175 GHz, 400-fs-pulse harmonically mode-locked surface emitting semiconductor laser.

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Abstract: We report a harmonically mode-locked vertical external cavity surface emitting laser (VECSEL) producing 400 fs pulses at a repetition frequency of 175 GHz with an average output power of 300 mW. Harmonic mode-locking was established using a 300 µm thick intracavity single crystal diamond heat spreader in thermal contact with the front surface of the gain sample using liquid capillary bonding. The repetition frequency was set by the diamond microcavity and stable harmonic mode locking was achieved when the laser cavity length was tuned so that the laser operated on the 117th harmonic of the fundamental cavity. When an etalon placed intracavity next to the gain sample, but not in thermal contact was used pulse groups were observed. These contained 300 fs pulses with a spacing of 5.9 ps. We conclude that to achieve stable harmonic mode locking at repetition frequencies in the 100s of GHz range in a VECSEL there is a threshold pulse energy above which harmonic mode locking is achieved and below which groups of pulses are observed.

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

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1. Introduction

Over the past 20 years since the introduction of femtosecond mode-locked solid-state lasers the parameter space covered by such lasers has expanded significantly. A relatively recent advance has been to push the pulse repetition frequency up towards tens of GHz or more, aiming at applications such as optical clocking and sampling, arbitrary waveform generation, large-mode-spaced continuum generation and high bandwidth telecoms.

Passively mode-locked solid state lasers have to date achieved fundamental repetition frequencies up to 160 GHz with picosecond pulses [1] and 10 GHz with femtosecond pulses [2]. The key challenge is to avoid the Q-switched mode locking regime that appears when the intracavity pulse energy is too small to saturate the absorber adequately. Mode-locked edge-emitting diode lasers are by contrast intrinsically suited to high repetition frequency operation, typically in the range 20-100 GHz [3]. The average power from these semiconductor pulse sources, however, is typically only a few mW.

An alternative route to high repetition frequency is that of harmonic mode locking, where more than one pulse circulates in the laser cavity, and pulses are emitted at an integer multiple of the fundamental cavity repetition frequency. Techniques that have been used to produce harmonic mode locking include active modulation [4], colliding-pulse mode locking [5], or coupled-cavity mode locking in which the pulse repetition frequency is set by a sub-cavity [6]. To date, with harmonic mode locking, fiber lasers have attained pulse repetition frequencies up to 200 GHz [4], and diode lasers reach 100s or even 1000s of GHz [5,7,8]. For all of these harmonically mode-locked lasers, however, with repetition frequency > 100 GHz, average power is limited and pulse duration is > 1 ps.

The vertical-external-cavity surface-emitting laser (VECSEL) offers an alternative approach to the generation of GHz repetition frequency mode-locked pulse trains with high average power and brightness. The low saturation fluence of the quantum well gain structure suppresses Q-switching instability, while the external cavity allows access to and control over the laser mode. The excitation region of the gain structure is a thin disk, about 100 μm in diameter and 1 μm thick, from which heat can be extracted efficiently and dispersed in a diamond heat sink. The heat sink may be outside the laser cavity, so that heat is extracted

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through a semiconductor Bragg mirror; or it may be a plate of optical quality material inside the laser cavity, in direct contact with the excitation region.

Femtosecond mode-locked VECSELs have produced pulses as short as 60 fs in pulse groups [9] and 100 fs with a single intracavity pulse [10]; average power up to 1 W with 784-fs pulse duration [11], and peak power up to more than 300 W with pulses of 260 – 335 fs [12,13]. They are capable of fundamental repetition frequencies up to 50 GHz [14,15]; moreover continuous cavity-length tuning of the repetition frequency over many GHz has been demonstrated [16–18]. Passive harmonic mode locking of VECSELs has also been demonstrated at 92 GHz with 200 fs pulses and 30 mW average power [10]. In that work harmonic mode locking occurred spontaneously driven by gain and absorber dynamics. More recently, a harmonically mode-locked VECSEL was reported where the SESAM substrate was used as an external coupled cavity to produce 147 GHz repetition frequency with 1.1 ps pulses and 40 mW average output power [6]. Femtosecond VECSELs are moreover ideally suitable as sources of high repetition rate seed pulses for ytterbium-doped fiber amplifiers in the parabolic regime, with 50 W average power reported for a 1.1 GHz pulse train [19].

