Long-wavelength monolithic mode-locked diode lasers

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Abstract. A detailed study of the design issues relevant to long-wavelength monolithic mode-locked lasers is presented. Following a detailed review of the field, we have devised a validated travelling wave model to explore the limits of mode-locking in monolithic laser diodes, not only in terms of pulse duration and repetition rate, but also in terms of stability. It is shown that fast absorber recovery is crucial for short pulse width, that the ratio of gain to absorption saturation is key in accessing ultrashort pulses and that low alpha factors give only modest benefit. Finally, optimized contact layouts are shown to greatly enhance pulse stability and the overall operational success. The design rules show high levels of consistency with published experimental data.
1. Introduction

High-frequency optical pulse sources have been researched for a number of years for applications as diverse as high-speed sampling [1], analogue to digital conversion [2], microwave and millimetre wave measurements [3] and for fibre optic communications. Picosecond pulse sources have been designed for clock distribution [4], fibre radio [5], ultrahigh-speed logic [6], high-speed clock acquisition [7], ultrafast signal processing [8] and optically time division multiplexed transmission [9]. Compact diode laser pulse sources offer the potential for direct cost savings as well as improved pump efficiency over solid-state pulse sources, but they have generally not been able to match the pulse quality. Pulse durations have been longer, stability impaired, pulses asymmetric, spectra chirped and peak power compromised.

Monolithic picosecond pulse diode lasers have been proposed using a wide range of schemes such as gain-switching, Q-switching, self-pulsation and mode-locking [10]. The techniques mentioned above lead to pulse durations of order 10 ps, with excess chirp and significant timing jitter [11]. The advantages of optical technologies are also more fully exploited when the pulse repetition frequency exceeds the capability of electronic systems. Monolithic mode-locked lasers facilitate picosecond and subpicosecond duration pulses with repetition rates of tens of GHz and above [12], significantly beyond the direct modulation bandwidth of reported lasers [13]. With conventional mounting and temperature control, the cavities may be extremely stable, and buttcoupled regrowth technologies are not susceptible to the intracavity reflections, which can impair performance in discrete mode-locked systems [14]. Indeed, the stability is such that monolithic mode-locking lasers are now implemented in fibre transmission field trials [15, 16].
A number of detailed reviews have been presented on mode-locking [10, 12, 17]; however, work specifically addressing the design of monolithic mode-locking is relatively sparse. This work therefore focuses on long-wavelength monolithic schemes, which are promising in terms of manufacturability, highlighting design criteria for optimum picosecond pulse generation. Section 2 outlines the key techniques that have received the most significant research effort. Performance comparisons are made for state-of-the-art experiments, and the key parameters for ultrashort pulse generation are identified. Section 3 introduces the travelling wave technique used in the simulation of monolithic mode-locked diode lasers. Experimental and theoretical comparison is made in section 4, which enables a detailed analysis of the role of key parameters in section 5. The implications and design rules resulting from both experimental and simulated performances are subsequently discussed in the context of advanced mode-locked laser design in section 6.

2. Monolithic mode-locking techniques

Pulse generation in diode lasers through the phase locking of longitudinal modes leads to oscillations at a pulse-train repetition frequency defined by the cavity length and the number of pulses circulating in the cavity. The reported monolithic laser diode designs therefore exhibit repetition frequencies from less than 10 to in excess of hundreds of GHz depending on the cavity length and whether harmonic mode-locking is implemented [18, 19]. To facilitate picosecond pulse generation at such repetition rates, fast recovery of the gain and absorption in the optical cavity is required. A number of researchers have identified the requirement for enhanced absorption nonlinearity and carrier sweep-out time constant for achieving ultrashort pulse durations. It is therefore of interest to clarify how such parameters relate quantitatively to mode-locked laser design. While the laser cavity may comprise sections for gain, absorption, passive waveguide extension, phase tuning and grating sections, the operation of the gain and absorber sections is the most complex in terms of their mode of operation. Therefore, prior to a review of the key mode-locking techniques in monolithic structures, a review of the current understanding of gain and absorber operation is presented.

2.1. Gain section characteristics

The finite gain bandwidth in the laser diode active region set lower limits for pulse widths from mode-locked semiconductor lasers of order 50–100 fs, which is far shorter than the experimentally measured pulse widths. Numerical techniques to describe such a bandwidth limitation have included digital filter techniques [20, 21], delays in the local photon transient [22], convolution integrals [23], rate equations for polarization dephasing [24] and frequency domain analysis [12]. When explicitly accounted for, gain and index dispersion have been observed to lead to only minor changes in pulse width for picosecond-duration mode-locked pulses [25]. Pulse broadening from the gain bandwidth limit is widely attributed to gain saturation [22].

Gain saturation is attributable to a number of mechanisms. A sublinear gain current relation is commonly implemented in semiconductor laser modelling, with logarithmic functions giving particularly good experimental agreement [26]. Gain saturation due to the photon depletion of carriers is key in describing power saturation in semiconductor optical amplifiers and is explicitly accounted for through carrier photon coupling in the rate equations. Further gain saturation results
from the reduced instantaneous gain due to finite scattering times associated with spectral hole-burning and carrier heating. Time constants are of the order of 50–100 fs and may be explicitly modelled [24, 27] or indirectly modelled through the phenomenological nonlinear gain $\varepsilon$ [20, 21]. Explicit inclusion of a time constant for dynamic carrier heating has been shown to broaden actively mode-locked pulses from 0.97 to 1.14 ps [27] and has been identified as a key mechanism in the broadening of picosecond pulses with increasing gain current [28].

Gain saturation can be exacerbated through increased modal overlap as evidenced by pulse broadening for increased well thickness [29]. Figure 1 compares a range of published pulse durations for monolithic mode-locking experiments with a range of gain section quantum well numbers. A number of trends are readily discerned even though only one design parameter is considered. As the epitaxy is unavailable for much published work, the number of quantum wells is considered and not the more appropriate optical overlap, although there will be a close correlation. Pulse duration generally decreases with well number for the active, hybrid and passive schemes. Colliding pulse mode-locking (CPM) experiments do not however follow the trend. The scatter for low quantum well numbers indicates that the pulse duration will be more sensitive to other design parameters, such as contact geometries and absorber epitaxy. Also shown in figure 1 are two lines that represent the anticipated pulse duration for pulses of mean power 0 and 4 dBm, assuming that the peak power is limited by the saturation of the gain medium. The laser parameter values assumed for this steady-state calculation are given in table 2.

Self-phase modulation has been shown to incur a doubling of the pulse width in simulations with long gain regions [17, 20]. However, the simulated broadening incurred in the gain section may also be matched by narrowing in the absorber [22]. Evidence of both blue and red shifted chirp has been obtained from both discrete mode-locking schemes [30] and monolithic devices [31], and transform-limited pulses are readily achievable for a number of quantum well designs. This has also been observed for colliding pulse mode-locked lasers, where simulation indicates

Figure 1. Optimum pulse widths for a range of experimental measurements for monolithic mode-locked 1.5 $\mu$m wavelength lasers. The values are taken from table 1.
that near-Fourier-limited pulse widths are readily achievable and the pulse profile is determined by the interplay of pulse broadening in the gain sections and pulse compression in the saturable absorber [32].

