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Femtosecond synchronously mode-locked vertical-external cavity surface-emitting laser

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Abstract: The behavior of a room temperature synchronously mode-locked vertical-external cavity surface-emitting laser (VECSEL) operating at 980 nm is reported. The laser performance was found to be qualitatively the same for different pump pulse duration (3.6 ps and 70 fs). The pulse duration of the laser is limited by strong self-phase modulation to around 10-40 ps. By compressing the strongly chirped pulses generated directly from the laser, ultrashort pulses with duration of around 200 fs with maximum peak powers of 1.3 kW at 80 MHz were obtained. Multiple pulsing of the laser was observed and the effects of cavity length detuning on pulse width and spectral bandwidth have been investigated.

OCIS codes: (140.4050) Mode-locked lasers; (250.7260) Vertical cavity surface emitting lasers; (320.7090) Ultrafast lasers; (320.1590) Chirping; (320.5520) Pulse compression

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1. Introduction

Optically pumped vertical-external cavity surface-emitting lasers (VECSEL) [1] combine the advantages of multiple quantum well semiconductor lasers with optical pumping. Hence, they have the potential to generate high output powers with excellent beam quality. VECSEL technology is maturing rapidly and is finding applications in many diverse areas of science ranging from high-resolution spectroscopy through to medical imaging. The broad gain bandwidth associated with the multiple quantum well system means that the VECSEL should be an ideal source for the production of ultrashort pulses. To date most research effort aimed at the generation of ultrashort pulses from VECSEL systems has concentrated on the passive mode-locking approach with a semiconductor saturable absorbing mirror (SESAM) acting as the mode-locking element [2]. With this approach sub-picosecond pulses have been generated with repetition rates in the 10's gigahertz regime [3]. Such high repetition rates are ideal for communications applications, however the low peak power (~10W) associated with the generated pulses, which is a direct consequence of the high repetition rate, makes the passive mode-locking approaching using a SESAM unsuitable for many other applications such as two-photon fluorescence microscopy for biological imaging, or frequency conversion applications, where high peak powers are needed. Furthermore, low repetition rates in the hundred of MHz range are beneficial in the biological imaging applications due to the lifetimes of the typical dyes used.

An alternative mode-locking technique is required in order to generate ultrashort pulses at low repetition rates from a VECSEL system. The most obvious approach is to use an active mode-locking technique whereby an external drive signal is used to induce the necessary mode coupling to produce the desired short pulse [4]. However, the carrier lifetime in a VECSEL is of the order of nanoseconds making active mode-locking somewhat problematic. First, the average power drops in proportion to the drop in repetition rates for round trip times that are greater than the storage time. Second the system has a propensity to multiple pulsing for repetition rates lower than the inverse of the storage time.

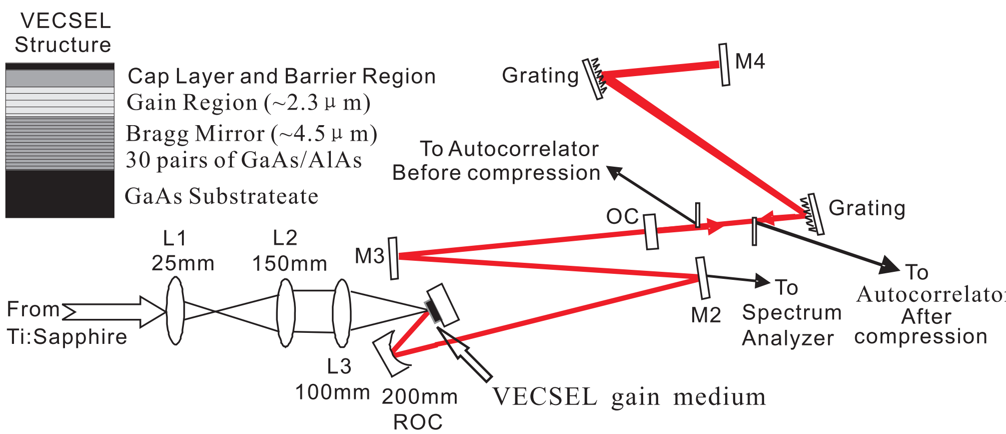
Some of these problems can be overcome by the use of synchronous pumping where the pump laser is mode-locked and a VECSEL cavity length is matched to the pump laser repetition rate. Synchronous pumping of VECSELs should be an attractive option for generating high peak power pulses and indeed it has shown previously that it is possible to synchronously mode-lock a vertical cavity semiconductor laser in an external cavity configuration based on GaAs (wavelength of 880-890 nm) or InGaAs/InP (wavelength of 1.5 μm) material [5-7, 23]. In most of those systems the gain medium comprised of many (120-200) quantum wells [5-7] and - at least in the case of the InGaAs/InP material - the laser operation temperature was very low (77 K). In this communication we describe our work on

#9445 - $15.00 USD Received 10 November 2005; revised 26 January 2006; accepted 17 February 2006

the synchronous mode-locking of a room temperature VECSEL at 980 nm with a gain medium containing 14 single quantum wells placed in a resonant periodic gain structure. We find that, although the pulses are severely chirped by self-phase modulation, it is possible to externally compress that pulses to a duration of less than 200 fs. The dependence of the laser characteristics on detuning is systematically investigated in order to identify the potentials of the scheme.

