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Picosecond pulse sources with multi-GHz repetition rates and high output power

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Abstract. We review and compare several recently introduced approaches for the generation of picosecond pulse trains with multi-GHz repetition rates and relatively high average output power (up to several watts). Specifically, we consider passively mode-locked lasers with different gain media (Nd:YVO$_4$, Er:Yb:glass, and surface-emitting semiconductor structures) as well as optical parametric oscillators.

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1. Introduction

In recent years, passively mode-locked lasers have been pushed into regimes with extreme operation parameters [1]. One direction has been to generate extremely high mode-locked average powers, so far up to 80 W [2, 3]), directly from a passively mode-locked laser (i.e., without using an amplifier). Another very active field and the topic of this article is the development of passively mode-locked lasers with very high pulse repetition rates of several GHz or more. Such laser sources may be used, e.g., for telecommunication systems [4] with bit rates of 10 Gbit s^{-1}, 40 Gbit s^{-1}, or even higher, where the use of a pulse-generating multi-GHz laser as the primary light source leads to significantly lower demands on the modulator when compared with a system based on a continuous-wave laser. A multi-GHz laser with, e.g., 25, 50 or 100 GHz can also be used as a multi-wavelength source [5]–[7], generating tens, hundreds or even thousands of continuous-wave carriers for a corresponding number of telecom channels. Other applications of multi-GHz lasers include very diverse fields such as optical clocking [8], photonic switching [9], high-speed electro-optic sampling [10], analogue-to-digital conversion, time-resolved spectroscopy [11], and the generation of polarized electron beams for particle accelerators [12].

Particularly in the telecom area, multi-GHz pulse sources have so far almost always involved either an edge-emitting semiconductor laser [13, 14], which is usually actively or hybrid mode-locked, or a harmonically mode-locked fibre laser [15]. Edge-emitting semiconductor lasers appear very attractive due to their very compact and stable optical setup, but expensive electronics are required for active mode locking, and great care is required to achieve a high pulse quality. Multi-GHz fibre lasers can easily generate high-quality pulses, but they have very long laser cavities and thus require sophisticated means to obtain stable mode locking with a large number of precisely equidistant pulses in the cavity. Both types of lasers typically deliver small average output powers of a few tens of milliwatts or even below 1 mW. Although amplification is possible, e.g., with an erbium-doped fibre amplifier, this significantly adds to the complexity and cost of a system, apart from increasing the noise level.

In this paper, we concentrate mostly on novel passively mode-locked solid-state lasers and surface-emitting semiconductor lasers (VECSELs), both of which have been demonstrated, in recent years, to be well suited for mode locking with multi-GHz pulse-repetition rates, very good pulse quality and comparatively high output powers. Due to the passive mode-locking approach, all these features are achieved without using any multi-GHz electronics. Here, we give an overview on recent achievements and compare the potential of various approaches. In sections 2 and 3 we begin with passively mode-locked solid-state lasers at 1 and 1.5 μm. The former type can be used to pump multi-GHz optical parametric oscillators (section 4), leading to ultra-broadband tunability in the 1.5 μm regime. In section 5, we describe the concept of surface-emitting semiconductor lasers (VECSELs), and finally we conclude with a comparison of the potentials of all these approaches.

2. Nd:YVO_4 lasers at 1064 nm

Compared with other laser crystals and glasses, Nd:YVO_4 is an excellent gain medium for passively mode-locked lasers with very high repetition rates. Apart from its high power capability, power efficiency and convenient pump wavelength of 808 nm for diode pumping, the most important parameters for passive mode locking are the unusually high emission cross-section

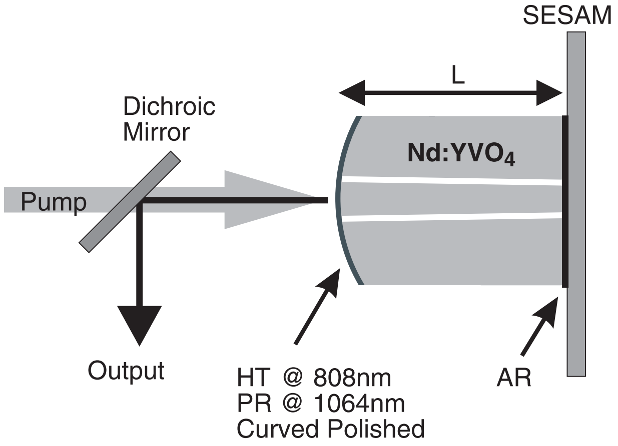

Figure 1. Setup of a miniature Nd:YVO$_4$ laser with 157 GHz pulse repetition rate. The crystal length L is only 0.44 mm. Mode locking is achieved with a SESAM directly attached to the crystal.

