4.35 kW peak power femtosecond pulse mode-locked VECSEL for supercontinuum generation

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Abstract: We report a passively mode-locked vertical external cavity surface emitting laser (VECSEL) producing 400 fs pulses with 4.35 kW peak power. The average output power was 3.3 W and the VECSEL had a repetition rate of 1.67 GHz at a center wavelength of 1013 nm. A near-antiresonant, substrate-removed, 10 quantum well (QW) gain structure designed to enable femtosecond pulse operation is used. A SESAM which uses fast carrier recombination at the semiconductor surface and the optical Stark effect enables passive mode-locking. When 1 W of the VECSEL output is launched into a 2 m long photonic crystal fiber (PCF) with a 2.2 µm core, a supercontinuum spanning 175 nm, with average power 0.5 W is produced.

OCIS codes: (140.4050) Mode-locked lasers; (140.5960) Semiconductor lasers; (140.7090) Ultrafast lasers.

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1. Introduction

Since its inception, the VECSEL has been developed into a versatile class of laser suitable for high power CW operation, intra-cavity frequency conversion [1] and femtosecond pulse mode-locking at gigahertz repetition rates [2–5] at a broad range of wavelengths. The mode-locked VECSEL has many features making it a promising laser for applications including flexible frequency combs and arbitrary optical waveform generation [6]. Gigahertz mode spacing enables isolation of individual modes and significantly increases the power per mode compared to typical MHz repetition rate laser systems [7]. The repetition rate of mode-locked VECSELs can be continuously tuned over several GHz without detriment to the quality of the output pulse train; the mode spacing can be tuned to any value within this range [8, 9].

The power of continuous wave VECSELs has been scaled rapidly over the past five years [1] and in the 1 μm spectral range the use of substrate removal techniques and highly efficient heat extraction from the back of the active region using diamond heat spreaders has enabled the average output power to be scaled above 100 W [10].

Efforts to apply the same thermal management techniques to femtosecond pulse mode-locked VECSELs have enabled an increase in the average power into the Watt level, with Sieber et. al. reporting 1W average power with 784 fs pulses [11] and Scheller et. al. reporting 5.1 W average power with 682 fs pulses [4]. However, combining multi-Watt power with sub-500-fs pulse durations has remained a challenge. The shortest pulse durations, down to 60 fs, have been achieved at the expense of low average power, of a few to tens of mW [2, 12].

In this work we combine the power scaling techniques developed in CW VECSELs with the femtosecond mode-locking techniques developed at low power and report a 3.3 W average output power mode-locked VECSEL at a repetition rate of 1.67 GHz producing near-transform limited 400-fs sech^2 pulses with a peak power of 4.35 kW. We launch a portion of the output power into a 2 m long, 2.2 μm diameter core PCF and generate a continuum with a bandwidth of 175 nm and average power 0.5 W.

2. Gain structure, SESAM and laser cavity

Two gain structures were used in this work. Both structures consisted of a 6-λ-thick active region at 1010 nm, containing 10 InGaAs QWs with GaAsP barriers, emitting at 1000 nm at low excitation. A 23 pair $Al_{0.2}Ga_{0.8}As/AlAs$ distributed Bragg reflector (DBR) centered at 1010 nm completed the structures. The structures were bonded by solid-liquid inter-diffusion bonding onto a diamond heat spreader before chemical etching to remove the substrate [13]. The InGaP cap of the resonant sample was left with its original thickness of λ/2. The InGaP cap of the second sample was chemically etched to a thickness of 1.25 × λ/4, approaching an antiresonant design. Schematics of the resonant and near-antiresonant structures are shown in Fig. 1(a, b). By etching the cap to near-antiresonance, the spectral filter from the microcavity is significantly reduced, but the overall modal intensity overlap is also reduced by a factor of ten at the design wavelength as shown in Fig. 1(c). This reduction of the gain filtering and corresponding increase of the gain bandwidth of the structure, combined with the low device dispersion associated with the near-antiresonant design (Fig. 1(d)), enables short pulse operation to be achieved. The relative advantages and disadvantages of resonant, antiresonant and dielectric antireflection coated resonant structures are described in detail in [14].

