Compact laser-diode-based femtosecond sources

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Abstract. This paper describes the development of compact femtosecond laser systems that are capable of being directly pumped by laser diodes or are based directly on laser diodes. The paper demonstrates the latest results in a highly efficient vibronic based gain medium and a diode-pumped Yb:KYW laser is reported that has a wall plug efficiency > 14%. A Cr^4+:YAG oscillator is described that generates transform-limited pulses of 81 fs duration at a pulse repetition frequency of > 4 GHz. The development of Cr^3+:LiSAF lasers that can be operated using power supplies based on batteries is briefly discussed. We also present a summary of work being carried out on the generation of fs-pulses from laser diodes and discuss the important issues in this area. Finally, we outline results obtained on the generation of pulses as short as 550 fs directly from a two-section quantum dot laser without any external pulse compression.

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1. Introduction

The generation of sub-picosecond optical pulses has been an active area of research for many years and has opened up a range of applications from real-time monitoring of chemical reactions to ultra-high bit-rate optical communications [1, 2]. Without doubt, the best results in terms of shortest pulse durations and highest average powers belong to the vibronic-crystal-based Kerr-lens-mode-locked Ti:Sapphire laser that was first demonstrated in 1989 [3]. This particular laser, however, suffers from some practicalities that limit its application outside major research laboratories. These include the emission wavelength (800–1200 nm), which is not well matched to telecommunications windows, the requirement for high-power and expensive (>1 W) green pump lasers and the relatively low operating efficiency. Early versions of this laser system relied on water-cooled Ar:ion lasers as pumps and, in this case, many kWs of electrical power were required to produce at the very best average power of a few watts in the femtosecond-pulse regime. More recently, with the advent of diode-pumped frequency-doubled solid-state pump lasers, overall wallplug efficiency has increased up to around 1% for the generation of 1 W level output powers. Furthermore, many Ti:Sapphire lasers are large and have a requirement for active cooling, although recent commercial developments in this field have reduced these requirements somewhat and provided high-repetition rate lasers (see http://www.kmlabs.com/NewFiles/MTS.pdf and http://www.gigaoptics.com/gigajet20.pdf). It has also not yet been possible to obtain diode lasers to pump Ti:Sapphire directly and whilst the efficiency of the overall system has greatly improved since the introduction of the solid-state pump lasers discussed above, the cost and size of typical pump lasers remain significant barriers to the widespread ownership and application of such femtosecond lasers. Many research groups have, therefore, been examining alternative options for the generation of coherent, femtosecond optical pulses.
In this paper, we review the recent progress in the development of efficient and practical femtosecond sources based on diode lasers. Specifically, we will examine two areas: (i) the generation of pulses from crystal-based lasers that are compatible with diode-pumping and (ii) the development of semiconductor-based sources of sub-picosecond pulses in both edge- and surface-emitting geometries.

Substantial recent progress has been made with crystal-based lasers for which demonstrated wallplug efficiencies have been as high as 14% [4] and experimental compact versions of the lasers have been exploited in a systems testbed to produce data rates up to 1.36 Tbit s\(^{-1}\) at 1550 nm [5]. The progress in semiconductor lasers has led to the production of ultrashort pulses from simpler system configurations which, whilst not easily achieving the sub-100 fs pulse durations that are routinely available from the diode-pumped crystal-based lasers, are showing real promise for efficient and simple operation in the 100s femtoseconds regime from electrically pumped devices. One particular avenue of interest is the exploitation of gain materials based on quantum-dot semiconductor materials [6]. When layers of different size dots are produced, their bandwidths can be compatible with the generation of femtosecond pulses, but there is a challenge relating to the coherent engagement of the entire gain bandwidth so that the shortest pulse durations can be achieved. A further application of the quantum-dot devices may be to exploit their fast optical nonlinearities to produce passive mode-locking elements for either crystal or external cavity semiconductor-based lasers that will allow the generation of short pulses with enhanced performance characteristics [7].

The remainder of the paper is divided into three sections. In section 2 we consider the present state-of-the-art in crystal-based femtosecond lasers, paying particular attention to sources having high efficiencies and those operating at high pulse repetition rates in the telecommunications window that is centred around 1550 nm. In section 3, we examine the progress in the development of sub-picosecond-pulse semiconductor lasers. This section covers both work on edge-emitting lasers before moving on to the rapid and impressive development of vertical extended cavity surface emitting lasers (VECSELs). At the end of this section, some recent results that imply particular promise for quantum-dot-based semiconductor lasers are discussed. The final section contains brief concluding remarks and the authors’ views on the future in this exciting and rapidly expanding field.