of 114×10^{-20} cm^2 [16] and the reasonably broad emission bandwidth of ≈1 nm. The former allows us to suppress Q-switching instabilities [17] even for very high pulse repetition rates, whereas the latter results in reasonably short pulses even when the modulation depth of the passive-mode locker is relatively small. In addition, the short absorption length (e.g., 90 μm for 3 at.% Nd doping) allows us to use very short laser crystals, which makes possible very short cavities and relaxes the constraints on the pump beam quality.

As the state of the art has recently been described [18], we briefly summarize some of the key results and then discuss in some detail the scaling limitations of this technology. The highest repetition rate of nearly 160 GHz [18] has been achieved with a quasi-monolithic laser cavity, basically consisting of a ≈0.44 mm long Nd:YVO$_4$ crystal with the output coupler mirror coating evaporated on a curved end and a semiconductor saturable absorber mirror (SESAM [19, 20]) directly attached to the other (flat) end (see figure 1). This laser generated 2.7 ps pulses with a 157 GHz repetition rate and 45 mW average power. The pulses are remarkably short, despite the low modulation depth of the SESAM; this is due to the effect of spatial hole burning [21] which increases the effective gain bandwidth. With a 2.7 ps pulse duration and a pulse spacing of only 6.4 ps, subsequent pulses begin to overlap to some extent. It becomes apparent that with this laser we have reached the fundamental limit for the repetition rate which is given by the gain bandwidth, because a higher repetition rate would require shorter pulses. Unfortunately, all known ion-doped laser crystals or glasses with a significantly broader amplification bandwidth appear to have much lower laser cross-sections compared with Nd:YVO$_4$, so that the repetition rate for passive mode locking is then typically limited to significantly smaller values by the Q-switching tendency [17] and not by pulse overlap.

The 157 GHz laser was pumped with 0.5 W from a Ti:sapphire laser. The required nearly diffraction-limited pump beam quality would exclude the use of broad-area diode lasers. However, nearly diffraction-limited laser diodes with ≈0.5 W output power at 808 nm have become available, so that direct diode pumping of a 160 GHz laser appears to be feasible. With systematic optimization of the SESAM and output coupler, the output power might reach up to ≈0.2 W.

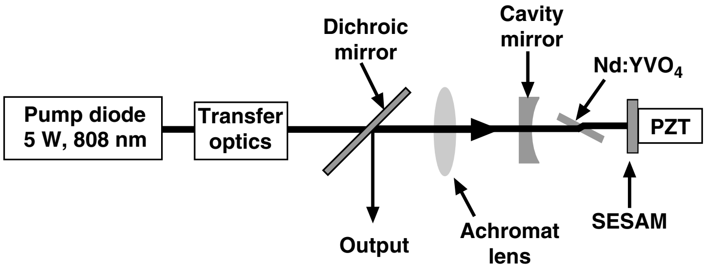

Figure 2. Setup of a 10 GHz $Nd:YVO_4$ laser with an average output power of ≈2 W. The cavity length of ≈15 mm can be fine-tuned with a piezoelectric translator (PZT).

So far, the highest repetition rate achieved with direct diode pumping is 40 GHz [22]. The laser design is basically the same as that of the previously mentioned 157 GHz laser, except for an increased crystal length of 1.74 mm. The pump source is a laser diode from Bookham, delivering 0.4 W with an M^2 value of ≈1.3 in the slow axis direction. This laser delivers 2.7 ps pulses with 50 mW average output power. Another 40 GHz laser [22], pumped with a high-brightness laser diode, has been optimized for a higher output power of 288 mW, but is generating longer pulses with 6.5 ps duration.

