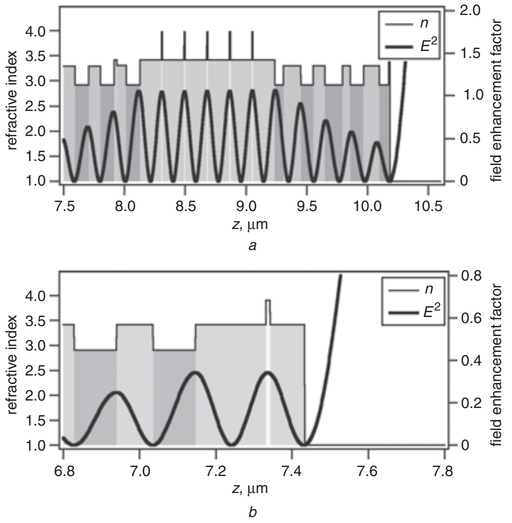


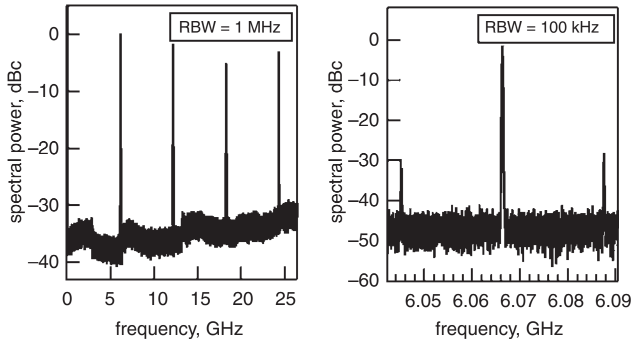
Fig. 1 *VECSEL and SESAM design*

a VECSEL design: refractive index (left axis) and electric field enhancement factor (right axis) against device thickness in last 3 μm of device
b SESAM design: refractive index (left axis) and electric field enhancement factor (right axis) against device thickness in last 0.6 μm of device

The GaInNAs SESAM was fully grown by MBE. The bottom DBR consisted of 35-pair AlAs/GaAs centred at 1310 nm, on top of which were grown a 90 nm GaAs spacer layer, a 10 nm $Ga_{0.65}In_{0.35}N_{0.016}As_{0.984}$ absorber, and a 90 nm GaAs cap layer, to make the device antiresonant, i.e. with a negligible group delay dispersion at the central wavelength of 1310 nm. We designed the absorber to be in the antinode of the electric field as shown in Fig. 1*b*. The photoluminescence (PL) peak of the GaInNAs absorber, corresponding to the onset of the absorption edge, was at 1311 nm. The absorption edge was designed very close to the laser emission to achieve minimum saturation fluence [8]. This SESAM was characterised by degenerate pump-probe experiments and nonlinear reflectivity measurements [9]. We measured a low saturation fluence of 6.8 (± 0.2) $\mu J/cm^2$, a low modulation depth of 0.76%, non-saturable losses of 0.12% and a recovery time of about 47 ps, which is suitable for modelocking in the few ps-pulse regime.

Laser setup: The laser setup consisted of a simple V-cavity described in [10]. The VECSEL was mounted on a copper heatsink, temperature stabilised by a Peltier element. The 808 nm free-space pump laser diode was positioned at a 45° angle with respect to the VECSEL. The SESAM was mounted approximately 8 mm away from the VECSEL. A 0.7% transmission output coupler with a radius of curvature of 25 mm was positioned at a distance of about 16 mm from the VECSEL for a total cavity length of 24.7 mm. A 25 μm uncoated fused silica etalon was also placed in the cavity to allow for wavelength stabilisation and dispersion management.

Results: We obtained stable self-starting CW modelocking at 6.1 GHz repetition rate as can be seen in Fig. 2*a* from the microwave spectrum at a full frequency span from DC to 25 GHz. In Fig. 2*b* a 50 MHz-span microwave spectrum centred around the pulse repetition rate with 100 kHz resolution bandwidth (RBW) provides a more detailed view of the modelocking. The small peaks at around 20 MHz offset from the main peak at the pulse repetition rate are suppressed by more than 30 dB. We believe that higher-order mode beating is the most likely reason for this instability because they move further away or closer to the main peak depending on slight cavity length changes. The pulse duration of 18.7 ps was measured with a noncollinear intensity autocorrelation and fitted with a sech^2 pulse shape as seen in Fig. 3. The inset of Fig. 3 shows the measured optical spectrum with a FWHM of 0.29 nm obtained with a 0.1 nm resolution optical spectrum analyser. Average output power was 57 mW, operating the laser with 3 W of pump power and cooling the VECSEL to a temperature of 5°C. The use of the etalon was necessary to stabilise the laser emission wavelength. Beam profile measurements were performed on an identical setup at a later time, giving M^2 values of 1.03 in the horizontal and 1.13 in the vertical direction, being slightly higher than for a fundamental Gaussian beam (i.e. $M^2 = 1$). This confirms the possibility of higher spatial mode beating being the reason for the observed side-peaks.



a *b*

Fig. 2 *Microwave spectra*

a Span 25 GHz, resolution bandwidth 1 MHz
b Span 50 MHz, resolution bandwidth 100 kHz

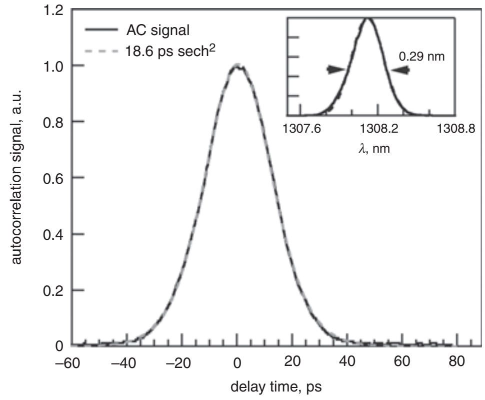


Fig. 3 *Intensity autocorrelation signal (measurement (black solid line) and* sech^2 *fit (grey dashed line))*

Inset: Optical spectrum taken with 0.1 nm resolution

Conclusion: We have demonstrated the first passively modelocked 1.3 µm VECSEL. Both the active and the absorbing media use GaInNAs-based quantum wells, that have been optimised for their different application.

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