2. VECSEL structure and experimental setup

The semiconductor wafer sample used as the gain medium in this work was grown by a commercially MOCVD to our specifications. The structure of the wafer and the set-up of the resonator are both shown in Fig. 1. A highly reflective (HR) Bragg reflector, made from 30 GaAs-AlAs layers, was deposited onto a GaAs substrate. On top of this HR mirror a gain region was grown containing 14 $In_{0.15}Ga_{0.85}As$ quantum wells, each 8nm thick. Spacing layers of a 103 nm thick $Al_{0.06}Ga_{0.94}As$ barrier and a 2.9 nm GaAsP strain-compensating layer were used to separate each quantum well. An $Al_{0.3}Ga_{0.7}As$ layer was used to cap the structure. The 3 mm x 3 mm sized sample was cleaved from the wafer and bonded to a copper heat-sink by using indium foil. The back surface of the sample was roughened so as to minimize the etalon



effect of the substrate layer.

Fig. 1. Experimental setup for the mode-locking of a VECSEL synchronously pumped by a Ti: Sapphire laser (ROC radius of curvature, OC output coupler)

The resonator consists of the HR Bragg mirror, a mirror of 200 mm radius of curvature, two plane HR mirrors and a 0.88 % transmitting output mirror which was mounted on a translatable stage providing cavity length adjustment. The distance between the HR Bragg mirror and the curved mirror was 103 mm and between the curved mirror and the output coupling mirror was 1.761 m. This gives a cavity mode size of 32 μm radius on the sample. Two flat HR mirrors were used between the curved mirror and the output coupling mirror in order to fold the cavity. The round trip time of cavity was matched to the repetition rate of the pump laser at around 80 MHz. The pump pulses were generated by a Kerr-lens mode-locked Ti sapphire laser (Spectra Physics Tsunami) which can provide both 3.6 ps pump pulse with a maximum average power at the sample of 450 mW at a central wavelength of 796 nm and 70 fs pulse with a maximum average power of 450 mW at a central wavelength of 791 nm. The pump pulses were focused into the gain medium by a lens relay system designed to match the pump mode to the laser cavity mode. The temporal profile of the pulses produced from the synchronously pumped VECSEL was monitored using an autocorrelator (APE pulse check) that had a 50 ps sampling window and the spectral profile of the pulses was observed by use of an optical spectrum analyzer (OSA, HP 86140).

3. Experimental results

3.1 Synchronous pumping with 70 fs pulse

In this case, the VECSEL was pumped by 70 fs pulses with an average incident power of 450 mW. By carefully aligning the laser cavity, a maximum output power of 40 mW was obtained and the operating wavelength was 974.3 nm. The cavity length, where the maximum average output power was achieved, was assumed to be the matching length. The detuning range where the power dropped to half its value was about 200 μm (FWHM). However, the quality and duration of the pulses depend strongly on the timing mismatch and good quality pulses can be only achieved in a much smaller region.