Significantly higher average output powers are possible only at lower repetition rates. Mainly for pumping parametric oscillators (section 4), we have developed a diode-pumped 10 GHz $Nd:YVO_4$ laser with an average output power of 2.1 W [18]. The cavity setup is shown in figure 2. Here, the pump source was a beam-shaped laser diode (from unique-m.o.d.e.) with 5.6 W output power and an M^2 value of ≈20 in both directions. Because of the high thermal load, we used a relatively low (0.5%) doped $Nd:YVO_4$ crystal, which needs to have a 1 mm length for efficient pump absorption. (Higher doping levels lead to a thermal roll-over or even fracture of the crystal.) Pump beam quality and crystal length then limited the radius of the pump spot to ≈50 μm in air, and for stable single transverse mode operation we had to choose a slightly larger laser mode: the beam radii in the Brewster-angled crystal were 143 and 67 μm in the horizontal and vertical directions, respectively. For stable mode locking (i.e., without Q-switching instabilities [17]) at a given pulse repetition rate, the laser mode area (together with other factors such as the cavity losses) leads to an upper limit of the order of 0.25% for the modulation depth of the SESAM, which is close to the chosen value. (This limit for the modulation depth is calculated for relatively strong saturation of the SESAM, ≈10 times above the saturation fluence.) As the modulation depth is small, compared with the output coupler transmission of 2%, the obtained pulses have a duration of 14 ps, i.e., significantly longer than that of other $Nd:YVO_4$ lasers. Another reason for the longer pulse duration is that spatial hole burning did not occur in this laser cavity.

It becomes apparent that the need to suppress Q-switching instabilities leads to a compromise between highest output power, highest repetition rate and shortest pulse durations. For example, shorter pulses would require a higher modulation depth of the SESAM, which is compatible with stable mode locking, only for lower pulse repetition rates (i.e., longer cavities). This compromise is also affected by the pump brightness: for example, a better beam quality allows for a smaller laser mode area in the crystal, reducing the Q-switching tendency and thus allowing for a higher repetition rate and/or shorter pulses. A limit for the output power may also arise from crystal fracture which prohibits too strong pump focusing even if the pump beam quality would be significantly improved. In any case, it appears that the reported laser performance approaches the limits given by the parameters of the crystal material and the pump source.

For a more quantitative description of the scaling limits, we use the condition

$$\frac{E_\mathrm{p}}{E_\mathrm{L,sat}} > \frac{\Delta R}{S} \tag{1}$$

(modified from [17]) for stable mode locking without Q-switching instabilities, where ΔR is the modulation depth of the SESAM, E_p the intracavity pulse energy, $S = E_\mathrm{p}/E_\mathrm{A,sat}$ the saturation parameter of the SESAM, and $E_\mathrm{A,sat}$ and $E_\mathrm{L,sat}$ are the saturation energies of the SESAM and the gain medium, respectively. This holds under conditions of significant SESAM saturation ($S > 2$), absence of a significant roll-over for high pulse energies (as it can occur, e.g., due to two-photon absorption [23]), and complete recovery of the SESAM between the pulses. We note that these conditions are not always well fulfilled for high-repetition-rate lasers, so that (1) gives only some estimate of the threshold for stable mode locking, apart from useful general guidelines.

From (1) we see that an increase of the repetition rate, which decreases E_p, makes it necessary to reduce ΔR. (We can keep the saturation parameter S constant by adjusting the mode area on the SESAM.) We now use the estimate

$$\tau_\mathrm{p} \approx \frac{1.07}{\Delta f_\mathrm{g}}\sqrt{\frac{g}{\Delta R}} \tag{2}$$

for the pulse duration (full-width at half-maximum) [24], neglecting the influence of spatial hole burning, where Δf_g is the gain bandwidth and g the saturated round-trip gain (which equals the total losses per round-trip). It becomes apparent that, e.g., if we start with a laser design close to the Q-switching limit and want a four times higher repetition rate, we have to use a SESAM with four times smaller modulation depth and thus accept two times longer pulses, if we use the same pump source and the same saturation parameter of the SESAM. For a too high repetition rate, the required modulation depth ΔR may become so small that the laser becomes very sensitive to weak spurious reflections. Also, an increased pulse duration together with a decreased pulse spacing leads towards a situation with significant overlap of subsequent pulses. These effects finally limit the obtainable repetition rate. The limit depends on the brightness (not just the power) of the pump source, as the brightness (together with the crystal length and parasitic losses) determines the achievable value of $E_\mathrm{p}/E_\mathrm{L,sat}$.

Assuming that we require a given pulse duration τ_p, we can combine (1) and (2), to obtain an estimate for the maximum achievable repetition rate

$$f_\mathrm{rep,max} \approx 2.6\frac{I_\mathrm{av,int}(\Delta f_\mathrm{g}\tau_\mathrm{p})^2}{F_\mathrm{L,sat}\,g}, \tag{3}$$

where $I_\mathrm{av,int}$ is the obtainable average laser intensity in the gain medium and $F_\mathrm{L,sat}$ is the saturation fluence of the gain medium (divided by 2 for a standing-wave cavity). The saturation parameter of the SESAM has been assumed to be 3, a reasonable value, for which the estimate of (2) is valid. Some improvement may be achieved by working with a higher value of S (e.g. $S = 10$), which requires only a small increase of ΔR to reach the given pulse duration, while the Q-switching tendency is significantly reduced. This may lead to a nearly three times higher repetition rate.