2. Crystal-based femtosecond laser systems

Crystal-based solid-state femtosecond lasers have developed rapidly over the past decade due to their ability to deliver many attractive features that are well suited to a wide range of applications. They can be efficient, relatively simple, robust and can operate in a number of pre-specified laser regimes. One of the well-known features of such lasers is their potential to produce high peak power, high repetition rate ultrashort pulses in high-quality laser beams by using a passive mode-locking technique [3, 8]. For example, pulses as short as 5 fs can be directly produced from a Kerr-lens-mode-locked Ti:Sapphire laser [9], up to 60 W of average power has been generated in femtosecond pulses from a thin-disk Yb:YAG laser [10] and picosecond pulse generation at repetition rates up to 160 GHz has been reported for a passively mode-locked, diode-pumped Nd:YVO\(_4\) laser [11].
2.1. Portable and efficient laser options

Whilst the lasers reported to date have been very successful and demonstrated unparalleled performance, there remains a perception that femtosecond lasers based on vibronic crystals are inconvenient as optical sources. To counteract this, it is important to review the recent progress made in developing femtosecond laser configurations that offer enhanced efficiency and portability together with specifications that can be tailored to particular applications. To highlight the impressive progress made in this area, the first femtosecond lasers based on organic dyes typically required more than 100 kW of electrical power to produce 5 mW of femtosecond pulses, whereas our recent lasers have produced femtosecond pulses at average powers of 14 mW for less than 1 W of total electrical drive power! Furthermore, it is now possible to obtain more than 100 mW of average power outputs for 100 fs pulse lasers having wallplug efficiencies exceeding 14%. This represents an efficiency improvement of some five orders of magnitude in the past 20 years.

2.1.1. Cr:LiSAF lasers. The development of low-cost, portable and robust ultrafast lasers could be especially useful for diagnostic measurements away from the confines of the laboratory. Recently, we demonstrated a simplified, prismless, femtosecond Cr:LiSAF laser (figure 1) pumped by two narrow stripe AlGaInP laser diodes (total pump power \(\sim 90 \text{ mW}\)). This laser was powered by just six penlight (AA) batteries for which the total electrical drive power was below 1 W. The battery pack enabled mode-locked operation to be achieved for more than 12 h. The entire laser system, including the pump stage, power source and drive electronics, is accommodated on a 22 cm \(\times\) 28 cm breadboard, and operates with an overall electrical-to-optical efficiency of approximately 4%. The associated pulses had durations of 130 fs, at an average output power of 14 mW and a time-bandwidth product of 0.42. We have also demonstrated the flexibility of this compact, low-threshold laser by pumping it with two pairs of diode lasers.
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(total pump power $\sim 180$ mW) to achieve kilowatt pulse peak powers [12] as well as GHz pulse repetition rates [13]. Specifically, we have generated 122 fs pulses at average powers of 35 mW—an optical-to-optical efficiency of 20%. This corresponded to peak powers of 1.2 kW and a time-bandwidth product of 0.3. The 1.002 GHz pulse-repetition rate system, which is to our knowledge the highest reported for a directly diode-pumped, non-harmonically mode-locked bulk femtosecond laser, produced transform-limited 146 fs pulses at an average output power of 3 mW. Both the kW and GHz laser configurations utilize very simple cavity geometries and illustrate the effectiveness of a compact and integrated approach to dispersion compensation using negative group velocity dispersion (NGVD) mirrors.

2.1.2. Yb-doped tungstate crystals. There is a continued interest in the development of novel solid-state materials for constructing diode-pumped femtosecond lasers that possess yet higher efficiencies and output powers. Yb-doped crystals are very attractive candidates for this purpose. The basic energy-level scheme of trivalent ytterbium implies an absence of parasitic processes such as excited-state absorption, up-conversion, cross-relaxation and concentration quenching. Moreover, the strong absorption bands of these laser crystals are well matched with the outputs of commercial InGaAs ($\sim 980$ nm) laser diodes and the small Stokes shift ($\sim 600$ cm$^{-1}$) between absorption and emission implies both low thermal loading and high quantum efficiency. The reduced thermal loading in the crystal obviates the requirement for any active cooling (e.g. circulating water or thermoelectric devices) even for output powers in the 100s mW range.