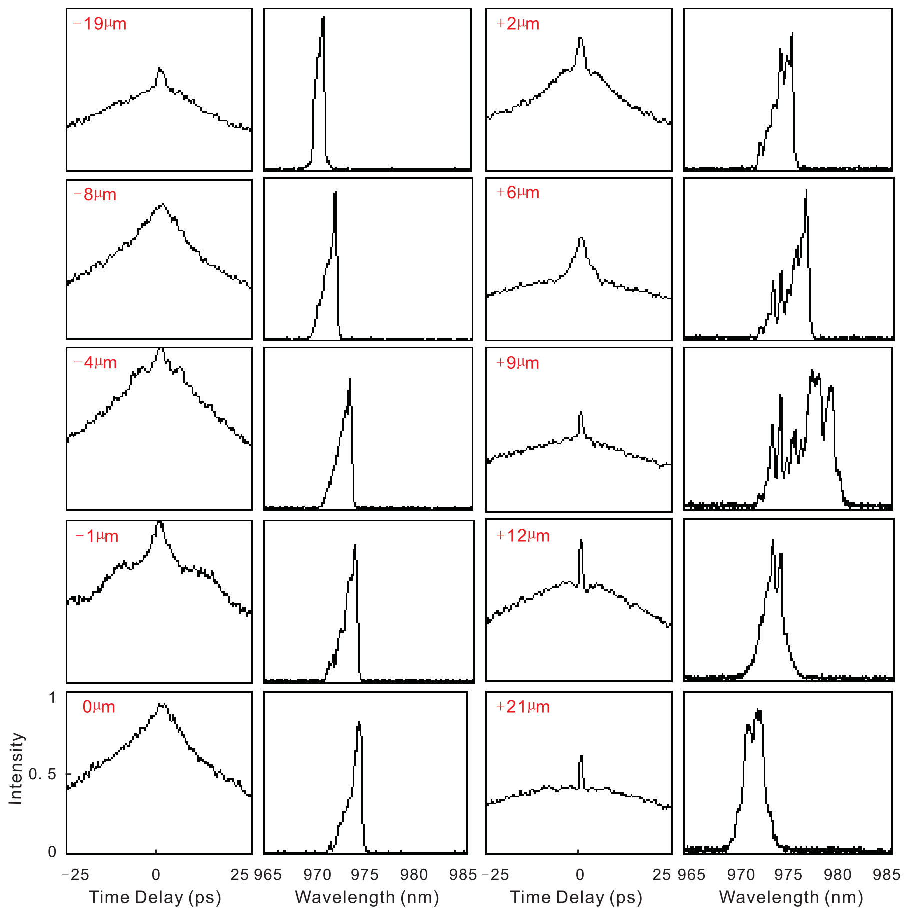


Fig. 2. Series of autocorrelation traces of pulses (left hand side) and spectrum (right hand side) obtained from VECSEL at different settings of the cavity length (fs-pumping); A more detailed animation of the changes in autocorrelation functions and spectra can be obtained here (file size 61.5 KB)

Figure 2 shows how the autocorrelation traces and the spectra change with the amount of cavity length mismatch. If the cavity was much shorter than the optimal length, the lasing pulse was very broad. The autocorrelation trace contains a coherence spike, which indicates the presence of substructure in the pulse. As the cavity was lengthened, the coherence spike disappeared and the pulse duration narrowed until the laser cavity was set to be close to the matching point. During this process, the spectral width of the pulses increased and the peak wavelength shifts towards higher wavelengths. Around the matching point, modulations in the

#9445 - $15.00 USD Received 10 November 2005; revised 26 January 2006; accepted 17 February 2006

autocorrelation traces were observed, which are believed to be caused by satellite pulses (described and analyzed in the following in more detail). The spectral width increased considerably, when the cavity length was lengthened, reaching a maximum of 6.1 nm (FWHM) at a length 9 µm longer than the optimum length. During this process a coherence spike started to appear on the top of the autocorrelation traces. Beyond a cavity mismatch of 9 µm, spectra and autocorrelation traces began to narrow again and the peak wavelength shifts back towards short wavelengths again. Finally, the laser was not mode locked anymore and the pulses were rather broad.

The pulse duration varied in the range of 10–40 ps as the cavity length was changed and hence was far (at least 10 times than) from the inherent limit (a few hundred femtoseconds) imposed by the spectral width of the VECSEL. We attribute this to the frequency chirp imposed on the pulse by the phase modulation occurring in the gain medium due to the optical pumping and gain saturation. We mention also that the laser was unpolarized with about equal power in the horizontal and vertical direction.

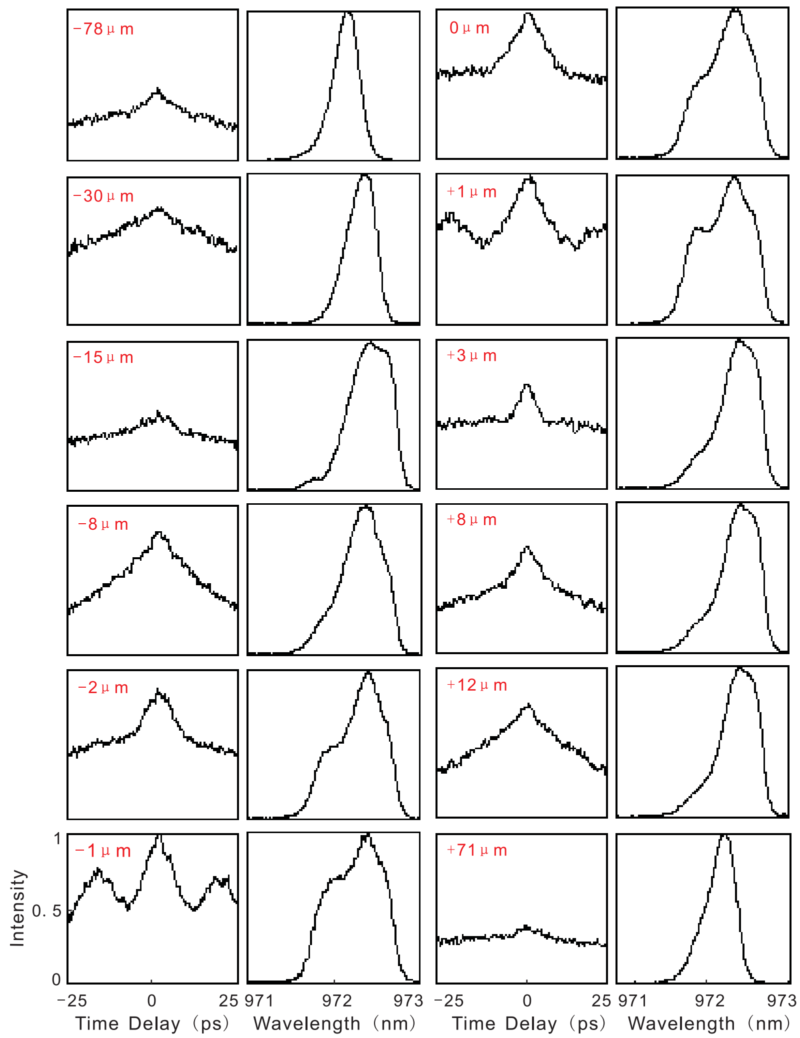


Fig. 3. Series of autocorrelation traces of pulses (left hand side) and spectrum (right hand side) obtained from VECSEL with BRF at different settings of the cavity length (fs-pumping); A more detailed animation of the changes in autocorrelation functions and spectra can be obtained here (file size 56.5 KB)

