Repetition-frequency-tunable mode-locked surface emitting semiconductor laser between 2.78 and 7.87 GHz

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Abstract: We report a repetition frequency tunable, passively mode-locked vertical-external-cavity surface-emitting semiconductor laser (VECSEL) with continuous repetition frequency tuning between 2.78 and 7.87 GHz using mechanical tuning of the laser cavity length. The laser emits near-transform-limited, sub-500-fs pulses over almost an octave tuning range between 2.78 and 5 GHz. At repetition rates above 6 GHz the pulse duration increases to ~2.5 ps. Over the entire tuning range the laser emits an average output power of 40 ± 5 mW in a fundamental transverse mode. The change in pulse duration highlights a change in the dominant mode-locking mechanism which forms the pulses. At high repetition frequencies the pulse duration is set by the saturable absorber recovery time. At low repetition frequencies the fluence and peak intensity on the SESAM increases to a point where the fast pulse shaping mechanisms of the optical Stark effect and carrier thermalization dominate the pulse shortening.

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References and links


1. Introduction

Femtosecond mode-locked solid state lasers produce regularly spaced trains of pulses set by the cavity length. Over the last 20 years since their inception, significant advances have been made to the pulse duration, noise characteristics and repetition rate available [1]. One key application that femtosecond mode locked lasers have enabled is optical frequency comb generation, which allows optical frequencies to be referenced directly to radio frequency standards, with an absolute precision better than 1 part in $10^{15}$ [2]. These frequency combs benefit from high repetition frequency drive lasers, as this increases the power per mode and mode spacing to a point where they can be individually resolved and manipulated using optical gratings [3]. Whilst frequency combs have been an enabling technology for a range of applications such as multiheterodyne spectroscopy, optical arbitrary waveform generation and optically referenced microwave generation amongst many others [4], the potential for combs with tunable mode spacing has not been explored.

To enable mode-space tuning and large mode spacing, significant efforts have been directed to developing microcavity generated combs. Octave spanning spectra with mode spacing of 850 GHz and mode spacing tuning amounting to 50% has been demonstrated [4]. However to date there are several challenges with microcavity combs which limits their application. Combs generated by this technique have modes which are not evenly spaced in frequency across the whole spectrum, which prevents self-referencing of the comb, and the mode spacing is limited to the 100’s of GHz range, beyond the range of RF electronics [4].

Microcavity generated combs are of particular interest as the repetition frequency of femtosecond oscillators isn’t traditionally a degree of freedom which can be exploited. Kerr lens mode-locked (KLM) lasers rely on a cavity close to the stability limit, with pulse characteristics sensitive to small cavity length changes. In soliton mode-locked lasers, pulse duration is controlled by the energy of the intracavity pulse. As repetition frequency is increased a decrease in pulse energy is seen with a constant output power. This leads to a variation in pulse length with repetition frequency tuning. Furthermore all-fiber cavities allow only limited length variation by stretching or heating. It has however been this type of laser which has to date shown the largest repetition frequency tuning ranges for femtosecond oscillators. Repetition rates of ± 1% are now available in commercial fiber lasers [5].

Significant tuning ranges are often demonstrated in external cavity edge emitting semiconductor lasers [6]. However, in external cavity configuration these lasers produce pulses of duration several picoseconds and have typically sub-mW average power, which varies significantly with repetition frequency.
Passively mode-locked optically pumped vertical-external-cavity surface-emitting lasers (VECSELs) produce femtosecond pulse trains at gigahertz repetition frequencies and utilize fast pulse shaping effects in semiconductor saturable absorber mirrors (SESAMs) to control the pulse duration. Typically the optical Stark effect is used to produce pulses of duration 260 fs [7] to 500 fs [8] with peak powers up to 315 W [9]. Carrier thermalization in the SESAM can also be exploited and has been used to generated sub-200-fs pulses [10] and pulses as short as 107 fs [11]. VECSELs using quantum dot SESAMs and gain structures, rather than those based on quantum wells, have generated femtosecond pulse trains with Watt level average output power [12]. The shortest pulses produced by a VECSEL, and indeed any semiconductor laser, are groups of 60 fs pulses [13]. Femtosecond mode-locked VECSELs do not rely on KLM or soliton pulse formation, making them potentially uniquely positioned as tunable multi-gigahertz repetition frequency oscillators. Near identical sub-500-fs pulse VECSELs have been reported at both 1 and 10 GHz with intracavity pulse energies of 5.95 nJ and 0.433 nJ and fluences on the SESAM on 585 µJ/cm² and 82 µJ/cm² respectively despite using identical gain and SESAM structures [8,14], clearly demonstrating the large dynamic range over which femtosecond pulse operation can be achieved in VECSELs.