Here we report harmonic mode locking of VECSELs controlled by an intracavity etalon. When the VECSEL cavity length is tuned to be an integer multiple of the etalon thickness, harmonic mode locking is observed at a repetition frequency set by the free spectral range of the etalon. We describe two different lasers. In the first laser, a 0.5-mm thick sapphire etalon was placed touching, but not thermally contacted to, the surface of the optically-pumped gain structure. The intensity autocorrelation of the laser output showed a group of 300 fs pulses spaced at regular time intervals corresponding to a repetition frequency 169 GHz. The optical spectrum of the laser was modulated at 0.6 nm (169 GHz) intervals, with an overall full width half maximum (FWHM) bandwidth of 5.3 nm. The average output power was 20 mW. This regime has features in common with Q-switched mode locking, where the intracavity pulse energy is too low to stabilize continuous-wave mode-locked operation. In the second laser that we describe, liquid capillary bonding was used to contact a 300-μm thick single crystal diamond plate to the surface of the gain sample. The diamond allowed efficient heat extraction from the active region, which therefore tolerated more pump power. Stable continuous-wave harmonic mode locking was observed with repetition frequency of 175 GHz, pulse duration of 400 fs and an average output power of 300 mW.

2. Samples and cavity

A three-mirror laser cavity, producing two output beams from the 25 mm radius of curvature 0.3% output coupler, was used in this work. This enabled the flat gain structure to be used as an end mirror, with the intracavity etalon perpendicular to the cavity mode. The cavity was closed with a surface recombination semiconductor saturable absorber mirror (SESAM) acting as the other end mirror. The cavity lengths were chosen such that the laser mode matched the 60 μm radius pump spot and produced a waist of 20 μm radius on the SESAM. The distance between the gain structure and the output coupler was approximately 85 mm and the distance between the output coupler and the SESAM approximately 15mm. The fundamental repetition frequency is ~1.5 GHz. A schematic of the laser cavity is shown in Fig. 1.

The gain sample, designed at 1035 nm, consisted of a 27.5 pair GaAs/AlAs distributed Bragg reflector (DBR) on which an active region containing six 8 nm thick $In_{0.25}Ga_{0.75}As$ quantum wells in a 7 $\lambda/2$ long microcavity was grown. The gain sample was completed with a $\lambda/4$ AlAs window layer and an 8 nm thick GaAs capping layer to stop oxidation.

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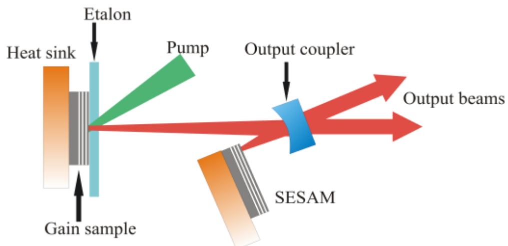

Fig. 1. A schematic diagram of the laser cavity. The 0.3% output coupler had a 25 mm radius of curvature. The cavity length was 85 mm from the gain to the output coupler and 15 mm from the SESAM to the output coupler.

Two SESAMs were used in this work; a high modulation depth (~0.7%) and a low modulation depth (~0.25%) SESAM. Both consist of identical DBRs to that of the gain sample and contain a single surface recombination 8 nm $In_{0.25}Ga_{0.75}As$ quantum well capped by 2 nm GaAs on top. This allows efficient tunneling of carriers to the air-semiconductor interface where localized surface states cause fast carrier recombination. The quantum wells are positioned 13 nm or 40 nm from the top layer of the DBR using a GaAs spacer layer to produce a modulation depth of ~0.7% and ~0.25% respectively. The gain and SESAM samples were grown by molecular beam epitaxy under optimal conditions. The samples were grown on 500 µm thick GaAs substrates and no post growth processing was undertaken to remove these.

3. Results

Before mode locking the laser we tested the CW characteristics of the laser with the etalons intracavity in a 2 mirror straight cavity. When the VECSEL was used with the 500 µm sapphire placed in contact with, but not liquid capillary bonded to, the gain sample the laser operated with a maximum output power of 300 mW before thermal rollover was observed. Thermal rollover was observed at an incident pump power of 1.7 W. The threshold remained nearly identical to the case when no etalon was present at 0.3 W of incident pump power. When the diamond etalon was liquid capillary bonded to the front of the gain sample the maximum power achieved was 2.5 W at 14 W of incident pump power. Thermal rollover was observed above this pump power, which was caused by the non-optimal thermal contact between the diamond and the heat sink. However, the threshold of the laser with intracavity diamond heat spreader was significantly higher, with a threshold pump power of 1 W.