#9445 - $15.00 USD Received 10 November 2005; revised 26 January 2006; accepted 17 February 2006

In order to improve the quality of laser pulses as well as controlling the spectrum and polarization, a 1 mm thick birefringent filter (BRF) was put into the laser cavity at Brewster's angle. The resulting autocorrelation traces and the spectra are shown in Fig. 3. The mismatch sensitivity of the average power is again about 200 µm (FWHM). Compared to the spectra of the laser without a BRF, the widths of the spectra are reduced. In addition, the phenomenon of multiple pulses is much clearer and more strongly pronounced. Since the multiple pulsing only appears in a very short region (~10 µm), it is difficult to accurately resolve the scenario by using a mechanical translation stage for controlling the cavity length.

Hence a piezoelectric transducer with an expansion parameter of 4.5 nm/V was attached to one of the plane HR mirrors of the laser cavity. The maximum movement of the piezoelectric transducer was limited to 4.5 µm by the 1000 V power supply available. After realigning the cavity to get maximum output, the operating wavelength of the laser shifted to 973 nm, but this did not affect the observations. Figure 4 shows the changes in the multiple pulse structure around the matching length by continuously tuning the voltage applied to the piezoelectric transducer. For a short cavity length, the central pulse was strong and the satellite pulses were weak and far away from the central one. When the cavity was lengthened, the satellite pulses became stronger and moved closer to the central pulse. This change stopped at some cavity length, from where the satellite pulses started to move away from the central pulse again and died out gradually. If the cavity is lengthened further, the amplitude of the central pulse jumped up again showing weak satellite pulses and a similar sequence repeated. As shown in Fig. 3, the spectra typically show indications of a shoulder or additional bump at both cavity detuning lengths of -1µm and +1µm. The closer the satellite pulses moved toward the central pulse, the stronger the bump in the spectrum. One possible interpretation is that the different parts of the spectrum actually correspond to different pulses. The origin of the satellite pulses is the dynamic interaction between the intra-cavity circulating pulses and the gain, which will be discussed in section 4.

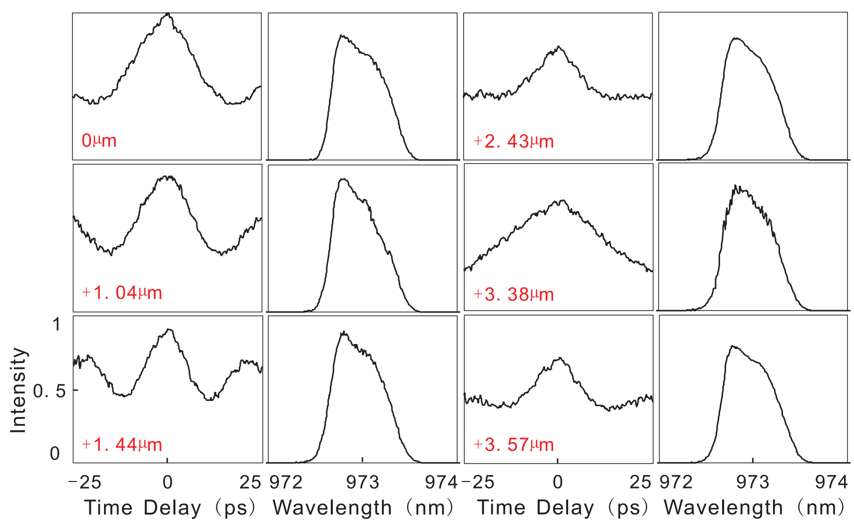


Fig. 4. Series of autocorrelation traces of pulses (left hand side) and spectrum (right hand side) obtained from VECSEL with BRF around the optimum cavity length (fs-pumping); A more detailed animation of the changes in autocorrelation functions and spectra can be obtained here (file size 103 KB)

3.2 Extra-cavity compression of pulses for femtosecond pumping

In order to compensate the chirp of the pulse, we employed a grating pair compressor shown in Fig. 1. The grating pair compression was accomplished by double-pass transmission of pulses from the VECSEL through a pair of identical 1200 lines/mm diffraction gratings.