2.2. Absorber section characteristics

Saturable absorption allows for reduced loss at the peak of the pulse and therefore pulse narrowing. The pulse width is observed to reduce with decreasing saturable absorber length [33] and decreasing sweep-out time in the saturable absorber [20]. The contact defines the pulse transit time and therefore ultimately limits pulse duration and so for ultrashort pulses, absorber lengths of order 20–80 µm are implemented. The saturable absorption is commonly modelled through a saturation term \( \varepsilon \) and, in a manner similar to the gain section, allows for the modelling of phenomena faster than the pulse duration.

The requirement for enhanced absorber saturation and decreased absorber carrier lifetime with respect to the gain section in mode-locked lasers [10, 17, 34] is consistent with the requirements for self-pulsation [35]. Indeed, a number of lasers designed for monolithic mode-locking operation have been prone to self-pulsation for a wide range of bias conditions [22, 36]. Self-pulsation may either dominate or coexist with partial mode-locking and the occurrence of self-pulsation depends on both cavity design and bias conditions. Minimized threshold gain and maximized cavity photon density have been identified as routes to favouring mode-locked operation and have been confirmed through the use of high-reflectivity coatings [36, 37]. Conversely, an increase in threshold gain has been found to promote self-pulsation [20]. The operating range for mode-locked operation has been correlated to the electrode geometry, with absorber lengths required to be 1–3% of the cavity length for moderate repetition rate colliding pulse structures [20, 28], although this requirement is relaxed for shorter cavities.

The absorber carrier lifetime is also required to be shorter than the gain section carrier lifetime [10, 17, 34]. For monolithic implementations, the achievable sweep-out time will be longer than the pulse duration. This still affects the long-term stability and pulse-shaping mechanism of the absorber. The pulse width is found to decrease with decrease in saturable absorber recovery time [28], which correlates to the strong dependence of the carrier sweep-out time on absorber reverse voltage [38]. A reduction in the simulated pulse duration from 8 to 3 ps is observed for absorber lifetime reduction of 40–20 ps, although no further reduction is observed for faster lifetimes for the structures simulated [22].

Epitaxial regrowth has been considered for the detuning of saturable absorber relative to the gain section. Negatively detuned absorbers have been shown to relax the bias tolerance for mode-locking [39]. For −24 nm detuning, the pulse duration was also reduced from 2.6 to 1.2 ps. The improvement might be attributed to reduced loss for a given carrier sweep-out time. Larger numbers of quantum wells in the absorber region have also been considered, relative to the gain region, to reduce the absorber saturation energy while minimizing the absorber transit time [40]–[42]. As the absorber length is short and may be placed at a facet in many designs, regrowth may present a challenge for reliable manufacture. Shifted band-edges are, however, more widely used for defining extended cavities without using long gain sections. Quantum well intermixing has been implemented to directly compare passive and active extended cavities [43]. Here, a pulse width reduction from 10.2 to 3.5 ps was achieved for the shorter gain section. A number of researchers have implemented regrown extended cavities for this reason as shown in table 1, where a W in the cavity configuration indicates a passive waveguide and P indicates a low
Table 1. Examples of optimum performance for monolithic mode-locked lasers operating at 1.5 μm wavelength. Legend for the cavity configuration: A, absorber or modulator; D, distributed Bragg reflector; G, gain; M, modulator; P, phase adjustment section; W, passive waveguide.

| Repetition frequency (GHz) | Pulse width (ps) | Time-bandwidth product | Wavelength (nm) | No. different waveguides | Cavity configuration | Wells in gain section | Reference |
|---------------------------|------------------|------------------------|-----------------|--------------------------|---------------------|----------------------|-----------|
| **Active**                |                  |                        |                 |                          |                     |                      |           |
| 40                        | 4                | 1.4                    | 1462            | 2                        | G-W                 | Bulk                 | [44]      |
| 4.4                       | 9                | 9.6                    | 1565            | 2                        | G-W                 | 6                    | [45]      |
| 8.1                       | 20               | 0.34                   | 1550            | 2                        | G-W-D               | 6                    | [46]      |
| 8.6                       | 6.2              | 7.0                    | 1565            | 2                        | A-G-W               | 6                    | [47]      |
| 16.3                      | 2                | 1.2                    | 1593            | 2                        | A-G                 | 4                    | [48]      |
| 20                        | 4                | 0.5                    | 1555            | 2                        | A-D-G-M             | 2                    | [40]      |
| 50                        | 3.2              | 1.0                    | 1552            | 2                        | A-G                 | 2                    | [41]      |
| **Hybrid**                |                  |                        |                 |                          |                     |                      |           |
| 8.6                       | 4.4              | 7.0                    | 1565            | 2                        | A-G-W               | 6                    | [47]      |
| 16.3                      | 2.0              | 1.38                   | 1598            | 2                        | A-G                 | –                    | [49]      |
| 4.9                       | 8.0              | 0.3                    | 1565            | 2                        | A-D-W-G             | 6                    | [50]      |
| 33                        | 5.3              | 0.35                   | 1550            | 2                        | A-G-P-D             | 3                    | [51]      |
| 33                        | 7.1              | 0.47                   | 1550            | 2                        | A-G-P-D             | 3                    | [52]      |
| 10                        | 8.0              | 0.35                   | 1554            | 2                        | A-G-W-D             | 8                    | [53]      |
| 20                        | 0.79             | 0.39                   | 1557            | 2                        | A-G-G-W             | 6                    | [54]      |
| 10                        | 6.4              | 0.38                   | –               | 2                        | A-G-W-D             | 7                    | [55]      |
| 20                        | 8.3              | 0.32                   | –               | 2                        | A-G-W-D             | 7                    | [55]      |
| 40                        | 2.0              | –                      | –               | 1                        | A-G-W-P-D           | –                    | [56]      |
| 40                        | 2.8              | 0.40                   | –               | 1                        | A-G                 | 1                    | [57]      |
| **Passive**               |                  |                        |                 |                          |                     |                      |           |
| 8.6                       | 5.5              | 7.00                   | 1565            | 2                        | A-G-W               | 6                    | [47]      |
| 80                        | 5.4              | 0.65                   | 1534            | 1                        | G-D                 | 3                    | [58]      |
| 40                        | 3.5              | 0.43                   | 1557            | 2                        | A-G-P-D             | 5                    | [59]      |
| 8.7                       | 8.3              | 0.62                   | 1554            | 1                        | A-G-G-D             | 5                    | [60]      |
| 37                        | 6.0              | 0.48                   | 1552            | 2                        | A-G-G-P-D           | 5                    | [61]      |
| 40                        | 4.2              | 0.44                   | 1550            | 2                        | A-G-G-P-D           | 3                    | [62]      |
| 17.7                      | 1.7              | 0.68                   | 1550            | 2                        | A-G-G-W             | –                    | [63]      |
| 33                        | 7.5              | 0.30                   | 1582            | 2                        | A-G-P-D             | –                    | [64]      |
| 17.7                      | 3.7              | 1.7                    | –               | 2                        | A-G-W               | –                    | [37]      |
| 48.5                      | 1.5              | 0.41                   | 1577            | 1                        | A-G-G               | –                    | [65]      |
| 37                        | 1.2              | 2.01                   | 1584            | 2                        | A-G                 | –                    | [39]      |
| 37                        | 2.6              | 3.11                   | 1584            | 1                        | A-G                 | –                    | [39]      |
| 40                        | 5.0              | 0.44                   | 1547            | 2                        | A-G-P-D             | –                    | [66]      |
| 40.4                      | 8.8              | 0.45                   | 1540            | 2                        | W-D-W-G-W           | 8                    | [67]      |
| 36                        | 3.4              | 0.56                   | 1534            | 1                        | A-G                 | 5                    | This work, section 4 |
| **CPM**                   |                  |                        |                 |                          |                     |                      |           |
| 80                        | 1.28             | 0.34                   | 1532            | 1                        | G-A-G               | 5                    | [68]      |
| 300                       | 1.0              | 0.43                   | 1538            | 1                        | G-A-G               | 5                    | [69]      |
loss phase tuning section. Comparable picosecond duration pulses may also be achieved with a continuous epitaxy [56, 57], although this may be attributable to the low confinement factors used in the gain region [57]. A double gain section implementation has also been proposed whereby one section is designed to equalize the loss and the other section introduces nonlinear amplification to allow subpicosecond pulses with a five-quantum-well all-active epitaxy [65]. The shortest subpicosecond pulses do, however, also include a low-loss passive extended cavity [54].