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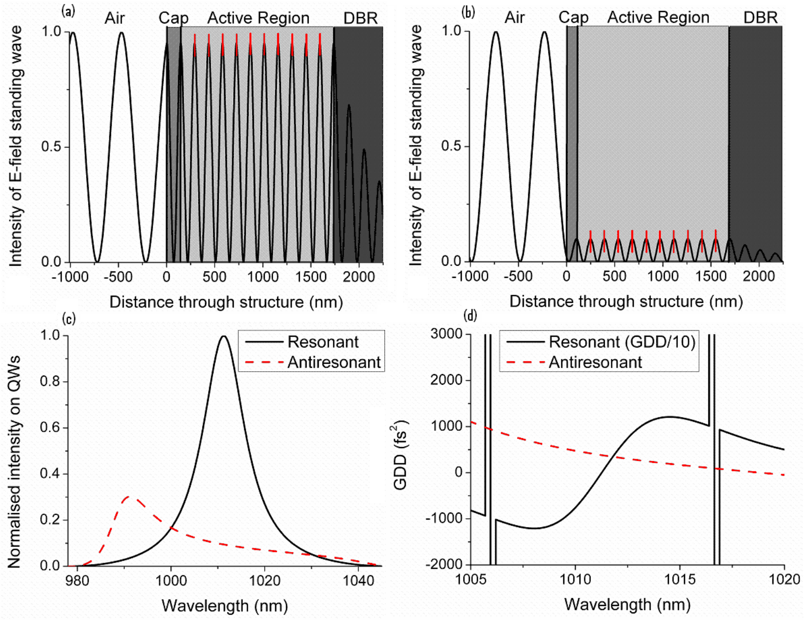

Fig. 1. Schematic of the resonant (a) and near-antiresonant (b) gain structures. The positions of the quantum wells are represented by short vertical red lines. The calculated intensity on the quantum wells versus wavelength is shown in (c) and the device dispersion is shown in (d).

The semiconductor saturable absorber mirror (SESAM) used in this work is a surface recombination SESAM with a single $In_{0.2}Ga_{0.8}As$ quantum well positioned 2 nm from the air-semiconductor interface, grown on top of a 27 pair AlAs/GaAs DBR centered at 1010 nm. The quantum well is positioned 13 nm above the top AlAs layer of the DBR using a GaAs spacer layer. The E-field on the quantum well is near a maximum of the standing wave formed by the DBR mirror. The SESAM is cleaved into a 5mm x 5mm piece and mounted onto a copper heat sink using silver paint with no post growth processing. The SESAM has been used previously to generate ~300 fs pulses in mode-locked VECSELs at 1000 nm [15].

A V shaped cavity is used to study both the CW and mode-locked properties of these VECSEL gain samples. A 100 mm radius of curvature output coupler with transmission of either 0.7% or 1.45% was used as one cavity end mirror. The VECSEL gain chip formed a flat fold mirror and either a flat high reflector, 1.45% output coupler, or the SESAM was used to close the cavity. The gain structures were pumped using a fiber-coupled 808 nm diode laser with up to 30 W pump power. The output of the fiber is focused onto the gain sample, producing a 250 µm radius spot. Due to the highly multi-mode fiber, a near-top-hat pump spot profile is produced. The laser cavity length is adjusted to achieve optimal mode-matching on the gain structure, and produce a waist with radius 100 µm on the SESAM. The total laser cavity length was 9 cm with a distance of 7 cm from the output coupler to the gain structure.

Each gain structure is inserted into the VECSEL in turn by mounting it onto a water-cooled copper heat sink using a clamp and thermal paste and held at 18 °C. The SESAM is mounted on a thermoelectric-cooler-controlled heat sink, which can be held at a temperature between 20 °C and −10 °C. A flow of dry nitrogen gas is passed over the SESAM to ensure condensation does not occur on the semiconductor surface.

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3. Experimetal results

3.1 Photoluminescence and CW characterization

The two gain structures were characterized by measuring the top photoluminescence (PL), emitted at normal incidence to the surface of the structures using a spectrometer, and characterizing the continuous wave (CW) performance. The top PL for both the resonant and near-antiresonant structure is show below in Fig. 2(a).

In the near-antiresonant case, the full width half maximum (FWHM) width of the emission spectrum is two times broader, at 20 nm, and is seven times less intense at the laser design wavelength of 1010 nm than in the resonant case. This reduction of PL intensity and increase in its bandwidth agrees well with the modeled spectral enhancement of the microcavity (Fig. 1(c)) combined with the intrinsic emission spectrum expected for the quantum wells in both the resonant and near-antiresonant cases.

The output power versus pump power for several values of output coupling is shown in Figs. 2(b) and 2(c). In all cases the maximum output power was pump power limited, by the 30 W 808 nm pump laser used. A maximum output power of 8 W was achieved in the near-antiresonant gain structure case when a 1.45% output coupler is used.