Recently developed Yb-doped double tungstates Yb$^{3+}$:KY(WO$_4$)$_2$ (Yb:KYW) and Yb$^{3+}$:KGD(WO$_4$)$_2$ (Yb:KGDW) exhibit similar spectroscopic properties [14, 15] and are the two most efficient vibronic crystals amongst the Yb-doped family of materials for longitudinal pumping [16, 17]. A remarkable advantage of both crystals is that, together with a relatively broad emission bandwidth that can support sub-100 fs pulses, they have large emission cross-sections ($\approx 3 \times 10^{-20}$ cm$^2$), which lead to the suppression of Q-switching instabilities during mode-locked operation [18]. In the first reported femtosecond Yb:KGW laser [19], 176 fs pulses were generated at an average power of 1.1 W with semiconductor saturable absorbing mirror (SESAM) stabilized mode locking, and pulses of 71 fs duration were obtained from a Kerr-lens-mode-locked version of a Yb:KYW laser [20]. The disadvantage of Yb$^{3+}$ is that the final laser level is thermally populated (in a quasi-three-level energy manifold) and so high-efficiency operation requires good mode overlap of the pump and laser beams as well as high pump intensities to facilitate laser operation at room temperature. These requirements can be satisfied readily by using a diffraction-limited pump beam that satisfies the additional requirement of a small beam waist inside the laser medium to reduce the saturation energy and to enable stable mode-locking [18].

Using a single narrow-stripe InGaAs laser diode as a pump source and a SESAM structure for passive mode-locking, a highly efficient and compact femtosecond Yb:KYW laser has been developed (figure 2) [21]. Pulse durations of 123 fs (corresponding FWHM spectral width was 9.2 nm around 1047 nm—see figure 3) were generated with 107 mW of output power from only 308 mW of pump power. This corresponded an exceptional optical-to-optical conversion efficiency of 35%, which is more than a factor of two higher than that previously reported in similar systems [22, 23]. The corresponding electrical-to-optical efficiency with respect to the input electrical power to the diode laser exceeded 14% which represents an improvement of more than three times in comparison with the best results previously reported from a Cr:LiSAF femtosecond laser [12]. These excellent results can be attributed to the high performance of the
Figure 2. Schematic of the femtosecond Yb:KYW laser. DL, narrow-stripe InGaAs laser diode ($P_{\text{out}} = 350 \text{ mW}$); AL, 6.2 mm aspherical lens; M1 and M2, folding mirrors ($r = 100 \text{ mm}$); HR, broadband high reflector; SESAM, semiconductor saturable absorber mirror; OC, output coupler ($T = 1, 2$ and $3\%$ near 1045 nm).

Figure 3. (a) Measured intensity autocorrelation and (b) corresponding optical spectrum of the mode-locked Yb:KYW laser. The time-bandwidth product is 0.31. Dotted curves are fits assuming an ideal sech$^2$ pulse shape.

Yb:KYW laser crystal combined with the nearly diffraction limited diode pumping technique and the low-loss SESAM-mode-locking. We believe that this laser design can be further simplified and its efficiency improved yet further by replacing the pair of prisms with NGVD mirrors. Moreover, the use of such a technique with further minimization of the laser should provide a scheme by which femtosecond pulses can be generated at significantly higher repetition rates.

We have also demonstrated a low threshold and highly efficient diode-pumped femtosecond Kerr-lens-mode-locked Yb:KYW laser [4]. The pump source was a 470 mW single-mode fibre-coupled InGaAs diode laser. A compact three-element laser geometry [24] was used (figure 4) and mode locking was achieved with a soft-aperture Kerr-lensing effect. Stable femtosecond operation was obtained in the 1040–1075 nm spectral range (figure 5) with a
Figure 4. Three-element KLM Yb:KYW laser set-up. LD, single-mode fibre-coupled InGaAs laser diode; CL, 5.9 mm aspherical collimating lens; HW, half-wave plate; FL, 63 mm focusing lens; M1, high-reflector plane mirror directly coated to the endface of the gain crystal; M2, high-reflector folding mirror ($r = 50\,\text{mm}$); OC, 1% output coupler.

Figure 5. Tunability of the three-element femtosecond Yb:KYW laser within a wavelength range of over 30 nm. Lower panel: measured pulse spectra; upper panel: corresponding output powers (left axis) and pulse duration (right axis).
pulse repetition frequency of 294 MHz. Near-transform-limited 107 fs pulses (10.5 nm FWHM spectral width) at a centre wavelength of 1054 nm were produced at an average mode-locked power of 126 mW. The maximum output power of 227 mW was obtained during femtosecond operation when the laser operated near 1042 nm and this corresponded to an optical-to-optical conversion efficiency of 53%. We believe that this represents the highest reported efficiency for any femtosecond laser to date. The development of such a compact, highly efficient and low-cost femtosecond laser should permit its application in many fields such as three-photon microscopy, ultrafast spectroscopy, THz generation and the synchronous pumping of optical parametric oscillators for femtosecond-tunable infrared sources.