2.3. Active and hybrid mode-locking

Direct electrical modulation may be used to synchronize the optical pulse train to system clocks and reduce the timing jitter. Modulation of the gain or loss medium at a frequency equal to the intermodal spacing results in each mode being driven by the modulation sidebands of its neighbours [75]. Schemes without separate saturable absorber sections have also been successfully implemented with extended active [17] and passive Fabry–Perot cavities [44, 45] and also with Bragg gratings [41, 46]. Devices with active cavities are prone to poor time-bandwidth products of order 3.0. DC-biased saturable absorber sections have also been considered both with [40, 41, 43] and without passive extended cavities [43, 47]. Pulse durations of order 3–10 ps are observed for Fabry–Perot designs, without significant correlations between cavity geometries. Estimated time-bandwidth products are however high for the Fabry–Perot designs, commonly exceeding 1.0.

Hybrid schemes have been proposed whereby the absorber section is electrically modulated. The experimental data summarized in table 1 indicate comparable performance with active mode-locked operation. For the structures considered, distributed Bragg reflectors were used as bandwidth-limiting elements to facilitate time-bandwidth products in the range 0.32–0.47. Near-transform-limited pulses are however achieved for most of the reported hybrid and active mode-locked lasers with Bragg reflectors. The voltage modulation of the absorber may be characterized through a voltage dependent loss and lifetime. A more detailed implementation has included the voltage-dependent quantum-confined stark shift [28].

Electrical tuning of the repetition frequency is highly advantageous in active and hybrid schemes and may accommodate cavity length inaccuracies in fabrication. As the repetition rate is tuned off the cavity mode-separation frequency however, the pulse train becomes jittered, and the pulses broaden. The total repetition rate tuning range has been measured to be of order

| Repetition frequency (GHz) | Pulse width (ps) | Time-bandwidth product | Wavelength (nm) | No. different waveguides | Cavity configuration | Wells in gain section | Reference |
|---------------------------|-----------------|-----------------------|-----------------|--------------------------|---------------------|----------------------|----------|
| 40                        | 1.1             | 0.34                  | 1545            | 1                        | G-A-G               | 5                    | [70]     |
| 80                        | 0.83            | 0.31                  | 1545            | 1                        | G-A-G               | 5                    | [70]     |
| 160                       | 1.0             | 0.34                  | 1545            | 1                        | G-A-G               | 5                    | [70]     |
| 350                       | 0.64            | 0.32                  | 1545            | 1                        | G-A-G               | 5                    | [70]     |
| 192                       | 0.75            | 0.31                  | 1565            | 1                        | G-A-G-A-G           | –                    | [71]     |
| 16.7                      | 8               | –                     | 1560            | 1                        | G-A-G               | –                    | [72]     |
| 480                       | 0.52            | 0.31                  | 1535            | 1                        | G-A-G               | –                    | [73]     |
| 480                       | 0.58            | 0.5                   | 1555            | 1                        | G-A-G               | –                    | [74]     |
100 MHz for 10 GHz pulse trains [29, 76, 77] and 500 MHz for 40 GHz pulse trains. Chirped grating cavities have been proposed to extend the repetition frequency tuning to 1 GHz for a 19 GHz centre frequency [78]. Limited repetition frequency tuning has been explained in terms of dynamic detuning [27]. By increasing the modulation frequency above the natural cavity frequency, the pulses are forced to arrive at the absorption section at a later point within the modulation cycle, and so the increased loss further shortens the pulse.

Stability is conventionally quantified through timing jitter and amplitude noise. Frequency domain measurements integrate the noise side bands attending the carrier frequency [79, 80]. Time domain techniques such as nonlinear cross-correlation [81, 82], sampling oscilloscope assessment [83, 85] and demodulation techniques have also been used [86]. Most recently, the impetus for pulse source development has been communication sources where jitter requirements are defined by viable clock recovery techniques. For example, the ITU recommendations for 40 GHz sources specify a root-mean-square timing jitter below 2.5 ps for the integration range 20–320 MHz [87].

Timing fluctuations originating in the laser may be attributable to coupled spontaneous emission and carrier density noise [17, 29, 57]. Spontaneous emission causes gain, refractive index and photon density variations, with the refractive index variation leading to changes in the round trip time. Gain and photon density fluctuation can also lead to jitter through amplitude to phase conversion. The modelling of timing jitter has been performed for a wide range of time scales and integration limits. A correlation between the very short term timing jitter in pulsed lasers and the carrier lifetime has been identified through measurements with monolithic mode-locked lasers [81]. Broadband timing jitter from below 100 to 5 GHz can be of the order of 2–3 ps and is attributable to amplitude to phase conversion and spontaneous emission noise. This may be decreased through reductions in carrier lifetime, linewidth broadening factor and reduced threshold gain [29]. For the narrowband timing jitter of particular relevance to communication links, a timing jitter of less than 100 fs is routinely measured. Simulations for this range have confirmed experimental findings, suggesting that the timing jitter is dominated by the electrical oscillator [76]. Further reductions in narrow band jitter may be achieved through reduced threshold gain and enhanced optical power in the cavity relative to spontaneous emission power [57]. Low well numbers with low optical overlap and low scattering loss have therefore been proposed for low jitter operation.