#9445 - $15.00 USD Received 10 November 2005; revised 26 January 2006; accepted 17 February 2006

For the case without the BRF, a short pulse with a FWHM of the autocorrelation trace of 377 fs [shown in Fig. 5 (a)] was obtained when the separation between the two gratings was set to be 31 cm. Here the laser cavity was tuned close to a position slightly shorter than the matching length where the spectral bandwidth was maximum. If a hyperbolic secant profile is assumed, the measured autocorrelation function corresponds to pulse duration of 244 fs. The spectral bandwidth was measured to be 4.3 nm. Hence, the time-bandwidth product was 0.33, i.e., the pulse is nearly transform-limited. The average power after passing the grating pair compressor was about 8.5 mW. So the peak power of the laser pulse was calculated to be 435 W. The chirp of the initial pulse can be estimated from the dispersion of the grating-pair to be about 20 ps^2 (by using the equations given in Ref. [9]). It is up-chirped.

If the cavity length was increased beyond the point where the laser had the broadest spectrum (denoted as `switching point' in this paper), compression was not achieved anymore. This indicated that the sign of the chirp of the laser pulses reversed from positive to negative or that the pulse did not have a simple linear chirp at all.

Hence a piece of standard telecommunication fibre working in the normal dispersion region was used to test the possibility of compression. Focused by a lens with 4.5 mm focal length, the laser light was directly launched into a 220 m long fibre with coupling efficiency of 55% to 60%. Effective pulse compression by the fibre was achieved when the laser cavity was slightly lengthened beyond the switching point. The autocorrelation trace in Fig. 5(b) is the compressed pulse with a width of 925 fs (FWHM) corresponding to a pulse duration of 600 fs (assuming a hyperbolic secant profile). The time bandwidth product was 0.9. The average power emerging from the fibre was 22 mW so the peak power of the pulse was then about 458 W. The small pedestal is probably caused by the nonlinear chirp under the wings which could not be compensated. When the laser cavity was lengthened even further, the spectrum of the laser started to fluctuate strongly. This indicated that feedback from the fibre was affecting the laser. However no such feedback was observed when a short piece (30 cm) of fibre was used. The feedback effect was believed to be caused by nonlinear effects such as Stimulated Brillouin Scattering (SBS) inside the fibre. At that region, a nearly transform-limited but unstable pulse with an autocorrelation width of 300 fs (pulse duration of approximately 200 fs) was observed. The peak power of the compressed pulse was 1.4 kW. This experiment demonstrates that not only the pulse width and the laser spectrum depend on the cavity length mismatch, but also the sign of the chirp of the laser pulse.

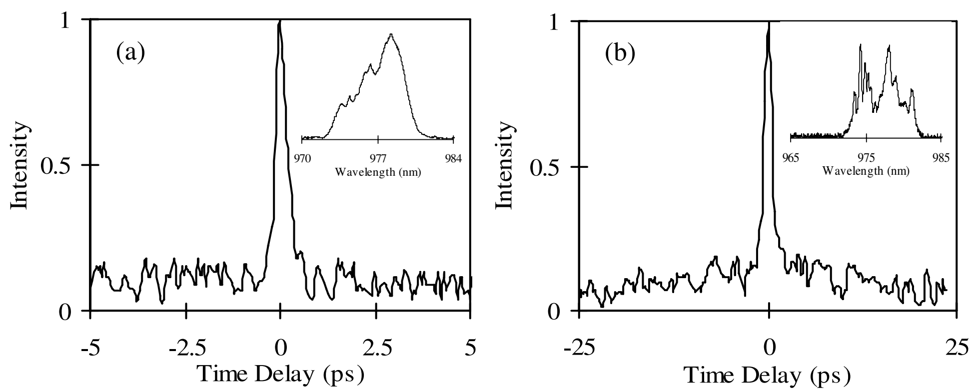


Fig. 5. Autocorrelation and spectrum of the compressed pulses (fs-pumping, without BRF): (a) up-chirped pulse was compressed to 244 fs (assuming a hyperbolic secant profile; cavity detuning length was around +8 μm); (b) down-chirped pulse was compressed by fiber to 600 fs (assuming a hyperbolic secant profile; cavity detuning length was around +10 μm)

#9445 - $15.00 USD Received 10 November 2005; revised 26 January 2006; accepted 17 February 2006

Pulse compression for the case of an intra-cavity BRF was also investigated by using the same grating pair separated 65 cm apart. The shortest pulses were obtained, if the cavity length was adjusted to be in the region with multiple pulses. The shortest autocorrelation width obtained was 4.2 ps [see Fig. 6(a)] corresponding to a pulse width of 2.7 ps, if a hyperbolic secant profile is assumed. The time bandwidth product for this pulse was 0.5. This experimental result indicates that the pulses were up-chirped (about 40 ps^2). By tuning the laser to generate strongest satellite pulses and meanwhile changing the zero position for the autocorrelator; we found that the satellite pulses were compressed as well, shown in Fig. 6(b). This could possibly explain why the compressed pulse has some background and noisy wings, as the wings of the satellite pulses could overlap the central pulse.

All the experimental results on chirp compensation demonstrated that the laser pulses have very strong chirping induced by the phase modulation in the active region of the semiconductor gain medium.