Recently we reported a tunable repetition frequency VECSEL with an 8% repetition tuning range between 1 and 1.2 GHz, with 450 fs pulses which did not change across this tuning range [15]. Here, we report a tunable repetition frequency VECSEL continuously tuned from 2.78 to 7.87 GHz by cavity length variation. The highest repetition frequency is >2.8 times that of the lowest. As the repetition frequency is tuned the pulse duration remains near-constant at sub-500-fs between 2.78 and 5 GHz, representing almost an octave tuning of repetition frequency. At repetition frequencies between 5 and 6 GHz a sharp transition between femtosecond pulse duration and picosecond pulse duration is seen. Above 6 GHz the pulse duration remains near constant at ~2.5 ps. The laser produces a constant average output power of 40 ± 5 mW across the entire tuning range.

This laser highlights the potential that repetition frequency tunable femtosecond mode-locked VECSELs hold, as well as providing a significant insight into the laser dynamics which form pulses in VECSELs. It allows average intracavity power, cavity loss and laser mode areas on the active components to remain constant; only the intracavity pulse fluence and peak intensity on active structures are varied. This insight is particularly useful in mode-locked VECSELs where the cavity dynamics which control the mode-locked behavior are yet to be completely understood.

2. Samples and cavity

The key components of the mode-locked VECSEL are a semiconductor multilayer gain structure and a SESAM, both of which are active mirrors in the 4 mirror laser cavity. The gain structure consists of 6 In₀.₂Ga₀.₈As quantum wells grown on top of a 27.5 pair GaAs/AlAs distributed Bragg reflector (DBR) with a design wavelength of 1000 nm. The quantum wells are positioned at the antinodes of the E-field standing wave, and are distributed in a non-uniform manner within the 7λ/2 long GaAs microcavity so as to compensate for the gradient in carrier density resulting from pump absorption. The structure is finished with a 3/4 thick AlAs window layer, which acts as a carrier blocking layer and forces the sample to be antiresonant at the design wavelength. An 8 nm GaAs capping layer to prevent oxidation finishes the structure. The gain structure is optically pumped with an 830 nm fibre coupled pump diode, producing up to 2 W of pump power, which is focused into a 60 µm radius spot on the gain sample. The SESAM consists of a single In₀.₂Ga₀.₈As quantum well grown on top of an identical DBR. The quantum well is separated from the top layer of the DBR by a 13 nm GaAs spacer, and has a 2 nm GaAs capping layer on top, completing the structure. The SESAM uses surface recombination to reduce the recovery time. The samples are identical to those previously reported in [9].

The laser cavity, shown in Fig. 1. is formed between a plane 0.3% output coupler which acts as one end mirror, a 25 mm radius of curvature high reflector, the gain sample which acts
as a folding mirror, and the SESAM which closes the cavity. The laser mode is near-collimated between the plane output coupler and the curved high reflector, with a large mode waist on the output coupler. The position of the gain relative to the curved high reflector is controlled to ensure mode matching between the 60 µm radius pumped region and the convergent mode of the cavity. The mode reaches a tight focus on the SESAM. At each repetition frequency the mode radius on the SESAM is calculated by measuring the beam divergence after the output coupler and was found to vary between 9.15 and 7.8 µm.