2.2. High repetition rate Cr:YAG femtosecond lasers

High-repetition-rate femtosecond lasers with tunable emission around 1550 nm are promising for high bit rate and high-capacity wavelength-division-multiplexed data/telecommunications. Within this spectral domain, lasers based on Cr$^{4+}$:YAG crystals have attracted strong interest since their initial demonstration in 1991 [25]. Conveniently, the broad absorption band around 1000 nm for Cr$^{4+}$-doped crystals matches well with several commercially available pump sources. These include Nd-doped solid-state lasers, compact diode-pumped Yb-fibre laser sources and InGaAs diode lasers operating around 970 nm [26, 27]. The luminescence band of Cr:YAG extends over the 1200–1600 nm region and supports the generation of ultrashort optical pulses that can have durations below 20 fs [28].

In their use in optical communications studies, it is vital to obtain a high-pulse repetition frequency. Mellish et al [29] reported femtosecond pulses at 1 GHz from a 3-element Cr:YAG laser, whereas Tomaru later demonstrated 3- and 2-element laser configurations operating at 2.33 GHz [30, 31] and 2.6 GHz [32], respectively. The authors have developed a 3-element cavity Kerr-lens-mode-locked Cr:YAG laser, which allowed the generation of 81 fs pulses at repetition rates up to 4 GHz and average powers of 85 mW.

Figure 6 shows the configuration of the 3-element cavity that was used for this demonstration. The 11.6-mm-long crystal had one plane facet with a dielectric coating that provided broadband

![Schematic diagram of three-element KLM Cr$^{4+}$:YAG laser.](http://www.njp.org/)

**Figure 6.** Schematic diagram of three-element KLM Cr$^{4+}$:YAG laser. M1, HR, plane mirror, broadband high reflector; M2, HR, folding mirror ($r = 12, 15$ and $18$ mm), broadband high reflector; M3, OC, output coupler ($T = 0.3$ and $0.5\%$ near 1525 nm).
high reflectivity centred at 1550 nm and high transmissivity at the pump wavelength, whereas the second facet was Brewster-angled to minimize intracavity losses. To investigate the characteristics of this Cr:YAG laser at different repetition rates, HR folding mirrors with radii of curvature ranging over 12, 15 and 18 mm were employed. A low loss infrared-grade fused silica Littrow prism was used for dispersion compensation and as the terminating element of the cavity where its dielectrically coated backface acted as the output coupler (0.3 or 0.5% output coupling depending on prism). The pump source consisted of a compact Yb:fibre laser capable of producing up to 10 W of near-diffraction-limited cw laser light at 1064 nm. It was found experimentally that 5–6 mm of fused silica was required to provide an appropriate amount of intracavity negative dispersion for stable mode-locked operation. This corresponded to a round-trip dispersion of \(-110 \text{ fs}^2\) at 1525 nm. Mode-locking was established at pump thresholds of approximately 2.6 W but the best stability was achieved at pump power levels around 5 W. The highest repetition rate of 4.02 GHz was obtained when the 12 mm RoC folding mirror was employed. The laser mode-locked with a centre wavelength between 1505 and 1550 nm and figures 7(a) and (b) show typical examples of the spectrum and intensity autocorrelation for the output pulses when operating at a pulse repetition rate of 4.02 GHz. Assuming a sech\(^2\) intensity profile, the pulse duration was determined to be 81 fs at a centre wavelength of 1525 nm. With the corresponding spectral width of 33 nm, the deduced time-bandwidth product was 0.34, indicating that the pulses were close to the transform limit. (The inset in figure 7 confirms the pulse repetition frequency of 4.02 GHz.) This result was achieved with 0.5% output coupling in which case the average output power was 85 mW.

A novel OTDM/WDM datacomms demonstration based on the spectral slicing of the mode-locked output from this Cr:YAG laser has also been carried out [5]. Total capacities up to 1.36 Tbits s\(^{-1}\) with spectral efficiencies of 0.2 bits s\(^{-1}\) Hz\(^{-1}\) and 0.4 bits s\(^{-1}\) Hz\(^{-1}\) were achieved. This demonstrates, for the first time, the compatibility of an ultra-high-capacity spectral slicing scheme with a femtosecond solid-state laser.