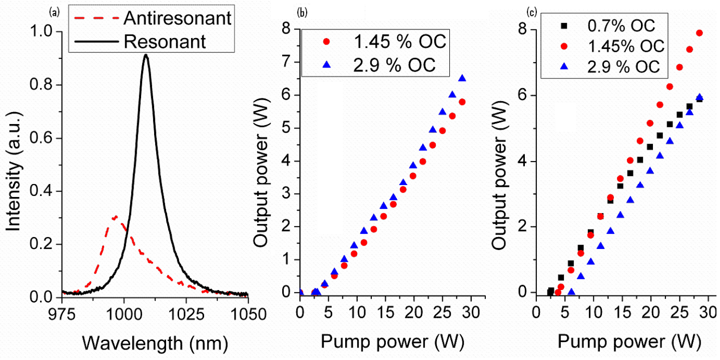

Fig. 2. (a) Top photoluminescence emitted from the resonant and near-antiresonant structures with an incident pump power of 28.5 W. (b) Output power versus pump power for different output coupler transmission for the resonant and (c) near-antiresonant structures.

When the resonant gain sample is used, the VECSEL is always significantly under output coupled, as can be seen from the near-identical threshold pump powers with both 1.45% and 2.9% of output coupling. There is also a slight upwards curve of the power curves, which corresponds to the peak quantum well gain tuning towards the microcavity resonance. For optimal CW performance of the resonant gain structure an output coupler around 5% transmission and a higher pump density than is reached here is needed [10].

In the case of the near-antiresonant sample the optimal output coupling can be seen to be close to 1.45%, with the maximum power and slope efficiency achieved decreasing for both 0.7% and 2.9% output coupling. The optical spectrum tunes to longer wavelength at a rate of 0.5 nmW^{-1} in the case of the near-antiresonant sample, which is 1.8 × the rate at which the wavelength tunes in the resonant sample.

3.2 Mode-locked performance

Mode-locked operation was achieved at incident pump powers greater than 14 W when the near-antiresonant gain structure was used with the surface recombination SESAM and a 1.45% output coupler. The laser threshold increased from 4 W for the case of only a 1.45% output coupler, to 6 W pump power, similar to the threshold observed when a total output coupling loss of 2.9% is used. This indicates that the insertion loss of the SESAM when it is unsaturated is approximately 1.45%.

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The output pulse train was characterized using a grating spectrometer, a calibrated power meter, a RF spectrum analyzer and a non-colinear second harmonic autocorrelator. The recorded pulse duration decreased with increasing intracavity power (output power), with a sech squared pulse profile of duration 530 fs FWHM and output power of 0.5 W at 14.7 W pump power, decreasing to a minimum of 400 fs FWHM pulse duration with 3.3 W output power at 28.5 W pump power. The mode-locked optical spectrum shifted to longer wavelength with increasing intracavity power, from 1008 nm at the minimum mode-locking power to 1013 nm at maximum power. The optical spectrum broadens with increasing intracavity power on the SESAM from 2.3 nm to 3.13 nm FWHM. The pulse duration and center wavelength versus average output power from the VECSEL is shown in Fig. 3.

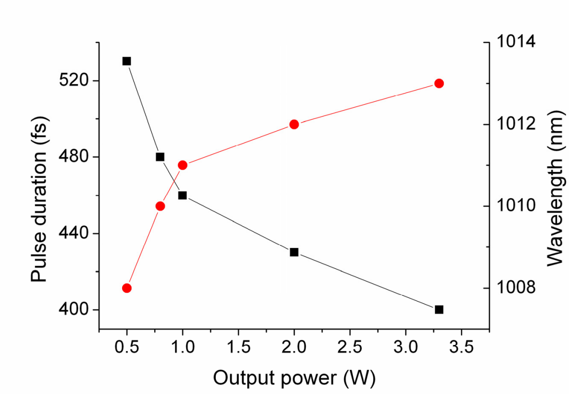

Fig. 3. Pulse duration (black squares) and centre wavelength (red circles) versus output power for the mode-locked VECSEL

To increase the average output power beyond 1 W, the SESAM heat sink temperature was reduced to −10 °C, to aid heat extraction from the unprocessed SESAM where a temperature dependent non-saturable loss was observed. The maximum average power of the mode-locked VECSEL is limited by heating in the SESAM, not by pump power or the gain structure.

The maximum average output power achieved was 3.3 W, with the laser producing 400 fs FWHM pulses at a repetition rate of 1.67 GHz. This corresponds to a peak power of 4.35 kW. The intracavity powers are significantly higher due to the low transmission output coupler used. In this case the intracavity power is 220 W, the peak intensity on the SESAM is 0.92 $\mathrm{MWcm^{-2}}$ and the fluence on the SESAM is 420 $\mu\mathrm{Jcm^{-2}}$. The autocorrelation and optical spectrum of this laser is shown in Fig. 4.