3. Results

The laser was optimized for mode-locked operation at the highest repetition rate of 7.87 GHz, which was near the mechanical limits of this cavity configuration. At this repetition frequency pulses of duration 2.5 ps were produced when an incident pump power of 1.3 W was used and the gain sample mount was temperature controlled to −3.6 °C using a thermoelectric element. The pump power and gain mount temperature remained constant throughout the experiment. The average output power was measured to be 40 ± 5 mW. The optical spectrum, RF spectrum and autocorrelation were recorded before the plane output coupler was translated away from the 25 mm radius of curvature high reflector. The laser characteristics were recorded at approximately 100 MHz intervals, until the maximum translation range was reached. Figure 2a) shows the recorded RF spectrum at the fundamental repetition frequency for each cavity length used. In each case a 10 MHz span scan is recorded with 100 Hz.
resolution bandwidth. Due to the large tuning range these appear as near-delta functions, but in all cases the signal is >60 dB above the noise floor. The measured autocorrelation and optical spectrum at a repetition frequency of 2.95 GHz, is shown in Fig. 2b). The pulse duration is 290 fs assuming a sech-squared pulse profile, and the pulses are 1.1 × Fourier limited.

The pulse duration, extracted from the measured autocorrelations, versus repetition frequency across the tuning range is shown in Fig. 3a). In Fig. 3b) the magnitude of the chirp of the pulses is shown. It can be seen that over the range where picosecond pulses are produced significant chirp exists, with the pulses several times Fourier limited. On the other hand in the femtosecond regime, below 5 GHz repetition frequency, the pulses remain near-transform-limited, with little chirp.

![Fig. 3. a) Pulse duration versus repetition frequency. b) Pulse chirp versus repetition frequency.](image)

In Fig. 4 the pulse duration and central wavelength of the output spectrum are plotted against the pulse fluence on the SESAM. Sharp transitions are visible in both graphs. In Fig. 4a) it is clear that the picosecond pulse regime occurs at lower fluence on the SESAM, whilst femtosecond operation occurs at high fluence. The transition occurs at a fluence of 1.4 mJ/cm². We estimate the saturation fluence of the SESAM, F_{sat,a} = 100 µJ/cm² [8]. The transition in center wavelength in Fig. 4b) occurs at a fluence of 1 mJ/cm², with the laser operating at longer wavelengths at low fluences and shorter wavelengths at higher fluences.

![Fig. 4. a) Pulse duration versus pulse fluence on SESAM. b) Optical spectrum center wavelength versus pulse fluence on SESAM.](image)

The observed shift of wavelength with fluence can be explained by examining the spectral characteristics of the loss and gain in the laser. Figure 5 shows the calculated gain and loss spectra of the laser. The loss curve has contributions from the small signal absorption of the SESAM, measured using a spectrophotometer, the 0.3% output coupling, and the fixed cavity
losses, estimated to be 0.5%. The small signal absorption of the SESAM amounts to ~1% above the background losses, which is in close agreement with the predicted modulation depth of this SESAM. The gain spectrum is calculated using a parabolic approximation of the gain profile. We assume a 2% roundtrip gain, based on testing the cw laser using various output couplers up to a maximum of 1.85%, which was the highest output coupling at which lasing could be achieved. The curvature of the parabolic gain approximation is calculated with a full width half maximum value of 50 nm. This is in agreement with values we have measured for similar gain structures using a spectrotemporal technique [16]. We center the gain parabola at 990 nm, which is the free running cw laser wavelength obtained under identical operating conditions to the mode-locked laser. It is important to note that the real gain profile is not parabolic over the entire range, but for a range of ~10 nm either side of the gain center the approximation is reasonable [16].

![Graph of Gain and Absorption](image)

**Fig. 5.** Measured small signal absorption profile plus fixed cavity losses (red) and gain profile assuming a parabolic profile centered at 990 nm with a width of 50 nm FWHM.

The wavelength shift in Fig. 4b) occurs because the increased pulse fluence on the SESAM saturates the absorber harder, reducing the loss at shorter wavelengths. At low fluence the laser will operate off the center of the gain spectrum to the long wavelength side where the unsaturated gain exceeds the small signal absorption by the largest amount. As the absorber is saturated harder the laser will tend to operate closer to the gain peak, which is centered at 990 nm. The wavelength shift of the laser, which is driven by increasing fluence on the SESAM, also increases the modulation depth of the SESAM, as can be seen by the small signal absorption.