3. Ultrafast semiconductor lasers

The crystal-based lasers discussed in section 2 have produced femtosecond pulse outputs having excellent characteristics. One practical drawback with this technique is the extended configuration of these sources. A separate pump laser is invariably required and there is no direct control over the laser gain medium. Many of the crystal-based systems also involve relatively involved geometries that require several discrete optical components to form the cavity. The crystals used also tend to be low-gain, implying that the physical length of the gain medium will provide the ultimate limit to pulse repetition frequency. In contrast, semiconductor lasers offer the potential for lasers that can be extremely compact, or even monolithic, along with direct electrical control over the gain excitation mechanism. In many cases, it is also possible to incorporate the components required for passive mode-locking directly into the gain medium, thereby further simplifying the fabrication techniques. In the following sections the progress made in the generation of sub-picosecond pulses using semiconductor lasers that utilize both edge-emitting and vertical-cavity device structures, before describing our latest results using a broadband semiconductor quantum dot gain material.
3.1. Mode-locked-pulse generation from diode lasers

In the recent years, mode-locked laser diodes have been at the centre of the quest for ultrafast, transform-limited and high-repetition semiconductor laser sources. To achieve these goals, a variety of mode-locking techniques and device structures have been demonstrated and optimized [33].

The first method for generating ultrashort pulses was based on an active mode-locking technique, which relied on the direct modulation of the gain section with a frequency equal to the repetition frequency of the cavity. Equivalently, an electroabsorption segment of a multielement device can be modulated to give the same effect. The greatest advantage of this technique is the ability to synchronize the laser output with the modulating electrical signal, which is a fundamental attribute for optical transmission and signal processing applications. However, high repetition frequencies are not readily obtained through direct laser driving as fast RF modulation...
of the drive current becomes progressively more difficult with increasing frequency. This can be circumvented to some extent by sub-harmonic mode-locking, where the modulating current is driven at a much lower frequency. In fact, such active mode-locking at repetition frequencies as high as 50 GHz was obtained using this technique [34], delivering 2.6 ps pulses. With careful optimization of the mode-locking frequency and the use of an external cavity technique, pulses as short as 580 fs were reported [35].

The frequency limitation imposed by electronic driving circuits can be overcome by passive mode-locking techniques. This scheme typically utilizes a saturable absorbing region in the laser diode, which accounts for the shorter and higher-quality pulses obtained. This region is formed by electrically isolating one section of a multi-section laser device and applying a reverse bias in contrast with the forward bias used to drive the laser section. A schematic of such a device is illustrated in figure 8. In practice, pulse durations as short as 650 fs (not transform-limited) have been obtained from a monolithic mode-locked diode laser [36]. In this case, the repetition frequency is determined by the cavity round-trip time. A straightforward way to increase the repetition frequency is to shorten the cavity length, but the laser length is limited by the available gain and if the device is too short, mode-locking can no longer occur. Harmonic mode-locking is a variation of this technique that allows higher repetition rates, without decreasing the cavity length and it is widely used in the context of colliding-pulse mode-locking, as mentioned below. Ararhira et al [37] demonstrated a more sophisticated approach to increase the repetition frequency with an extracavity approach. The laser output was coupled with a dispersive medium (usually a fibre). A careful balance between the laser pulse repetition frequency and the length and dispersion of the fibre resulted in a multiplication of the input repetition frequency. This is the so-called repetition-frequency multiplication method. Using this technique, 49 GHz output from a passively mode-locked diode laser was transformed into a sub-THz pulse train (98–196 GHz).

Colliding-pulse mode-locking is a variation of passive mode-locking, where the saturable absorber region is placed at the precise centre of the gain section. Two counter-propagating pulses from each outer gain section therefore meet in the saturable absorber region; bleaching is much more easy than if only one pulse was present. This process results in shorter and more stable pulses. Due to the device geometry, the pulse repetition frequency is double that of the cavity frequency. An alternative design for achieving colliding-pulse mode-locking is to coat a highly