When we mode-locked the VECSEL with the sapphire intracavity etalon the gain of this laser was high enough to allow us to use the high modulation depth SESAM without significant reductions in average output power. Stable groups of harmonically mode-locked pulses were observed by varying the cavity length until it was an integer multiple of the etalon optical path length. The optimal performance was observed when the gain sample heatsink was held at 10 °C and the incident pump power was 1.1 W. In this regime the laser had a combined output power of 20 mW and produced $sech^2$ profile pulses of duration 300 fs FWHM with a spacing of 5.9 ps, relating to a repetition frequency of 169 GHz, which can be seen in the autocorrelation in Fig. 2(a) A portion of the envelope of the group of pulses can be seen in the autocorrelation. The optical spectrum, shown in Fig. 2(b), has a FWHM bandwidth of 5.3 nm and the fringes in the spectrum are spaced by 0.6 nm. Figure 2(c) shows the autocorrelation of the zero delay peak with a $sech^2$ fit of a 300 fs FWHM pulse.

We observed the RF spectrum of the laser output using a 26 GHz fast photodiode and RF spectrum analyzer. No peaks were observed in the RF spectrum within its bandwidth confirming harmonic mode locking.

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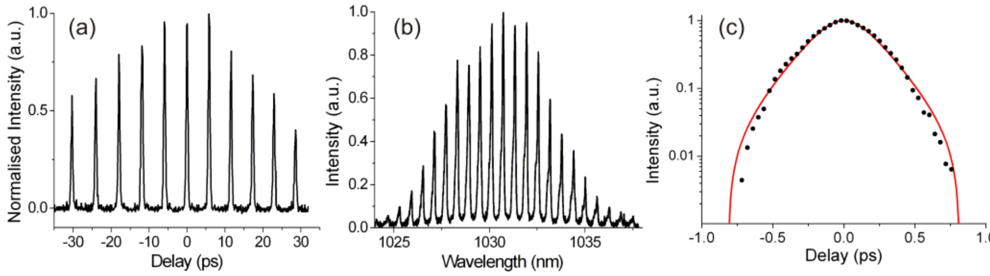

Fig. 2. (a) Autocorrelation of HML VECSEL with sapphire etalon operating on 112th harmonic. The pulse spacing is 5.9 ps. (b) Optical spectrum with FWHM of 5.3 nm and fringes spaced by 0.6 nm. (c) Zero delay autocorrelation peak showing a 300 fs FWHM $sech^2$ pulse.

When we used the liquid capillary bonded diamond heat spreader sample we again found stable regimes of harmonic mode locking when the main cavity length was tuned to integer multiples of the diamond etalon optical path length. In this laser the liquid capillary bond between the semiconductor gain chip and the diamond increases the loss of the cavity, as is seen in the increase in the CW threshold, and therefore we used the low modulation depth SESAM to obtain HML operation with slightly longer pulse durations to those reported above. Continuous wave harmonic mode locking was observed with no tendency towards the formation of groups of pulses. Optimum continuous wave harmonic mode locking performance produced pulses of duration 400 fs FWHM assuming a $sech^2$ profile, at a repetition frequency of 175 GHz and a pulse spacing of 5.7 ps, shown in the autocorrelation trace in Fig. 3(a). The small modulations seen in Fig. 3(a) are due to variation in the reflectivity of the rotating mirrors in our autocorrelator. The optical spectrum, shown in Fig. 3(b), has a FWHM of 3.5 nm at a centre wavelength of 1037.5 nm and again shows clear etalon fringes with a spacing of ~0.6 nm, corresponding to both to the transmission fringes of the diamond etalon and the observed 175 GHz repetition frequency. The zero delay autocorrelation peak and the $sech^2$ fit representing a 400 fs pulse FWHM is shown in Fig. 3(c). The combined average output power was 300 mW. An incident pump power of 9 W was used and the gain sample mount was held at 10 °C.