However, this regime requires tight focusing on the SESAM and thus leads to stronger SESAM heating, unless the saturation fluence of the SESAM is reduced in order to allow the use of a larger mode area.

We see that the relevant figure of merit of the gain medium will be

$$\frac{\Delta f_{\mathrm{g}}^2}{F_{\mathrm{L,sat}}} \propto \Delta f_{\mathrm{g}}^2 \sigma_{\mathrm{L}} \lambda_{\mathrm{L}} \tag{4}$$

with the laser cross-section σ_{L}. Nd:YVO$_4$ appears to have an unusually high value of this figure of merit, compared with other gain media for 1 μm lasers and particularly compared with gain media for longer wavelengths.

The influence of losses, which are also very low in Nd:YVO$_4$, is not considered in this figure of merit. Minimization of the cavity losses (and thus of g) is helpful (also because this increases $I_{\mathrm{av,int}}$), but even for a small output coupler transmission some unavoidable losses of $\approx \Delta R/S$ occur at the saturable absorber, in addition to some non-saturable losses. The latter tend to be higher for SESAMs with a fast recovery. However, it has been shown [24] that the recovery time can be allowed to be more than 20 times the pulse duration; it is not a critical parameter as long as it is short enough for stable mode locking and for nearly complete recovery between two pulses. In case of incomplete recovery, such a laser can work properly, but with a modified effective modulation depth and saturation fluence. We often employ MOCVD-grown SESAMs with low non-saturable losses and recovery times of the order of 50–100 ps.

For the above-described 10 GHz, 2 W Nd:YVO$_4$ laser, we find that it already operates near the limit estimated from (3). Improvements appear to be possible by using a pump source with further improved brightness. Further optimized SESAMs may also allow, e.g., for a reduction of the pulse duration by a factor of the order of 2.

We note that there are some additional factors which might allow the possible repetition rate to increase. One possibility is a saturable absorber where the slope of the saturation curve levels off earlier than that obtained for simple absorber models [23, 25]. Also the effective gain bandwidth can be increased by spatial hole burning when the gain medium is close to an end mirror of the cavity. Certainly, the limit given by (3) is only an estimate, but at least it appears to be difficult to exceed it by a large amount.

3. Er:Yb:glass lasers at 1.5 μm

Telecom applications usually require laser sources operating in the 1.5 μm spectral region, where the choice of gain media is rather limited. We developed various multi-GHz lasers based on Er:Yb-doped phosphate glass, an often used broadband gain medium, although this has by far less favourable properties for high power multi-GHz lasers compared with Nd:YVO$_4$ at 1064 nm: the low thermal conductivity of glass limits the output power level, while the low laser cross-sections lead to a strong tendency for Q-switching instabilities. Nevertheless, we managed to demonstrate passively mode-locked Er:Yb:glass lasers with 10 GHz repetition rate [26], later improved to 25 GHz [6], 40 GHz [27], and even to 50 GHz [28]. Cr:YAG would appear to be an alternative gain medium, offering significantly higher laser cross sections, but so far the maximum reported repetition rate from a Cr:YAG laser is 4 GHz [29]. Challenges arise from the difficulty to get a good crystal quality for high doping levels (as required for short lasers). Other

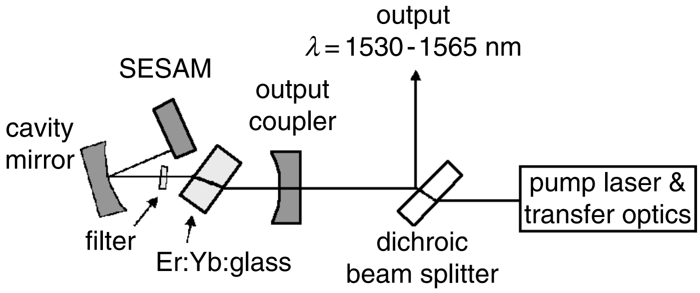

Figure 3. Folded cavity of a miniature diode-pumped Er:Yb:glass laser. Such lasers have been realized with 10, 25, 40 and 50 GHz (for >25 GHz without an etalon for wavelength tuning).

problems are the requirement of a high brightness pump source around 1 μm, the associated strong thermal lensing effects and induced absorption effects [30].