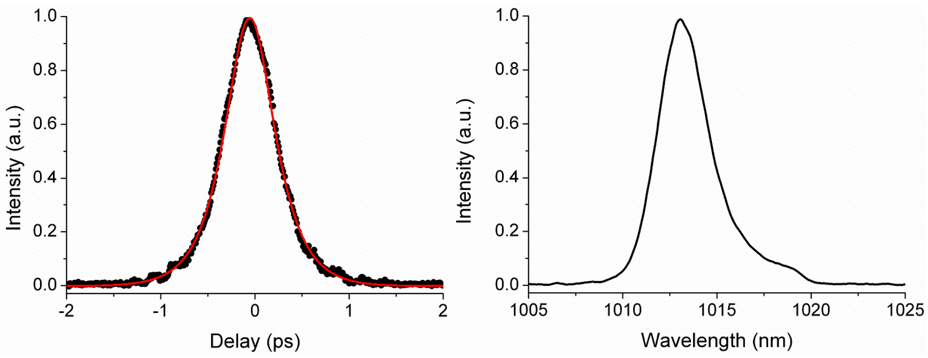

Fig. 4. Measured autocorrelation (left) and optical spectrum (right) of 400 fs sech^2 profile pulse with 3.3 W average output power.

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Mode-locked operation could not be achieved using the resonant gain structure and this surface recombination SESAM. This is due to the SESAM having too little modulation depth to stabilize mode-locked operation with the high gain and dispersion of the resonant structure.

3.3 Supercontinuum generation

The output of the mode-locked VECSEL was launched into a 2 m length of 2.2 μm diameter core photonic crystal fiber after passing through a half wave plate and a free space isolator, which was used to both control the power level at the fiber launch and isolate the VECSEL from back reflections off the fiber tip. The ends of the PCF were not collapsed, which limited its power handling capability to ~1 W of incident power. At this power level, a throughput of 50% was achieved, with 0.5 W measured at the output of the PCF. Above this power level the fiber tip would move due to the thermal load, which significantly reduced the coupling efficiency. The spectrum of the output of the PCF was recorded using a fiber coupled optical spectrum analyzer, and a 20 dB spectral width of 175 nm, spanning from 996 nm to 1171 nm was measured and is shown in Fig. 5.

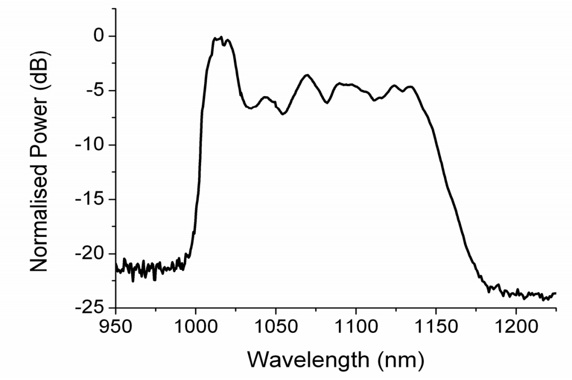

Fig. 5. Measured supercontinuum generated by launching 1 W of the VECSEL output power into a 2.2 micron core PCF. The supercontinuum has a width of 175 nm and a power of 0.5 W.

4. Conclusions

We report a mode-locked VECSEL producing 4.35 kW peak power with an average power of 3.3 W, a repetition rate of 1.67 GHz and a pulse duration of 400 fs FWHM. The optical spectrum was centered at 1013 nm and had a width of 3.13 nm FWHM. The pulses were 1.16 times transform limited. This performance was achieved by combining a near-antiresonant gain structure design with state of art thermal management techniques developed in CW VECSELs. The SESAM used was a surface recombination SESAM designed for 1 μm operation with no post growth processing. The average power of the mode-locked pulse train was limited by heating of the unprocessed SESAM, which introduced a temperature dependent non-saturable loss. Future work to apply processing techniques developed for gain structures to surface recombination SESAMs should allow the average power of gigahertz femtosecond VECSELs to be scaled to the 10 W level or above.

The output pulse train of the VECSEL was used to generate a supercontinuum with a bandwidth of 175 nm and average power of 0.5 W using a 2 m long, 2.2 μm core PCF. The power and spectral width of the supercontinuum was limited by thermal management of the un-collapsed fiber tip. Using optimal thermal management techniques for PCFs, including active cooling of the fiber tip and collapsing of the ends of the PCF, along with optimized PCF design for operation at this wavelength should allow for octave spanning supercontinuum to be generated using gigahertz repetition rate femtosecond pulse VECSELs.

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