Coherent spectral bandwidth combining by optical pulse injection locking in quantum dot modelocked semiconductor diode lasers

J. Kim, A. Ardey and P.J. Delfyett

An optical pulse injection locking technique is employed to generate shorter pulses from a passively modelocked quantum dot laser. The optical pulse injection locking enables the coherent addition of phase-locked longitudinal mode groups from two separate modelocked lasers without the use of stabilisation control loops, thus increasing the spectral bandwidth output resulting in optical pulses with shorter temporal duration.

Introduction: The modelocking technique is an excellent method to generate ultra-short optical pulses with high peak intensity. In modelocking, the number of phased-locked longitudinal modes plays an important role in the generated pulse duration and peak intensity. The peak intensity is proportional to the square of the number of longitudinal modes, and the pulse duration is inversely proportional to the number of longitudinal modes [1]. Therefore, obtaining a broader output bandwidth from a modelocked laser is essential for the generation of shorter pulses with higher peak intensity. Optical pulses with femtosecond pulse durations have also been achieved by using optical nonlinearities, such as self-phase modulation, followed by dispersion control [2]. Since spectral broadening using optical nonlinearity requires high peak intensity, compact low power semiconductor based cavities cannot take advantage of that technique. In this Letter, we introduce and experimentally demonstrate a simple and linear method to increase the bandwidth of low power semiconductor modelocked lasers. The bandwidth expansion is achieved by adding the phase-locked longitudinal modes from two separate modelocked lasers through optical pulse injection locking of overlapping and non-overlapping spectral components. Owing to the phase coherence of the spectrally broadened composite output, the pulse duration is effectively reduced as a result of the coherent bandwidth combining.

Experiment and results: Semiconductor gain elements using a two-section, curved waveguide geometry were fabricated from a quantum dot wafer whose active region consists of ten layers of self-assembled InAs/GaAs quantum dots covered with 5 nm $In_{0.15}Ga_{0.85}As$. Two external cavities, operating as master and slave laser, were constructed using the fabricated curved two-section devices. The grating coupled master laser was hybridly modelocked and the pulse train from the master laser was injected into the slave laser, which was passively modelocked. The fundamental cavity frequency of both modelocked lasers was adjusted to be similar, to ensure similar, equally spaced longitudinal modes of both lasers, resulting in a pulse repetition frequency of ~3 GHz. The phase relationship among the longitudinal modes of the master laser was well organised due to the hybrid modelocking, resulting in low timing jitter pulses. The experimental setup is shown in Fig. 1.

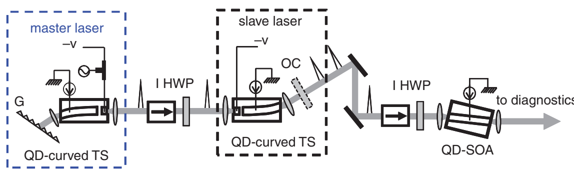

Fig. 1 *Experimental setup for coherent spectral bandwidth combining*

G: grating, QD: quantum dots, TS: two section, I: isolator, HWP: half wave plate, OC: output coupler, SOA: semiconductor optical amplifier

For the coherent spectral bandwidth combining experiment, the optical spectrum of the master laser slightly overlapped with the optical spectrum of the slave laser. The optical bandwidth of the master laser was tuned to the blue side of the slave laser's bandwidth by controlling the angle of the coupled grating because a lower linewidth enhancement factor and lower linear chirp are observed when quantum dot modelocked semiconductor lasers operate on the blue side of the gain peak [3]. The output pulse train from the injection locked slave laser is amplified through a quantum dot semiconductor optical amplifier, prior to the diagnostics. The result of coherent bandwidth combining is shown in Fig. 2.

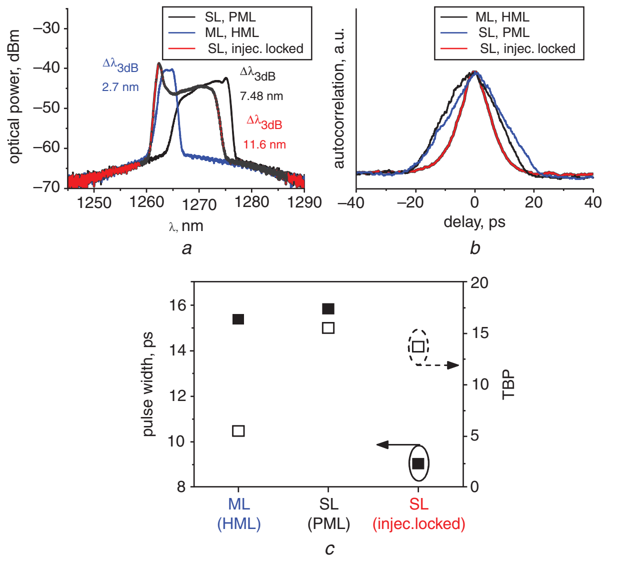

Fig. 2 *Optical spectra (Fig. 2a); intensity autocorrelation signal (Fig. 2b); autocorrelation FWHM of master, slave, and injection locked slave laser (Fig. 2c)*