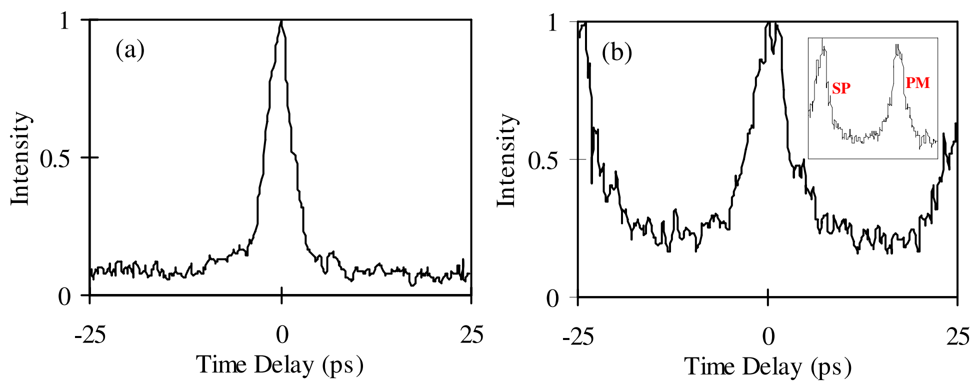


Fig. 6. Autocorrelation and spectrum of the compressed pulses profile (fs-pumping, with BRF):compression for primary pulse with weak satellite pulses and pulse duration was 2.7 ps (assuminga hyperbolic secant profile; cavity detuning length was around -8 µm); (b) compression forprimary pulse with strong satellite pulses profile (cavity detuning length was -1 µm and +1 µm,shown in Fig. 3); The inset shows both primary pulse and satellite pulse after shifting the zero position of time axis (region shown -40 to +10 ps, SP= satellite pulse, PM= primary pulse).

3.3 Synchronous pumping with 3.6 ps pulse

If pumped with 3.6 ps pulses, the VECSEL had an average pump power threshold of 70 mW. When excited with an average pump power of 420 mW, it gave an average output power of 27 mW at a wavelength of 972 nm. The detuning characteristics were found to be quite similar to the case of fs-pumping. Again, the FWHM detuning range in output power was measured to be about 200 µm. When the cavity was too short, the lasing pulse was long and the autocorrelation function contained a coherence spike. As the cavity was lengthened, the coherence spike disappeared, the pulse duration narrowed and the spectral width increased. After the cavity was lengthened over the position where the laser generated highest output power, the pulse width started to broaden again, the spectral width increased further and the coherence spike reappeared. For high positive mismatch, the spectra narrowed again. A more detailed animation of the changes in autocorrelation functions and spectra can be obtained here for the case with and without a BRF.

We found that the minimum autocorrelation width of 19 ps occurred at a cavity length about 10 µm shorter than the length that produced the maximum spectral width of 7.5 nm (FWHM). The wavelength of the peak of the lasing spectra of the VECSEL first shifted from 966 nm to 974 nm, and it moved back to 966 nm after the spectral broadening stopped. The laser pulse duration was in the range of 10-40 ps (assuming a hyperbolic secant profile), again

#9445 - $15.00 USD Received 10 November 2005; revised 26 January 2006; accepted 17 February 2006

far from the inherent limit imposed by the spectral width of the VECSEL.

Using the same grating pair as described above, the pulses could be compressed in a region below the point of maximal spectral width. Fig. 7 shows the result where the FWHM pulse duration before compression was measured to be about 25-30 ps with a 6.2 nm FWHM spectral bandwidth. By setting the distance of two gratings to be approximately 28 cm apart, we obtained a compressed pulse with FWHM of the autocorrelation trace of 286 fs corresponding to a duration of 185 fs, if a hyperbolic secant profile is assumed. This corresponds to a peak power of 300 W. The time-bandwidth product in this case was calculated to be 0.36, indicating that the initial up-chirp of the laser pulses was well compensated. The dispersion from the grating-pair was calculated to be about -15 ps^2 (by using the equations given in [9]).

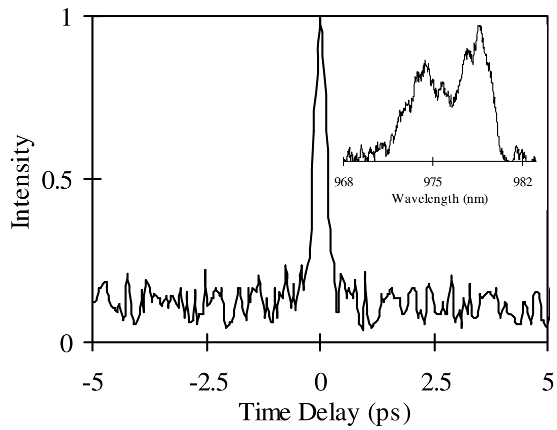


Fig. 7. Autocorrelation and spectrum of the compressed pulse (ps-pumping); The pulse width is 185 fs assuming a hyperbolic secant profile. (The detuning length was about +5~10 μm)

4. Discussion

4.1 Differences between picosecond and femtosecond pumping

It appears from our experiments that the key parameters for the operation around the optimum detuning condition as the bandwidth of the laser spectrum, the width of the autocorrelation function and the feasibility and fidelity of compression actually do not depend very much on the pulse duration of the input pulse. This is probably related to the fact that the optical pumping excites carriers in the barriers and that it takes about 20 ps [10] until the carriers relaxed down into the quantum well and provide gain at the lasing wavelength. The potential relevance of this delay was apparently not recognized by previous studies (e.g. [20]) of synchronously mode-locked VCSELs