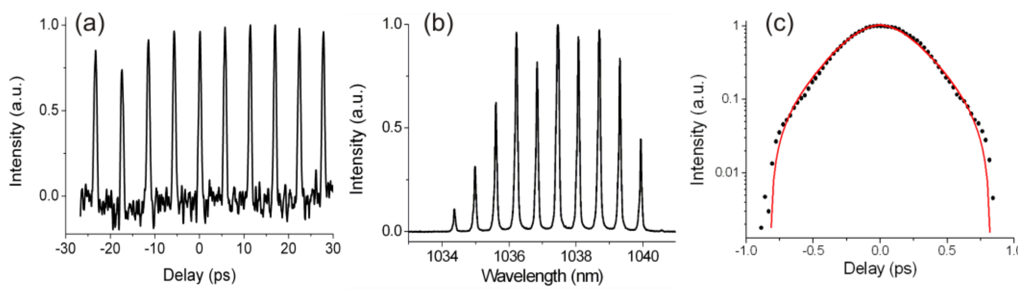

Fig. 3. (a) Autocorrelation of HML VECSEL with diamond etalon operating on 116th harmonic. The pulse spacing is 5.7 ps. (b) Optical spectrum with FWHM of 3.5 nm and fringes spaced by 0.6 nm. (c) Zero delay autocorrelation peak showing a 400 fs FWHM $sech^2$ pulse.

4. Discussion

Both lasers mode-lock harmonically and produce femtosecond pulses. In each case the laser cavity contains >100 optical pulses with a high level of mutual coherence, as shown by the modulation of the optical spectrum and the lack of beats at the fundamental cavity repetition frequency in the RF spectrum. No peaks were visible in the RF spectrum, within the bandwidth of the fast photodiode and analyzer, at the fundamental repetition frequency of the

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laser cavity or its harmonics. In the case of the 20 mW laser, the amplitude of the mode-locked pulse train is unstable and shows broad peaks, consistent with a slowly-varying envelope, reminiscent of Q-switched mode locking (Fig. 2(a)). The 300-mW laser, by contrast, appears to be free of amplitude modulations.

Honniger et. al. have derived the criterion for the stability against Q-switching of passively mode-locked pulses. For harmonic mode locking the stability requirement is shown below in Eq. (1) [20],

$$NE_p^{\ 2} \geq E_{sat,a}E_{sat,g}\Delta R, \tag{1}$$

where N is the number of pulses in the cavity, E_p is the intracavity pulse energy, $E_{sat,a}$; $E_{sat,g}$ is the saturation energy of the SESAM and gain respectively and ΔR is the modulation depth of the SESAM. The values used to evaluate the CW harmonic mode locking condition are shown in Table 1, the parameters for the gain and SESAMs are taken from [13,21].

Table 1. Q-switched mode locking parameters for HML VECSELs with sapphire and diamond etalons

Parameter	VECSEL with sapphire etalon	VECSEL with diamond etalon
$E_{sat,g}$	0.628 nJ^2	1.26 nJ^2
$E_{sat,a}$	33.9 nJ^2	33.9 nJ^2
ΔR	0.7%	0.3%
N	112	116
E_p	19.7 pJ	286 pJ
$NE_p^2/(E_{sat,a}E_{sat,g}\Delta R)$	0.29	74

It can be seen that in the case of the VECSEL with sapphire etalon the condition for continuous wave harmonic mode locking is not satisfied. On the other hand when the intracavity diamond heat spreader sample is used, the output power and intracavity pulse energy in are significantly higher. In this case the CW harmonic mode locking condition is satisfied and experimentally CW harmonic mode locking is observed.

7. Conclusion

We report harmonically mode-locked VECSELs at repetition frequencies in the 100's of GHz range using intracavity etalons to act as both sub-cavity and thermal heat spreader. When a 300 µm thick diamond heat spreader was liquid capillary bonded to the front surface of the gain sample 1.25 x transform limited 400 fs pulses at 175 GHz repetition frequency, with average output powers of 300 mW were observed.

When an intracavity sapphire etalon, not in thermal contact with the gain sample, was used the average output power was 15 x lower (20 mW) and the envelope of the train of pulses was seen to be modulated. This regime appears to be analogous to Q-switched mode locking in solid state lasers. Shorter pulses were obtained in this case as a higher modulation depth SESAM was used. We conclude that the intracavity pulse energy plays a critical role in determining if CW HML is obtained or if amplitude modulations are present on the pulse train.

Future work will explore the limits of power scaling and study the gain and absorber dynamics to enable modeling of the laser dynamics in this harmonic mode locking regime.

Due to the power scaling potential, as well as the fast semiconductor gain dynamics, harmonically mode-locked VECSELs present an interesting alternative to producing ultra-high repetition frequency femtosecond pulse trains for applications such as optical clocking, optical sampling and arbitrary waveform generation.

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