![Figure 8. Schematic diagram of a two-section passively mode-locked semiconductor laser. \( I_{\text{gain}} \) is the current applied to the gain section and \( V_{\text{abs}} \) the reverse bias applied to the absorber section (note that both \( I_{\text{gain}} \) and \( V_{\text{abs}} \) are dc).]
reflecting dielectric mirror on the saturable absorber facet of a two-section laser. In this way, self-colliding pulse mode-locking can be achieved. Colliding-pulse mode-locking was widely used in dye lasers before being implemented in semiconductor sources, in 1990 [38]. One of the earliest reports of this technique dates from 1991 [39] and the results obtained are still astonishing today: a monolithic multiple quantum well InGaAsP laser was able to generate transform-limited pulses of 640 fs, at 350 GHz! Terahertz-rate pulse generation was achieved in 1994 [40], by the harmonic mode-locking of a self-colliding-pulse diode laser having a distributed-Bragg-reflector (an in-depth study of this experiment can also be found in [41]). The 40th harmonic number of the fundamental repetition frequency was obtained, yielding 260 fs transform-limited pulses, at a 1.54 THz rate.

Inspired by active and passive mode-locking, the technique of hybrid mode-locking meets the best of both worlds: pulse generation is driven by an RF current imposed in the gain or absorber section, whereas further shaping and shortening is assisted by a saturable absorber section. This process results in high-quality pulses, synchronized with an external source. Direct generation of 730 fs pulses from a hybridly mode-locked laser diode, placed in an external cavity, was demonstrated by Weber et al [42].

3.1.1. Pulse compression. In general, the pulses produced by an ultrashort pulse semiconductor laser are not bandwidth limited. This means that the pulses can be further shortened by extracavity techniques. The simplest pulse compressors used are based on linear dispersion compensation, and comprise a prism pair, or a Gires–Tournois interferometer, or diffraction grating pair or optical fibre. The last of these is the easiest to implement [43], and as such is widely used. By simply using single-mode fibre pulse compression, a turn-key external cavity hybridly mode-locked laser diode was able to deliver pulses as short as 180 fs (1.4 times the transform limit) [44].

Unfortunately, linear dispersion compensation is usually not sufficient for achieving transform-limited pulses, which suggests the existence of non-negligible higher-order dispersion and non-linear chirp, as demonstrated by the work reported in [45]–[48]. In [46], for example, a carefully optimized four-path grating set-up is employed to compress by a factor of 7 the output pulses from the semiconductor laser resulting in 230 fs pulses, close to the transform limit of 190 fs. Yu et al [47] demonstrated an efficient suppression of non-linear chirp, employing a folded grating-mirror cavity. Second- and third-order chirp compensation were simultaneously achieved using sets of fibres with pre-selected dispersion and optimized lengths [49], delivering nearly transform-limited 500 fs pulses.

To further enhance compression, additional intracavity dispersion compensation [50] can also be performed. Intracavity spectral shaping has also been much explored by Delfyett and co-workers [51, 52] to prevent the natural gain-narrowing occurring during laser operation of the gain medium. This latter phenomenon, present in most semiconductor-based lasers, is another phenomenon that hinders the generation of ultrashort pulses that require wide operating bandwidths. The intracavity spectrum is artificially broadened by means of an etalon, which is tuned to promote minimum transmission at the peak of the gain and two maximum transmission peaks in the wings of the gain curve, resulting in a flat and broader spectrum. When the laser was actively mode-locked with the intracavity etalon, a 36-fold increase in bandwidth was observed [51]. With external dispersion compensation, the highly chirped pulses were compressed to pulse durations around 330 fs.
A very interesting set-up has recently been demonstrated [53, 54] based on chirped-pulse amplification. The purpose of this set-up is to minimize self-phase-modulation effects in the gain medium, which are stronger for the more intense shorter pulses. The layout consists of an external ring cavity, which comprises the semiconductor gain medium, a saturable absorber, a compressor in one arm and a pulse stretcher in the other. (Both the compressor and stretcher are dual-pass grating compressors with internal telescopes, but they can act as compressor/stretcher depending on the sign of the dispersion.) The pulse is stretched prior to amplification and afterwards is compressed to more readily bleach the saturable absorber. This cyclic operation of intracavity stretching and compression is called a breathing mode. With further external compression, pulses as short as 274 fs have been reported and this is just 10% higher than the transform limit.

As far as we are aware, a pulse duration of 20 fs from a compressed gain-switched laser output [55] holds the present record for the shortest pulse generated by a semiconductor source, as well as the highest compression factor (375). However, this level of performance requires the use of a relatively complicated and cumbersome multi-stage compressor, which comprises a four-stage fibre soliton pulse compressor, employing two EDFAs and four different types of optimized-length fibres! Currently, efforts are being made towards the reduction of number and size of the compression stages. Ultimately, for simplified and monolithic semiconductor lasers capable of generating near-transform-limited pulses, the design and fabrication of reliable devices that allow for integrated dispersion compensation must be further investigated and this represents one of the main challenges in this area of research. Other challenges include the minimization of timing jitter in passively mode-locked devices and the enhancement of pulse energy, as will be discussed in the following section.