2.4. Passive mode-locking

Passive mode-locking dispenses with direct electrical modulation to use only saturable absorption to lock the phase of the modes. While the early passive mode-locking experiments have considered aged devices with regions of uncontrollable defects [88, 89], and proton bombarded facets [90], much of the later work at longer wavelengths has used an electrically isolated absorber contact with a dc voltage-controlled loss and carrier sweep-out. The gain section is biased with a direct current to achieve round trip unity gain in the steady state. The lack of electrical modulation relaxes the electrical bandwidth requirement. The interplay between saturable absorption, gain saturation and carrier lifetimes in the gain and absorber regions leads to a self-stabilizing pulse that rotates around the cavity. The shorter absorber will have higher loss than the gain section, and for passive mode-locking, this will saturate faster than the gain. The saturation energy of the absorber should be lower than that of the gain section and, indeed, analytical approximations show that pulse durations will decrease with decrease in absorber saturation [10]. While the
A number of monolithic sources have been demonstrated with repetition rates of order 30–40 GHz and pulse durations in the range 1.2–5.5 ps for Fabry–Perot cavities [39, 47] and durations of 3.5–7.5 ps for the structures with bandwidth-limiting distributed Bragg gratings [58, 59, 61, 64, 66, 91]. Devices with distributed Bragg gratings have been near-bandwidth-limited with time bandwidth products in the range 0.3–0.5, while Fabry–Perot lasers have commonly exhibited pulses broadened from the Fourier limit. While a number of reported cavity designs include passive extended waveguide sections to define the round trip frequency to meet the application requirement, a number of two-section devices with a long gain section and short absorber are also reported. While being conceptually simpler, such devices can lead to pulses that are significantly broadened from the Fourier limit [39, 92]. Passive mode-locking has also been reported without the use of an absorber for a cavity with a centrally placed gain region in a dispersive cavity leading to near-transform-limited 8.8 ps duration pulses at 40.4 GHz [67].

Passively monolithic mode-locked lasers are highly susceptible to large amplitude and timing jitter instabilities, especially if the low-frequency resonance response is not highly damped [93]. Extensive research has focused on the external stabilization of pulse trains in the absence of direct electrical modulation [94], which can enable comparable jitter performance to hybrid schemes. These include optoelectronic feedback implementing phase-locked loops [95], optical injection with carrier suppressed double-sideband-modulated lasers [91], optical pulse injection [65] and subharmonic optical injection [18, 51, 52, 66, 96, 97]. While pulse durations are commonly shorter, the complexity of the stabilization scheme has led to system tests using hybrid schemes however [15, 16].

2.5. CPM

Considerable pulse shortening has been achieved through CPM by leveraging enhanced saturation of a centrally placed absorber [84]. Monolithic diode laser implementations have been explored for both ring cavities and linear Fabry–Perot cavities, with figure 2 showing the mostly commonly implemented arrangement. Here, a short absorber contact of a few tens of µm in length is reverse-biased and the adjacent forward-biased gain sections provide the gain to ensure laser oscillation. The counter-propagating pulses coexist in the cavity when optimally biased and doubly saturate the central absorber as they simultaneously enter. For symmetric
Figure 3. Schematic diagram showing the increase in repetition rate under CPM the lower black trace indicates colliding pulse operation with two counter-propagating pulses and the upper red trace indicates a single pulse propagating for a 1050 µm-long cavity.

cavities, the minimum threshold gain is achieved for pulses that overlap in the absorber. More complex geometries with additional electrodes have also been considered for harmonic CPM [19, 71].

The two simultaneously counter-propagating pulses also lead to a doubling of the repetition frequency and a halving of the pulse period and is shown in figure 3. Here, a schematic diagram is presented for the time-resolved output pulse train and the spectral power density for a 1050 µm-long cavity operating for both CPM and the previously discussed passive mode-locked condition where only one pulse circulates in the laser cavity. For the CPM case, the period halves to 12.5 ps and the repetition frequency doubles to 80 GHz.

Transient absorber gratings have been highlighted as being key to the pulse shortening observed in dye lasers and the effect has been predicted for diode lasers. Coherent interaction of the pulses builds up a transient standing wave optical field and causes periodic saturation modulation in the absorber [98]. The carrier generation rate is high at the peak of the standing wave and low at the nulls, forming an effective absorption grating. A direct comparison of the role of the transient grating has been explored for a dye laser with different width absorbers [99]. Here, a reduction in pulse duration from 0.4 to <0.1 ps is achieved as the absorber width is reduced from 300 to 30–40 µm. Two pulse shortening mechanisms have been proposed [99]. Firstly, the grating becomes more transparent as the pulses collide, which leads to a reduced absorber saturation power. Indeed, it has been proposed that this coherent coupling mechanism may also be modelled as an increased saturable absorption [100]. Secondly, the absorber grating allows for in-phase back coupling from the grating into the counter-propagating pulse, leading to a coupling of the trailing edge of each pulse to the centre of the counter-propagating pulse. It has been noted that the symmetry of the cavity is important. Asymmetry in the gain for the two paths leads to different pulse energies and strongly reduces the stability of the CPM.

For diode lasers, pulse durations of 0.52–1.28 ps have been generated for lasers operating in the range 40–300 GHz, as shown in table 1, with Fourier-transform-limited operation routinely achieved. For colliding pulse schemes implemented for the lower repetition rates of 16.7 GHz however, pulse durations have been as long as 8 ps [72]. Here, the gain sections are very long and no extended passive cavity techniques have been implemented. The critical dependence of pulse
quality on cavity symmetry can create a particular problem for linear cavities, as the facets must be cleaved. The accuracy of scribing is commonly of the order of 10 \( \mu \)m, which is comparable to the optimum absorber dimensions. Diode lasers do offer the advantage though of direct electrical drive of the absorber, and this has facilitated schemes for synchronization and jitter reduction even for CPM [101].

Self-colliding pulse mode-locking (SCPM) has been proposed whereby the absorber is placed at a high-reflectivity mirror. The transient grating would be formed by the interference of the incident and reflected pulses. The reflected pulse self-saturates to facilitate enhanced pulse shortening in the absorber. Very short absorbers of order 20–50 \( \mu \)m are used to ensure that the pulse power is not attenuated too highly prior to the region of pulse overlap and to ensure that the pulse transit time is comparable to the required pulse duration. The transition from self-colliding mode-locked operation to passive mode-locked operation might therefore be defined predominantly by absorber length and facet coating and is difficult to isolate. A number of published reports on hybrid mode-locking using high-reflectivity coating with short absorber sections might arguably exploit self-colliding pulse shortening [37, 62, 65, 102]. Again, near-transform-limited pulses are achieved 0.41–0.51 for pulses with durations of 1.5–5.4 ps.

Simulations indicate that comparable pulse durations may be generated for both CPM and SCPM for the case where the SCPM absorber length is one-half that of the CPM absorber [20]. Reducing the facet reflectivity from 100 to 55% at the end of the absorber is observed to be equivalent to doubling the absorber length. Measurements on external cavity devices also indicate a pulse broadening from 2.4 to 2.7 ps as the facet reflectivity is reduced from 80 to 14% with a reduction in peak power [17]. Pulse shaping attributable to a colliding-pulse-induced dynamic index grating is regarded as being a relatively weak effect in the presence of high carrier diffusion in diode lasers [17, 21].