**4. Discussion**

It is clear that as the repetition frequency (fluence on SESAM) is varied two distinct regimes of pulse duration are seen. At fluences between 0.7 and 1.3 mJ/cm² the pulse duration is long and is near-constant between 2.2 and 2.5 ps. As the fluence increases further there is a transition at approximately 1.4 mJ/cm². Over a fluence range between 1.5 and 1.85 mJ/cm² the pulse duration remains in the range 300-500 fs.

The intrinsic absorber recovery time of surface recombination SESAMs with 2 nm thick caps is typically in the range of 1-3 ps [17]. The pulse duration at lower fluence appears to be set predominantly by the intrinsic absorber recovery time. There is a significant wavelength shift to shorter wavelength with increasing fluence on the SESAM, amounting to 7 nm towards shorter wavelength between 0.7 and 1.3 mJ/cm². This wavelength shift results in an increase in the modulation depth seen by the laser, and therefore in the strength of the modelocking. The chirp of the pulse reflects the strength of the phase locking between the modes in the optical spectrum. It can be seen from Fig. 3b) and Fig. 4b) that the reduction in chirp seen in these picosecond pulses is related to the increase in modulation depth of the saturable absorber as the wavelength shifts closer to the absorber peak.
A sharp transition in pulse duration, and modelocking regime, can be seen around a fluence of 1.4 mJ/cm². At fluences above 1.5 mJ/cm² the pulse duration is in the sub-500-fs regime. The spectrum is centered on the gain peak, and is slightly on the long wavelength side of the absorber resonance, where a contribution to pulse shortening from the optical Stark effect is expected. The central wavelength of the laser spectrum is identical on both sides of the modelocking regime transition. The properties of the gain sample, such as dispersion and gain filtering, are therefore identical on both sides of the modelocking regime transition, and the properties of the SESAM such as absorber recovery time and carrier thermalization times are slowly varying. The only laser parameters that vary significantly across this transition are the pulse fluence and the pulse peak intensity. Whilst the fluence on the SESAM changes by only 15% across this transition, the peak intensity on the SESAM changes by a factor of ~5, from 0.6 GW/cm² to 3 GW/cm². The transition into the femtosecond regime therefore appears to be driven by peak intensity on the SESAM, implying that the optical Stark effect, which has been modeled to have a significant pulse shaping effect at peak intensities >1GW/cm² [7, 18,19], is responsible for the reduction in pulse duration.

Whilst in our case the evidence suggests that we exploit the optical Stark effect for femtosecond pulse formation, some femtosecond VECSELS reported appear to use carrier thermalization as the dominant pulse shaping mechanism [10,11]. In the future we will further explore the different modelocking regimes using this technique of repetition frequency variation, with additional control of the SESAM temperature, allowing us to vary the spectral position on the absorber resonance at which the laser operates. By doing this we will be able to access regimes where the optical Stark effect should and not be present, regimes where carrier thermalization should be dominant and regimes where the intrinsic absorber recovery time should dominate. This should provide an insight into the different mechanisms which can be employed to produce femtosecond pulse VECSELS.

7. Conclusion

We report a variable repetition frequency passively mode-locked VECSEL continuously tunable between 2.78 and 7.87 GHz. It produces sub-500-fs pulses with repetition frequencies between 2.78 and 5 GHz; above 5 GHz a transition to a different modelocking regime is observed with long pulses of duration 2.2-2.5 ps are produced up to a maximum repetition frequency of 7.87 GHz. In the reported laser the transition into the femtosecond regime is consistent with the optical Stark effect becoming the dominant pulse shaping mechanism.

The wavelength flexibility of the semiconductor active components allows for direct translation of this type of performance to a wavelength range commensurate with ytterbium fiber amplifiers (YDFAs) where parabolic amplification up to 50 W and pulses compressible to ~100 fs has been demonstrated [20]. Such a tunable GHz repetition frequency VECSEL-YDFA system should be of significant interest for the generation of frequency combs with high power per mode and tunable GHz mode spacing, allowing a new capability for comb systems to be realized.

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