3.1.2. Research challenges. Due to its self-starting nature, pulse generation arising from passive mode-locking in semiconductor lasers exhibits timing jitter [56], as well as the lack of controllable synchronization with an external clock. Both of these conditions are crucial requirements to be met in ultrafast optical communications and other applications [57]. Such problems can be circumvented by using stabilization techniques that involve optical or electrical injection into the laser cavity. The generated pulse trains then synchronize with this input, resulting in an output with similar or lower jitter than the stabilizing source. The input optical/electrical pulses must have a repetition frequency equal to or a sub-multiple of the laser roundtrip frequency. An electrical stabilization method, such as hybrid mode-locking, is more convenient to implement than an optical approach, because it removes the requirement for a secondary stable source and accurate optical alignment. On the other hand, optical stabilization gives a larger locking bandwidth and lower timing jitter than its electrical counterpart [58]. Optical stabilization of ultrashort pulses has been achieved with significant decrease of jitter, sometimes to less than that of the master laser pulses [58, 59]. More recently [60], a set-up using a master hybridly mode-locked laser diode reduced the timing jitter of a colliding-pulse mode-locked laser to about 0.14 ps (below that of the master laser).

A further limitation with mode-locked diode lasers that operate at high-pulse repetition frequencies is the low energy of the ultrashort pulses. By the use of external amplification schemes, the average output power can reach hundreds of mW, but at the expense of more complicated arrangements. Furthermore, the pulse quality degrades as it goes through sequential stages of amplification and compression. A more compact approach to generate ultrafast and high-power pulses is desirable and tapered waveguide devices have demonstrated higher output.
Figure 9. A typical optical scheme of mode-locked optically pumped VECSEL mode-locked using a SESAM. The gain material is a multiple-quantum-well (MQW) structure. The output coupler (OC) typically has a transmission ($T_{OC}$) of 0.8% at the laser wavelength and a radius of curvature ($R_{cc}$) = 15 mm.

power than untapered counterparts [61]. VECSELs could also play a decisive part in meeting this challenge, and these devices will be discussed in the next section.

3.2. Vertical cavity devices

The mode-locking of laser diodes by active and passive modulation of cavity loss, as described above, is a well-developed technique for the generation of picosecond to sub-picosecond optical pulses in the near-infrared spectral range [62, 63]. An alternative technique by which ultrashort pulses can be generated at high repetition rates involves the use an optically pumped VECSELs. This type of semiconductor laser combines the excellent beam quality associated with the vertical-cavity design with the potential for high output powers (100s mW). The relatively small gain saturation fluence of the active area of such lasers implies that they can be passively mode-locked at repetition rates from several GHz to tens of GHz.

High-power picosecond pulses at multi-GHz repetition rates have been generated from InGaAs multiple-quantum-well structures [64]. Hoogland et al used a similar technique to generate femtosecond pulses (≈500 fs) with repetition rates up to 10 GHz [65] (figure 9) from passively mode-locked optically pumped InGaAs MQW-based VECSELs operating near 980 nm wavelength by incorporating a SESAM element. In addition to the optically pumped technique, the realization of a high-power electrically pumped VECSEL [66] lasers has allowed the generation of passively mode-locked pulses with a significantly simplified optical scheme. The design of such devices also allows them to be used as an electrically controllable SESAM in a passively mode-locked crystal laser [67]. It is especially noteworthy that electrically pumped VECSELs combine both high output power and high wallplug efficiency. Indeed, by using electrically pumped VECSEL devices with an intracavity SESAM (figure 10) element, mode-locked operation with a frequency of up to 15 GHz and a pulse duration of 15 ps has been demonstrated [68].
Figure 10. A typical optical scheme of mode-locked electrically pumped VECSEL.