The restrictions on cavity symmetry in cleaved linear diode laser cavities are readily circumvented by using ring designs. Monolithic mode-locked ring lasers [103]–[105] have not, however, been extensively researched at long wavelengths, and this may be attributable to the difficulty in defining the oscillating wavelength. A monolithic ring laser has been demonstrated at 1550 nm wavelength with a pulse duration of 27 ps at a repetition frequency of 7 GHz and a time-bandwidth product of 0.46 [104].

3. Travelling wave model

The simulation of picosecond pulse propagation in monolithic diode lasers with round trip times of the order of tens of picoseconds require spatially resolved modelling techniques. To fully account for phase locking of the longitudinal modes, the spatially resolved optical field may be represented by a time- and space-dependent array of forward and reverse counter-propagating fields \( F(z, t) \) and \( R(z, t) \) [106].

\[
E(z, t) = F(z, t) e^{-\beta z - i\omega_0 t} + R(z, t) e^{\beta z - i\omega_0 t}.
\]

Here, \( \omega_0 \) is the centre oscillating rotational frequency and \( \beta \) the propagation constant, which in turn is defined by the local gain \( g \), loss \( \alpha \) and detuning \( \delta \), where \( \beta = g - \alpha - j\delta \). Field propagation is described through two coupled travelling wave equations. Distributed and facet reflections allow for coupling between the counter-propagating fields. Distributed Bragg reflectors are
implemented in the model using the coupling strength parameter $\kappa$ and the detuning $\delta$ from
the centre wavelength as

\[
\left( \frac{1}{v_g} \frac{\partial}{\partial t} + \frac{\partial}{\partial z} \right) F(z, t) = (g - \alpha - j\delta) F(z, t) + j\kappa R(z, t) + i_{sp}(z, t),
\]

(2)

\[
\left( \frac{1}{v_g} \frac{\partial}{\partial t} - \frac{\partial}{\partial z} \right) R(z, t) = (g - \alpha - j\delta) R(z, t) + j\kappa F(z, t) + i_{sp}(z, t).
\]

(3)

The differential field equations may include the coupling of spontaneous emission into the
oscillating modes through the spontaneous noise parameters $i_{sp}(z, t)$. The spontaneous noise
is accounted for by a zero mean complex Gaussian excitation [107]. The parameters $g$ and $\delta$
are spatially variant and influenced by the bias conditions. A monolithic mode-locked laser cavity
may include absorber, gain and passive and grating sections and these are all readily implemented
by appropriate parameter selection.

The dependence of $g$ on carrier density and therefore on current is the subject of a detailed
study in itself [108]. In the context of mode-locked lasers, it is numerically efficient to parametrize
gain in terms of a logarithmic carrier dependence. Not only does this enable a tractable solution,
but it also allows for clearer understanding of the measurable parameters that are key to design.
Theoretical gain curves have been analysed for a range of material systems and have been shown
to give a near logarithmic gain dependence on current density, particularly for short-wavelength
lasers [109]. Experimental evidence for longer wavelength 1550 nm lasers has subsequently
been provided for a range of operating currents, 0.2–2.0 kA cm$^{-2}$ [110], covering the anticipated
operating range of diode lasers. The general applicability of the logarithmic relationship has also
been investigated for quantum well lasers and bulk active layers alike [26]. In this work, the
gain current relationship has been estimated from gain measurements of lasers with different
quantum well numbers [111]. The carrier density is then inferred from the subthreshold current
carrier density relationship

\[
I_{\text{th}} = eV / \eta (A + BN + CN^2).
\]

(4)

Uniform injection for each quantum well is assumed for the low quantum well numbers
considered [112] and the recombination rates are summarized in table 2. The gain carrier
relationship implemented is given by

\[
g(z, t) = \frac{\Gamma G_0 \log(N/N_0)}{1 + \varepsilon_{g/a} S}.
\]

(5)

Here, $\Gamma$ is the optical confinement factor, $G_0$ the gain constant, $N$ the local carrier density and
$N_0$ the carrier density at transparency. The photon density $S$ is defined by square of the sum of
the forward and backward propagating fields. Gain and absorber saturation coefficients $\varepsilon_{g/a}$ are
also introduced into the gain equation to account for gain saturation and nonlinear absorption.

Carrier transport into the quantum well lasers has been shown to lead to damped small
signal [113] and large signal [114] operation, and so coupled differential equations are used to
solve for the time-dependent carrier density in the quantum wells $N_w$ and barriers $N_b$. Current is
injected into the barrier and confinement layers where there is a time-varying carrier density $N_b$. 
### Table 2. Design parameters used in the travelling wave semiconductor laser model.

| Parameter                              | Value       | Units     |
|----------------------------------------|-------------|-----------|
| Free space wavelength                  | 1533.6      | nm        |
| Width of cavity                        | 4.0         | µm        |
| Number of quantum wells                | 5           |           |
| Quantum well thickness                 | 7.5         | nm        |
| Total SCH layer thickness              | 65          | nm        |
| Confinement factor per well            | 0.016       | %         |
| Reflectivity at rear facet             | 33          | %         |
| Reflectivity at front facet            | 33          | %         |
| Group refractive index                 | 3.75        |           |
| Cavity waveguide loss                  | 9.2         | cm\(^{-1}\) |
| Gain constant                          | 3000        | cm\(^{-1}\) |
| Transparency density                   | 1.6 × 10\(^{18}\) | cm\(^{-3}\) |
| Spontaneous coupling factor            | 1.0 × 10\(^{-4}\) |           |
| Absorber lifetime                     | 5–40        | ps        |
| Nonradiative recombination rate        | 4.0 × 10\(^{8}\) | s\(^{-1}\) |
| Bimolecular recombination              | 1 × 10\(^{-10}\) | cm\(^{3}\) s\(^{-1}\) |
| Auger recombination rate               | 6.0 × 10\(^{-29}\) | cm\(^{6}\) s\(^{-1}\) |
| Barrier well capture time              | 10          | ps        |
| Thermionic emission time               | 200         | ps        |
| Nonlinear gain suppression factor      | 1.0 × 10\(^{-17}\) | cm\(^{3}\) |
| Nonlinear absorber suppression factor  | 7.5 × 10\(^{-17}\) | cm\(^{3}\) |
| Linewidth enhancement factor           | 2.0         |           |
| Well diffusion constant                | 16          | cm\(^{2}\) s\(^{-1}\) |
| Injection efficiency                   | 55          | %         |
| Model section length                   | 10          | µm        |

The two carrier populations are coupled through capture \(\tau_{\text{cap}}\) and emission \(\tau_{\text{em}}\) time constants, which are dominated by carrier diffusion in the confinement layer and thermionic emission from the quantum wells, respectively,

\[
\frac{dN_b}{dt} = \frac{J}{et_{\text{SCH}}} - \frac{N_b}{\tau_{\text{cap}}} + \frac{N_w}{\tau_{\text{em}}} \cdot \frac{t_{\text{QW}}}{t_{\text{SCH}}} - \frac{N_b}{\tau_{\text{abs}}}.
\]  

\[
\frac{dN_w}{dt} = \frac{N_b}{\tau_{\text{cap}}} \cdot \frac{t_{\text{QW}}}{t_{\text{SCH}}} - \frac{N_w}{\tau_{\text{em}}} - \nu_{gS}S - AN_w - BN^2_w - CN^3_w - D\nabla^2N_w.
\]  