SL: slave laser, ML: master laser, PML: passive modelocking, HML: hybrid modelocking, TBP: time bandwidth product

The pulse widths of the optical pulses from the master and slave laser were measured to be ~15 ps assuming a Gaussian pulse shape. The measured 3 dB optical bandwidth of the master and slave lasers were 2.7 and 7.5 nm, respectively. The 3 dB optical bandwidth was calculated from the second peak of the optical spectrum. When the slave laser was locked (when the phase of the slave laser followed the phase of the master laser) by optical pulse injection locking, the 3 dB optical bandwidth and the pulse width of the injection locked slave laser became 11.6 nm and 9 ps, respectively, as shown in Figs 2*a* and *b*. The time bandwidth product (TBP) of the slave laser before and after the injection locking was not significantly changed, as shown in Fig. 2*c*. The output optical bandwidth of the slave laser was increased by 55% due to the injection of the optical bandwidth of 2.7 nm, which was ~35% of the optical bandwidth of the slave laser. At the same time, a 43% reduction in the pulse width of the injection locked slave laser was achieved. The reduction of the output pulse can be explained by noting that there is an increase in the total number of phase-locked modes participating in the pulse forming process in the slave laser, resulting in a shorter pulse via the uncertainty relation. To understand the underlying physical mechanism, Fig. 3 illustrates the process.

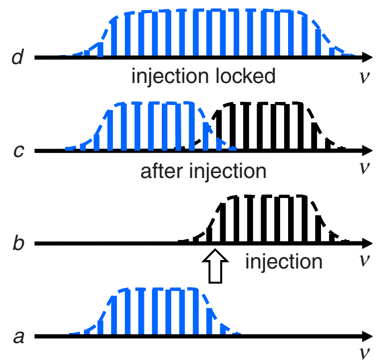

Fig. 3 *Illustration of coherent spectral bandwidth combining. Optical spectrum of master laser (Fig. 3a), slave laser (Fig. 3b), initial state of injected slave laser (Fig. 3c), and injection locked slave laser (Fig. 3d)*

Figs 3*a* and *b* represent the phase-locked longitudinal modes by hybrid modelocking and passive modelocking, respectively. The optical frequency comb of the master laser is injected to the slave laser, ensuring that there is some overlap of the spectral components of the master and slave laser, since in a passive modelocked laser, the pulse train is generated from noise spikes in the internally generated amplified spontaneous emission (ASE). If the injected signal is larger than the background ASE, the pulse train from the passive modelocked laser will possess characteristics of the injected source. As a result, in this experiment, the small spectral overlap induces coupling between the master laser and slave laser and hence, established coherence between the two optical frequency comb sets in the slave laser, generating a broader, phase coherent output optical spectrum (Figs. 3*c* and *d*). It should be clearly noted here that the slave laser's phase of the axial modes directly follows that of the master laser owing to the physics and dynamics of the injection locking process [4]. As a result there is no need for control loops to maintain the phase relationship between the master and slave laser, as would normally be required if the spectral beam combining were performed interferometrically, e.g. by using a beam combiner. Finally, the pulse train from the injection locked slave laser was externally compressed by adding negative group velocity dispersion (GVD). An output pulse width of 770 fs was achieved after the compression, assuming a Gaussian pulse shape with a TBP of 1.174. The intensity autocorrelation of the externally compressed pulse train is shown in Fig. 4.

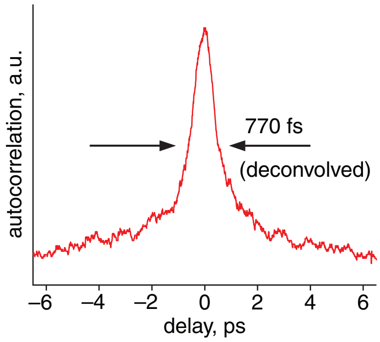

Fig. 4 *Intensity autocorrelation signal of externally compressed pulses of injection locked slave laser*

Conclusion: The optical pulse duration of a quantum dot modelocked laser is effectively reduced as a result of spectral broadening achieved by optical pulse injection locking. This leads to the coherent spectral bandwidth combining without the need for complex, and costly, interferometrically stabilised spectral beam combiners. This coherent spectral combining is a cost-effective and simple method compared to synthesis coherent optical pulse generation [5].

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One or more of the Figures in this Letter are available in colour online.

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References

1 Siegman, A.E.: 'Lasers' (University Science Books, Sausalito, California, USA, 1986)
2 Alfano, R.R.: 'The supercontinuum laser source' (Springer, New York, USA, 2005)
3 Kim, J., and Delfyett, P.J.: 'Above threshold spectral dependence of linewidth enhancement factor, optical duration and linear chirp of quantum dot lasers', *Opt. Express*, 2009, **17**, (25), pp. 22566–22570
4 Lee, W., and Delfyett, P.J.: 'Dual-mode injection locking of two independent modelocked semiconductor lasers', *Electron. Lett.*, 2004, **40**, (19), pp. 1182–1184
5 Hayes, C.L., and Laughman, L.M.: 'Generation of coherent optical pulses', *Appl. Opt.*, 1977, **16**, (2), pp. 263–264