3.3. Quantum-dot-based semiconductor lasers

As discussed in section 3.1, mode-locked laser diodes where a semiconductor saturable absorber is incorporated give excellent performance and have demonstrated enhanced characteristics over other optical pulse sources. Particular features include extremely high-pulse repetition rates exceeding hundreds of GHz, very short pulse durations, highly compact structures and direct electrical pumping. These advantages are very promising for future applications such as large-capacity optical communication systems, mm-wave communication with optical fibres and ultrafast data processing. Many different types of multi-section devices have been investigated in recent years [63]. However, most of these devices were based on quantum-well structures and generated picosecond pulses [69]. Significant progress in the fabrication of quantum-dot lasers [70] has allowed a number of groups to investigate these devices [71, 72]. Whereas the emission lines of conventional bulk and quantum-well lasers are predominantly homogeneously broadened, those of quantum-dot lasers exhibit characteristic inhomogeneous broadening, in which the resultant linewidths depend on the dot size distributions. The increased bandwidth is also resilient to temperature fluctuations and has a much higher frequency roll-off. Devices based on quantum-dot structures are therefore becoming of primary interest in the generation/amplification of femtosecond pulses, because of the significant spectral broadening offered by the combination of multiple layers of differently sized quantum dots.

The study of the dynamic characteristics of the quantum-dot structures and devices is of key importance. Recently, a high-gain amplification (>18 dB) of sub-200 fs pulses in a quantum-dot semiconductor optical amplifier was reported [73]. This work has also demonstrated that
quantum-dot devices can amplify ultrashort pulses in a relatively broad spectral range that extends to more than 100 nm and the gain performance of this device is illustrated in figure 11. The investigation did not show any significant drop in amplification for pump energies below 2 pJ as had been previously reported for a QD-SOA by Borri et al [71]. This behaviour can be explained by a straight comparison between the total numbers of quantum dots and the device length. We believe that it should be possible to raise the gain of this type of device and the input power level without saturation by increasing the number of dot layers from the 3 of this structure (investigated in this work) to perhaps 10–20 and also the number density of dots per layer. Indeed, investigations of the carrier dynamics of quantum-dot structures have demonstrated a fast (∼1 ps) recovery time [7] in a waveguide structure. Furthermore, the ultrafast carrier dynamics of quantum-dot structures (figure 12) imply that such devices could be used simultaneously as a broadband gain medium and as a fast saturable absorber.
Figure 12. Measurement of the carrier lifetime of a quantum-dot sample taken from [9]. The fast component of the decay indicates that such a system may be suitable for use as a saturable absorber in an ultrashort pulse laser system.

Figure 13. A simplified schematic for a two-section quantum-dot laser.
Our preliminary results [6] have demonstrated the potential of a passively mode-locked two-section laser based on quantum-dot structures for the generation of sub-picosecond pulses. A simplified schematic of the two-section laser investigated is illustrated in figure 13. The typical light-current characteristics for this structure under various reverse bias conditions for the saturable absorber section are included in figure 14 and average output powers up to 45 mW.
were obtained. Such devices have not been observed to have any pronounced hysteresis on the light-current characteristic. Mode-locked operation was obtained at injection currents above laser threshold (~30 mA) up to 360 mA bias current and for a wide range of reverse bias levels on the absorber section, $V_{ab} = 4.5–10$ V. Under conditions of a cw current supplied to the gain section and with a reverse bias on the saturable absorber section, the laser emitted pulses having a repetition period determined by the cavity round-trip time as expected. Measurements made for a range of drive conditions show typical pulse durations around 2 ps in a sequence having a repetition frequency of 21 GHz. (The pulse profile for this operation also exhibited a strong coherence spike which appears when the drive current exceeded threshold in both the cw and mode-locked regimes.) However, under a range of current–voltage parameters that represented the optimized conditions for the generation of the shortest pulses, the device generated pulses with durations as short as 390 fs directly from the diode laser without any form of pulse compression technique being required. A representative intensity autocorrelation profile for a pulse obtained in this regime is reproduced in figure 15 where the contrast ratio is close to 3 : 1. This figure also includes the corresponding optical spectrum which has a width of 14 nm. This implies a time-bandwidth product of ~1 indicating some residual chirp being present. The broad spectrum and the ultrashort pulse durations measured here demonstrate the potential of the simple two-section quantum-dot laser for the generation of pulses with durations in the femtosecond domain in near future.

4. Conclusions

It clear from this review that there is a continuing and steady evolution of femtosecond lasers from laboratory configurations to an increasingly practical and integrable status. This is especially notable if the progression towards femtosecond quantum-dot diode lasers can be sustained and confirmed because this category of device would offer excellent compatibility with a range of opto-electronic technologies. Further progress will rely both on new insights from the fundamental science as well as technical innovations and so we can predict that research and development activities in this field are set to remain at the forefront of international endeavour for some time in the future.

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