Here, \(J\) is the current density and \(A\), \(B\) and \(C\) are the nonradiative, bimolecular and Auger recombination rates, respectively, and \(D\) is an ambipolar diffusion coefficient. For the carrier density in sections within an absorbing region, an absorber carrier sweep-out time \(\tau_{\text{abs}}\) is also included. As the carrier rate equations are solved for densities \(N_w\) and \(N_b\), a volume scaling is required to ensure energy conservation, using the parameters for total thickness of the quantum wells \(t_{\text{QW}}\) and the thickness of the separately confined heterostructure \(t_{\text{SCH}}\).
Self-phase modulation is accounted for through the linewidth enhancement factor $\alpha_H$, and therefore the resultant detuning experienced by the propagating fields may be determined from the local gain $\delta = -\alpha_H g$. The coupled wave equations are solved using a finite-difference time domain scheme [107]. The laser cavity is divided into a number of discrete elements corresponding to different electrical contacts, defined as either an absorber, gain, passive or grating section as shown schematically in figure 4.

The ability to define different elements gives the model great flexibility, enabling the key proposed mode-locked laser device geometries to be simulated. Each element is discretized into sections of equal length $\delta z$. For constant group velocity $v_g$, the time step of the model will be defined by the pulse transit time through a section $\delta t = \delta z / v_g$. For each of these sections, the carrier densities $N_w(z,t)$ and $N_b(z,t)$ are evaluated to estimate the local gain and refractive index. This in turn allows for the evaluation of the fields $F(z,t)$ and $R(z,t)$ using the travelling wave equations. Spatial hole burning is therefore explicitly modelled through the spatially variant gain and refractive index. As the field and carrier density parameters are assumed to be constant over a section length $\delta z$, the value is minimized to be small enough to give a good approximation to a real laser. For a fixed cavity length and appropriate simulation time however, the processor run time scales as $\delta z^{-2}$. The relatively slow temporal variation in the carrier density rate equation relative to the travelling wave equation permits integration by either first-order Newton–Raphson or Runge–Kutta techniques. The parameters are updated at each time step and for each section of the laser.

### 3.1. Model parameter values

The parameter values required for travelling wave modelling are relatively easily extracted from conventional laser measurements and there is also an increasing consensus in the literature for many of the parameters for long-wavelength lasers. The model has been used successfully in the simulation of directly modulated long-wavelength edge emitting diode lasers [115], and the parameter values used are in good agreement. To calibrate the model specifically for...
monolithic mode-locking however, a number of parameter values have been taken from steady-state measurements of a mode-locked laser [111]. In this work, the slope efficiencies of a range of different length lasers is used to estimate injection efficiency and waveguide loss. The current gain relationship is estimated from Hakki–Paoli measurement and the linewidth broadening factor is subsequently estimated from variation in the mode spacing and therefore variation in refractive index $n_r$ with both wavelength $\lambda$ and current density $J$: 

$$\alpha_H(\lambda) = \frac{4\pi n_r}{\lambda} \frac{\delta n_r(\lambda)/\delta J}{\delta g(\lambda)/\delta J}.$$ (8)

The dependence of carrier density on the injection current is defined by the injection efficiency and recombination rates. The nonradiative recombination rate and the injection efficiency are adjusted to match the light current characteristics. The confinement factor is estimated through mode overlap calculations. The carrier capture time is readily calculated from the confinement layer thickness and the diffusion constant [116, 117], and the thermionic emission can be calculated from the effective carrier mass and the well barrier height [113].

A number of key parameters are not, however, so readily measured and so a range of values are considered in this work. Simulation values used for the reverse-biased saturable absorber lifetime $\tau_{\text{abs}}$ are restricted to experimentally measured values from 5 to 40 ps [38]. The nonlinear gain coefficient is in agreement with the literature values, which consider carrier heating and spectral hole-burning [118]. There is uncertainty in the absolute value of the nonlinear saturation in the absorber and so a range of values is considered here also.

The model section length is taken to be 10 $\mu$m, giving rise to a time step $\delta t = \delta z/v_g = 120$ fs. This is a sufficiently small time step to resolve mode-locked picosecond duration pulses and a sufficiently small spatial step to model short absorber lengths of order 50 $\mu$m required for high repetition rate mode-locking.

3.2. Pulse train characterization

The travelling wave model is run for a wide range of contact geometries and parameter sets to isolate the parameters with significant influence on pulse train characteristics. The model outputs time-resolved fields for both facets corresponding to $F(t)$ and $R(t)$ in a form that is directly comparable with experimental data. The output power, phase and chirp from the laser are calculated directly from the optical field. Fourier transformation is used to obtain the optical wavelength spectrum and radio frequency spectrum. Four possible representations of the model output are shown in figure 5. The pulse train is shown for the front facet output at the gain section end of the cavity. By replotting the time axis, the pulses may be overlaid to show variations in amplitude and timing. The radio frequency spectrum derived from the Fourier transform of the optical power may similarly be used to extract timing and amplitude noise. Finally, the optical power spectrum is calculated from the Fourier transform of the optical field.

Through closer analysis of the output pulse train of a mode-locked laser, one can obtain such parameters as pulse width, amplitude noise, timing jitter, extinction ratio, pulse shape, time-bandwidth product and pulse height variation. These parameters are used to assess the mode-locking performance.
4. Experimental verification

The model output is compared with an experimentally measured mode-locked Fabry-Perot laser diode. The device used for comparison is a GaInAsP/InP multi-quantum well laser. The active region consists of five compressively strained InGaAsP quantum wells, separated by InGaAsP barriers. A 4 µm-wide ridge waveguide laser was fabricated with as cleaved facets defining a cavity length of 1100 µm. The 50 µm-long absorber section gives an intercontact resistance of approximately 1 kΩ. The device is mounted p-side up and exhibits a continuous wave lasing threshold of 70 mA. To achieve mode-locking, a gain section forward bias of 160 mA and an absorber section reverse bias of −1.2 V is required. Mode-locking optimization is performed by monitoring pulse quality with second-harmonic autocorrelation and adjusting the gain and absorber bias conditions appropriately. Assuming a sech² pulse power profile, optimized mode-locked pulses with a duration of 3.4 ps are achieved as shown in figure 6. The spectral width at the full-width half-maximum power is measured to be 1.3 nm, leading to a time-bandwidth product of 0.563, corresponding to a pulse train that is broadened by a factor of 1.78 from the Fourier transform limit.

Good agreement between experiment and simulation is found for an absorber recovery time of 15 ps and an absorber nonlinear saturation coefficient of $7.5 \times 10^{-17}$ cm³. This agreement with
experiment therefore ensures confidence in the exploration of the role of the material parameter such as absorber lifetime, absorber and gain nonlinearity, contact geometries, drive current and linewidth broadening factor.