4.2 Form of autocorrelation functions and drift instability

Although details might be different for the different configurations, there are some common tendencies in the behaviour of the laser, if the cavity length is tuned trough zero. If the cavity is much shorter than the matched length, the autocorrelation traces are rather broad and the spectra are rather narrow. Increasing the length, the pulses narrow and the spectra become broader and asymmetric (with a shift to higher wavelength). Around the matched condition, the autocorrelation function displays satellite peaks indicating multiple pulsing (see below). If the cavity length is increased further, the pulses broaden again, but a strong coherence spike is present in the autocorrelation function (especially in the case without a BRF). This indicates the presence of a sub structure within the pulses. For even higher lengths, the spectra narrow again.

For an interpretation of these features we recall some results on synchronously pumped dye and color center lasers [11-14]. These lasers can exhibit stable pulsing in the sense that

#9445 - $15.00 USD Received 10 November 2005; revised 26 January 2006; accepted 17 February 2006

the pulses (or pulse sequences) are the same for each round-trip only in a very limited - though finite - interval of cavity mistuning. This is related to the fact that a timing offset due to a cavity length mismatch would accumulate over several round-trips and result in a temporal walk-off of the circulating pulses versus the optimal gain condition imposed by the time window of the synchronous pumping. A finite mismatch can be tolerated, since the gain gradients (in time) pull or push the circulating pulse versus the optimal condition. The width of this 'locking' region is given by the so-called cavity filtering time, either imposed by the spectral width of the gain medium or by frequency-selective intracavity filtering elements [11, 14]. For the longer cavity, if the cavity mismatch is too large, a drift instability occurs and perturbations wander across the pulses from round-trip to round-trip [11, 14]. The existence of these sub structures is witnessed by the coherent spike in the autocorrelation function for the long cavities. A cross correlation between subsequent pulses was done for color center lasers [14] and reveals that actually the maximum cross correlation is obtained for a nonzero delay confirming the existence of a drift. We can expect a similar feature in our laser.

The different filtering time in the case without (limited by the bandwidth of the gain spectrum) and with BRF (estimated to be 12 fs corresponding to a length mismatch of 1.8 μm) explain also why the features observed are less sensitive to the cavity length tuning, if the BRF is used.

Towards the low-cavity length limit, the regime with good mode-locking is limited by the fact that the circulating pulse has to arrive after the pump pulse established threshold inversion in order to achieve efficient amplification. Below this point, lasing might occur in the form of a broad pulse determined in width by the build-up time of the gain and gain saturation [22]. This is probably the origin of the broad pulses we observed for very short cavity lengths.

4.3 Multiple pulsing

The appearance of multiple pulses can be explained by the rather long time it takes to build up the gain after the pump pulse because the carriers need to relax into the quantum wells. Hence, the effective pumping time is rather long and in that limit multiple pulsing is a well known phenomenon in dye and color center lasers [11, 14-15]. They can be explained by the fact that the gain is not completely saturated by the main pulse and due to the ongoing pumping the threshold might be crossed a second time (or even repeatedly). The fact that the timing distance to the main pulse decreases for increasing cavity length (shown in Fig. 4) indicates that the circulating pulse arrives before the conditions for best gain is amplified and leaves enough inversion for a satellite pulse. Interestingly, this change of timing is different from most observations in dye and color center lasers, where the separation between pulses increases for increasing cavity mismatch [14, 22]. Close inspection of the data shows that there is actually a very small interval of detuning, where multiple pulsing reappears, after it seems to have ceased (just before the pulses broaden again, detuning length of +1 μm in Fig. 3, detuning length of 3.57 μm in Fig.4). Whether this second regime is related to the observations in dye lasers cannot be decided on the basis of our data because it is too small to be analysed in a systematic way.

A detailed theoretical analysis of the multiple pulsing and its possible relationship to the changes observed in the spectrum is beyond the scope of this paper. The interplay of different effects is probably more involved than in dye and color center lasers, because in semiconductor lasers, the frequency of peak gain and the group refractive index will depend strongly on the carrier density. In addition, both are highly dynamic, which is also demonstrated by the chirp of the pulses measured. We will turn to a discussion of the latter in the following.

4.4 Analysis of pulse chirp

As already mentioned, the chirp of the pulses was estimated to be on the order of 10 ps^2 in the regime where we can assume that chirp is the dominant pulse distortion (obviously high-order phase aberration will be present and also the envelope of the spectrum is not well behaved).

#9445 - $15.00 USD Received 10 November 2005; revised 26 January 2006; accepted 17 February 2006

The dispersion caused by the DBR structure and material dispersion for the related semiconductor materials in the transparent region and other intracavity elements like mirrors are all on the order of 10^{-4} ps^2 which should be negligible [16-18, 20]. So the dominant cause of pulse chirping is phase modulation in the laser amplifier [19, 20].