5. Simulations

To facilitate centre wavelength and repetition frequency control, the mode-locked cavity requires a Bragg grating reflector for spectral filtering and tuning and an additional phase section for fine tuning of the repetition frequency. The Bragg grating allows for reduced chirp as shown in table 1 and also control of the pulse duration through the finite grating bandwidth. Manufacturing tolerances and required pulse durations will determine the grating coupling strength and therefore the length of the grating. The length of the phase section will be compromised however by the available cavity length after allocations are made for the absorber, grating and gain sections. Extended passive cavities have commonly been implemented to enable shorter gain sections while maintaining the same cavity length. A key requirement therefore in the design of the contact geometry is the optimum gain section length.

5.1. Contact geometry

To identify the requirement of gain section length for optimized pulse generation, a series of simulations have been performed whereby the drive current and gain section length have been
varied for a range of absorber parameter sets. Simulations are performed for a fixed length cavity and so, as the gain section is shortened, an increasingly long passive section is introduced. A 20 GHz hybrid mode-locked laser is considered with a 350 µm-long Bragg grating reflector section. This grating bandwidth defines the minimum pulse duration of 6 ps. To quantify the regimes of optimum mode-locking, the variation in the peak power of mode-locked pulses is measured and compared. The simulations are subsequently summarized as a set of parameter maps in figure 7.

The plot of pulse height variation on the left of figure 7 shows regimes of mode-locking. For low current values, no oscillation will occur until the threshold gain is reached. At currents close to threshold, self-pulsation is evident and mode-locking is only achieved at a higher current. There is a limit to the bias currents over which the laser will mode-lock as the gain section current approaches 200 mA, where an unstable regime is encountered. This may be attributable to the elevated power over-bleaching the saturable absorber. The operating currents for which less than 5% variation in pulse height is achieved is also observed to narrow as the gain section length is increased, indicating that designs with shorter gain section lengths are more tolerant to variation in bias current. The right-hand contour map shows the relationship between pulse duration, gain section length and gain section current. There is a strong correlation between regimes of optimum pulse duration and regimes of stable pulse generation. While the structure simulated in figure 7 has been optimized for 6 ps duration pulses, it should be noted that this pulse duration has also been varied continuously down to 2 ps through appropriate grating design. For the example given, stable mode-locking with large tolerance to bias conditions is indicated by red circles and are realized for the shorter gain section lengths. For longer gain section lengths, the region of optimum mode-locking narrows and both pulse broadening and unstable mode-locking are evident.

Similar trends are observed both at higher frequency and for passively mode-locked operation. In figure 8, simulations are performed for a 40 GHz Fabry-Perot passively mode-locked laser. A large area of stable mode-locking is also in evidence for the shorter gain section

**Figure 7.** Gain section length optimization for a 20 GHz hybrid mode-locked laser incorporating a 350 µm-long distributed Bragg reflector section by considering variation in the peak power of the mode-locked pulses (left) and the mean pulse width (right).
lengths, with either unstable mode-locked or unlocked continuous wave operation dominating the longer gain section lengths.

The relaxed operating regime observed for shorter gain sections may be attributed to a number of effects. Considering equation (4), the differential gain may be expressed approximately as \( \frac{dg}{dn} = \frac{g_o}{n} \), and so the increased carrier density required to meet the threshold condition for shorter gain sections will give rise to a lower differential gain. The lower differential gain reduces the carrier depletion as the pulse propagates through the gain section and therefore leads to reduced gain saturation. The pulse will therefore experience less broadening as it propagates through the gain section. For the case of an overlong gain section, the absorber is not able to compensate for the pulse broadening, and so the laser self-pulsates or, at still higher currents, generates an unlocked continuous wave output.

5.2. Absorber dynamics

To investigate the operating regimes and limits to short-duration high-quality mode-locked pulse generation, the interplay between the recovery time of the absorber and the nonlinear saturation in both the gain and absorbers sections has been found to be of particular importance. To explore the role of absorber recovery time, simulated pulse durations have been measured for a range of simulated absorber sweep-out times. Figure 9 shows pulse duration as a function of lifetime, indicating a near linear relationship between lifetime and pulse duration.

The pulse shortening mechanism is most readily observed by considering the time-dependent gain and loss for one round trip period. Here, the net gain in the gain region and the net loss in the absorber region are plotted for a time axis referenced to the pulse peak power. The mean gain values correspond to the steady-state threshold gains and therefore the sum of the unsaturated cavity losses. The top right figure shows gain depletion as the pulse passes through the gain region. As the pulse passes through the absorber region, the loss is initially bleached, and then recovers with a fast 1 ps time constant. The fast recovery time leads to a pulse shortening. For the case of the slower absorber recovery time of 10 ps, the pulse is broadened from 1.7 to 2.3 ps. This may be considered in terms of regions of net gain as indicated by the dashed vertical lines. For both figures, these lines indicate the time at which cavity gain equals cavity loss. The time separation between the lines corresponds to the time during which the cavity experiences

**Figure 8.** Gain section length optimization for a Fabry-Perot 40 GHz passive mode-locked laser.
net gain and this therefore defines the pulse duration. As the absorber lifetime increases, the
time for net cavity gain and therefore the pulse durations increase. For very long sweep-out
times, the net gain window increases to the point where the absorber recovery is too slow to
effectively modulate the gain on the round trip period. This situation is undesirable for mode-
locking, although mode-locked operation has been achieved if the ratio of nonlinear absorption
to nonlinear gain is great enough.

Fast nonlinearities in the absorber and gain section also play an important role in the mode-
locking mechanism. These mechanisms are implemented through the nonlinear saturation term \( \varepsilon \). To achieve stable mode-locking, the absorber saturation needs to be stronger than the gain
saturation to ensure that the pulse shorting mechanism of the absorber is sufficient to overcome
the pulse broadening mechanism of the gain section. To quantify the mechanism, simulations
are performed for a range of absorber saturation values from \( 5 \times 10^{-17} \) to \( 20 \times 10^{-17} \) cm\(^3\) and
the trends are shown in figure 10.

Pulse profile and duration is not observed to be as sensitive to absolute gain saturation. The
shortest pulse widths are obtained for the largest absorber/gain saturation ratios. If the ratio is
too small, then stable mode-locking does not occur, and the laser is prone to self-pulsation above
threshold. Enhanced saturation is readily achieved through increased overlap of the optical mode
with the active layer. As indicated by published experimental data in figure 1, the gain section is
expected to give reduced pulse broadening for lower optical overlap, and so optimum geometries
may involve differing epitaxial designs for the gain and absorber sections. Figure 1 does indicate
that the reduction in well number alone does not help in reducing the pulse duration, and this is
attributable to the nonoptimum absorber where a common absorber and gain section epitaxy is
implemented.

Figure 9. Dependence of pulse duration on absorber lifetime (left) and time-
resolved gain and loss under mode-locked operation. The right-hand plots show
in detail the gain and absorber dynamics for 1 ps (above) and 10 ps absorber
sweep-out times (below).
While the minimum obtainable pulse width is defined by the absorber saturation, it is ultimately limited by the effective gain bandwidth of the mode-locked cavity. While increased gain bandwidth leads to a reduction in the achieved pulse width, there will be a deviation from this trend if there is a strong presence of chirp within the pulses. This is most evident in the simulation of time-bandwidth product for mode-locked lasers with varying linewidth enhancement factor as plotted in figure 11.

The chirp within a monolithic mode-locked laser results from the change in refractive index associated with a change in carrier density, and hence a change in the material gain. This is modelled through a single parameter called the linewidth enhancement factor or alpha factor. In quantum well lasers, this typically takes on values of around 2. The increase in the time-bandwidth product arises from the induced chirp on the pulses, and it can clearly be seen that a low alpha factor leads to pulses with reduced chirp. For reasonable values of linewidth broadening factor, the time-bandwidth product is in agreement with many of the reported experimental results shown in table 1. These simulations have however assumed that the linewidth broadening factor is the same for both the gain and absorber sections. While the length of the absorber will be very short compared to the gain section in an optimized mode-locked laser structure, a more rigorous analysis might include the bias voltage dependence of linewidth broadening factor.
6. Discussion

Efficient numerical techniques for device design require approximations to make the simulations both tractable and incisive. At the outset, a one-dimensional model has been used where time and distance along the cavity are intrinsically coupled and this imposes a constant discretization. The planes orthogonal to the propagating modes are not resolved and so only one transverse mode is assumed. While numerical techniques are available for designing multiple transverse mode lasers [119], mode-locking imposes a mode selection which warrants the single transverse mode assumption. The electrical injection of carriers into the quantum well active layer has also been assumed to be uniform. Drift diffusion techniques are available to model this, but the effect is considered weak for the small number of wells [111] common to many mode-locking structures and the gain current relationship may be measured directly. The treatment of uncoupled spontaneous emission affects the noise performance of pulse sources, and this would be the subject of a more focused study on pulse train stability.

The wavelength dependence of the gain is readily implemented using digital filter techniques [107]. A variation in absorber reverse bias is expected to lead to not only variation in absorber sweepout time but also a change in the band edge. This is nontrivial to isolate, however, in practical measurements. Detuning may be implemented on a section-by-section basis, and indeed, the gain asymmetry, peak and width may be defined in terms of the local carrier density [107]. Alternatively, the carrier energy distribution may be recalculated to estimate the gain at the oscillating wavelength [28]. Self-phase modulation is commonly incorporated through the linewidth broadening factor, and this will account for slow components. Wavelength and bias dependences become increasingly important for subpicosecond pulses and, with appropriate input parameters, may be implemented through appropriate dispersion parameters [28]. While field-envelope-based numerical techniques have been implemented to date leading to sub-Nyquist sampling, computational performance is improving, and the time step can therefore be reduced with appropriate resources while maintaining reasonable run times.

Ultimately, accuracy is determined by the available calibration data, and as models become more complex, the accuracy and detail of material and structural data becomes unwieldy. Measurement errors multiply to mask the very effects the simulation tool is being used to isolate. The travelling wave technique is therefore identified as being a particularly useful design tool for picosecond duration pulse mode-locked laser simulation. High-performance picosecond and subpicosecond pulse generation has been demonstrated using a range of monolithic mode-locking techniques. A verified travelling wave model has been used successfully to explore the impact of laser design parameters on stability, spectral chirp and pulse duration.

Comparisons made for a range of experiments indicate that pulse durations are correlated more closely to epitaxial and contact configuration design rather than the mode-locking scheme implemented. Clear exceptions are the subpicosecond pulse durations achievable under CPM operation where enhanced saturable absorption is exploited. Linewidth and pulse broadening appear to correlate to longer gain section lengths and higher active layer optical overlaps, indicating excessive gain saturation.

The lowest timing jitter and shortest pulse durations are observed for cavities where particular attention has been paid to threshold gain minimization. Variation in the differential gain alone has a relatively weak effect on pulse duration and jitter, indicating that the ratio of mode-locked power to amplified spontaneous emission noise power must be maximized for reduced pulse train noise. The pulse shaping is readily achieved by the absorber for sufficiently...
low gain section broadening. These observations are readily simulated using a travelling wave model, where regimes of stable operation and short pulse generation are correlated to shorter gain section lengths. Experimental data indicate that this is also achievable with low well numbers and short gain section lengths.

For optimum gain section design, pulse characteristics are limited by absorber characteristics. Here the role of spectral hole-burning and carrier heating has been considered through the nonlinear gain term $\varepsilon$. While performance is relatively insensitive to the values anticipated for the gain section, it is sensitive to the value considered in the absorber. This is clear from both simulation and the enhanced performance observed in CPM implementations. The long time constants relative to pulse duration are also observed to play a key role in pulse shaping. The transition from stable mode-locking to unstable pulsation is evident as the window of net gain expands relative to the round trip time.

Broadening from the Fourier limit is observed and is weakly sensitive to the linewidth broadening factor. This however may be engineered by balancing the absorber and gain section chirp through appropriate detuning or appropriate bias. The optimized values are in general agreement with the range of the best experimental data. The very high values measured for active mode-locking schemes may result from the lack of chirp compensation in the absorber section. Active schemes have not been simulated in this work as the hybrid and passive schemes have facilitated superior chirp performance.

As monolithic mode-locked sources are considered more seriously for system applications, control electrodes such as localized heaters, phase sections and gratings are being introduced. While these elements may be treated as passive linear media, the treatment will be more complex as pulse durations decrease below a 1 ps.

This work has been restricted to the study of long-wavelength quantum well lasers, but as the technology matures, long-wavelength quantum dot lasers may offer a number of highly desirable laser characteristics. Due to the unique properties of the three-dimensional confinement, quantum dot lasers exhibit reduced threshold current densities, enhanced temperature insensitivity, increased differential gain and low wavelength chirp [120]–[123]. Variation in dot dimension leading to an inhomogeneous gain broadening should facilitate further reductions in the achievable pulse width. Monolithic mode-locking has been demonstrated with picosecond duration pulses at wavelengths of up to 1.3 $\mu$m and repetition rates from 10 to 35 GHz [124]–[127]. Here, Fourier-transform-limited pulse generation is readily achievable. The design rules appear to differ from quantum well lasers, however, with considerable differences in absorber characteristics [128], and so further work will be required to identify design rules to fully exploit the enhanced bandwidth.

7. Conclusions

Travelling wave techniques are applied to the modelling of mode-locking in quantum well monolithic mode-locked lasers to clarify the key design parameters. The agreement with experimental data is good, facilitating a detailed study of the design for picosecond pulse sources with relaxed design parameter and operating parameter tolerances. A number of key parameters are identified, and their role in pulse generation is clarified. Electrode geometry is readily optimized to relax the tolerance of mode-locked pulse train stability to bias current variation, which in turn reduces the susceptibility to self-pulsation. The role of carrier lifetime, line-width
broadening factor and gain bandwidth are explored along with saturation in terms of their impact on pulse train stability, time-bandwidth product and pulse duration. Threshold gain minimization and the enhanced saturable absorption allow for shorter duration pulse generation, while optimum electrode design leads to relaxing the tolerance and enhancing the manufacturability. Routes to reliable picosecond and subpicosecond pulses are identified.

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