There are two main contributions: one is the phase modulation originating from the pulsed optical pumping, the other self-phase modulation (SPM) due to gain saturation [20]. The resulting changes in carrier density cause a change in refractive index due to the strong phase-amplitude coupling in semiconductors. This carrier-induced index change, responsible for SPM, is often accounted for through the linewidth enhancement factor α [20, 21].

A quantitative analysis for the sign and amount of the dispersion based on a GaAs VECSEL system has been given by Jiang et al. [20]. However, the equations of motion of the field and the carriers in the presence of the cavity are not solved consistently, but it is only calculated, what chirp a laser pulse with a Gaussian shape with a fixed width will acquire, if traversing the gain medium pumped by a pulse with a Gaussian shape.

Gain saturation alone is shown to result in an up-chirp of the laser pulse, whereas the optical pumping leads to a down-chirping. The relative strength of the two effects depends on the ratio between the duration of the pump pulse (better the build-up time of the gain, because there might be a delay before the carriers relaxed down into the quantum well) and the duration of the laser pulse. If the duration of the pump pulse is about the same or shorter than the laser pulse, then the chirp due to optical pumping is larger than the chirp due to gain saturation and the pulses are down-chirped. If the laser pulse is considerably shorter than the pump pulse, gain saturation dominates the chirp and the pulse becomes up-chirped. We explain the preference for up-chirp in our experiment with the fact that the build-up time for the gain is rather long due to the fact that we pump the barriers. Hence gain saturation is the prevailing chirp mechanism. In accordance with that a higher chirp was found for the case with BRF where the laser pulse before compression was shorter than without BRF.

The observation of a down-chirp in a small regime where the mode-locking process becomes unstable might be due to the fact that the pulses there are longer and hence optical pumping is dominating the chirp. We stress that the results of Ref. [20] also imply that in general no simple chirp can be expected and that the chirp depends on cavity tuning. This explains qualitatively the smallness of the regions where efficient compression could be achieved. We note that the chirp of 10 ps^2 measured is of the order of magnitude to be expected from the considerations in Ref. [20].

Our results qualitatively agree with findings in synchronously pumped long-wavelength VECSEL (emission in the 1.5 μm region) for long pump pulses (about 150 ps in Ref. [7]; about 8 ps in Ref. [6] showing however long tails and satellite pulses thus increasing the effective pulse length [20]). These authors find also up-chirping, if the cavity length is tuned to the position of maximal spectral bandwidth. They demonstrate also that the pulse is down-chirped for other cavity tuning conditions [6] though it is not clear under which conditions this change takes place. In Ref. [7], it is conjectured that the pulses are down-chirped, if the cavity tuning is adjusted to yield the shortest pulses (without compression), because it could not be compressed with a grating pair. However, the possibility of a compression in a fiber was not demonstrated. We consider our experiments to be clarifying in that respect. The absolute pulse length obtained were considerably longer (> 700 fs even after compression) than in the present work. However, a detailed comparison is probably not possible because of the different material systems.

Nice work was also done on GaAs systems operating in the 880 nm spectral region. Here, down-chirped pulses, which could be compressed down to 320 fs, were obtained for pump pulses with a duration of 5 ps. However, the compression involved a significant amount of spectral filtering also and the autocorrelation has a significant pedestal. The sign of the chirp is in agreement with the expectation from Ref. [20] for short pump pulses, though it can be suspected that the gain build-up time is actually higher also in their case. Possibly, they were investigating the regime slightly beyond the `switching point' of chirp where we also found

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down-chirping. The configurations are similar in the sense that there were no bandwidth-limiting elements and that they also observed a coherent spike in the autocorrelation function before compression. We could not reproduce the result in Ref. [23], where pulses - though low power (about 6 mW average power) with a duration of about 200 fs were obtained directly from an oscillator in the 890 nm region. This result was related to the filtering effects of resonant periodic gain [23]. Possibly our structure is less effective because we have only half the number of periods.

5. Conclusion

A synchronously mode-locked 980 nm VECSEL has been reported. Detailed studies of the laser characteristics as a function of pump duration and cavity tuning were performed showing the potentials as well as the limitations of the synchronous pumping approach for mode-locking. The output pulses had duration of 10-40 ps for ps as well as for fs pumping. This indicates strong chirping due to the optical pumping-induced carrier generation and due to SPM by gain saturation. These processes were analyzed in some detail. Chirp compensation was effectively achieved by using either a grating-pair or a fiber. Nearly transform-limited pulses with duration of a few hundred femtoseconds with peak power ranging from 300 W to 1.3 kW were obtained. Thus it appears that synchronous pumping might be useful to provide ultrashort pulse sources at repetition rates of about 100 MHz in spectral regions which cannot be accessed directly by other sources (mainly the Ti:Sapphire laser). Our results demonstrate that it is not necessarily beneficial to use very short pump pulses, but that the performance will stay about the same till the 10 ps range. We mention that it appears to be interesting to reconsider this issue in conjunction with the recently introduced technique of in-well pumping [24], where the dynamics of the gain build-up is expected to be faster. Obviously, more efficient techniques for external pulse compression or intracavity dispersion would be helpful in order to overcome the massive chirping present in these devices.

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