The above-mentioned Er:Yb:glass lasers are pumped by telecom-grade 980 nm laser diodes, which typically deliver ≈0.3 W of pump power in a nearly diffraction-limited beam. Most of the pump radiation is absorbed by the Yb dopant and then transferred to Er ions, generating gain in the 1.5 μm region. The doping levels must be properly chosen to optimize the efficiency of the energy transfer without causing too strong upconversion or quenching processes [31].

The good pump beam quality allowed us to construct miniature Er:Yb:glass lasers with fairly small laser spot radii in the Brewster-angled gain medium. The folded cavity (figure 3) also provides a rather small spot on the SESAM [26]. A small radius of curvature of the folding mirror allows us to realize the required small modes in gain medium and absorber even for a 50 GHz cavity [27], which has a geometrical cavity length of only 3 mm. Typical pulse durations are in the range of 1 ps up to nearly 20 ps, depending mainly on the SESAM parameters, while the average output power can be more than 50 mW and is more than 10 mW in most cases. An intracavity etalon can be included to adjust the laser wavelength by tuning the tilt angle; tuning over the full C-band for telecommunications (a range of ≈40 nm) has been demonstrated for 10 and 25 GHz repetition rates [6, 26].

A careful investigation of the parameters of these lasers shows that the observed Q-switching tendency appears to be significantly weaker than expected from (1): at these high pulse repetition rates, stable mode locking would not appear to be possible with the measured values of the SESAM modulation depth. For an Er:Yb:glass laser with a lower repetition rate of 61 MHz, we could demonstrate [25] that such an effect was caused by a modified saturation behaviour of the SESAM, and it is probable that the same effect is also fully responsible for the low Q-switching thresholds of multi-GHz lasers.

Pushing the repetition rates of passively mode-locked Er:Yb:glass lasers beyond 50 GHz appears to be feasible. Possible limiting factors are Q-switching instabilities and the extremely small cavity dimensions, which are particularly challenging for the construction of folded cavities.

Due to the wide gain bandwidth of Er:Yb:glass, the pulse durations can be further improved by proper dispersion control; the smallest pulse duration so far was 1 ps in a 10 GHz laser. It has so far not been possible to achieve pulse durations of below 500 fs, as achieved with Er:Yb:glass lasers operating at low repetition rates [32]. The reason is that at multi-GHz repetition rates the non-linear phase changes in the gain medium are too small for soliton pulse formation.

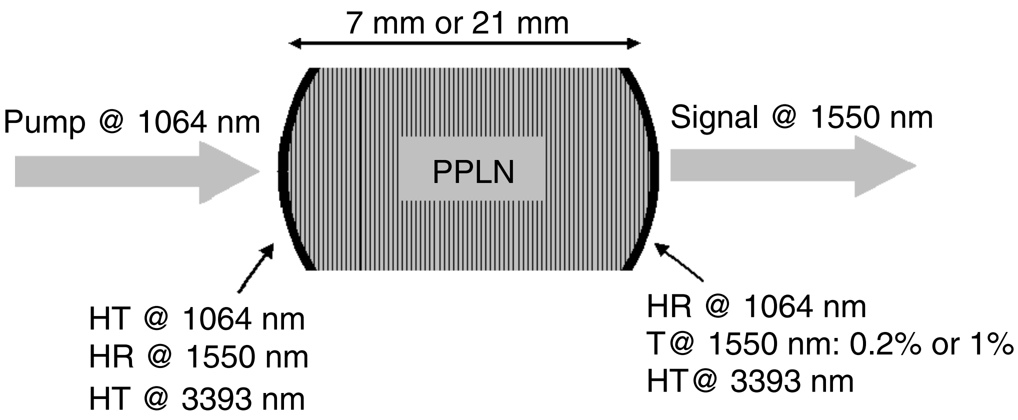

Figure 4. Monolithic 10 GHz parametric oscillator, consisting of a periodically poled $LiNbO_3$ crystal with dielectric coatings evaporated on the curved end faces. A 7 mm long crystal corresponds to a fundamental repetition rate of ≈10 GHz.

4. Optical parametric oscillators at 1.5 μm

Synchronously pumped optical parametric oscillators (OPOs) are well known for their potential to provide very large wavelength tuning ranges, significantly larger than possible with most laser media. This makes them interesting for telecom pulse sources. However, the possible repetition rate was until recently limited to values below ≈1 GHz, because higher repetition rates make it difficult to exceed the threshold value of the pump peak power of the OPO. By using an actively mode-locked diode laser and a semiconductor optical amplifier, sufficient pump power was generated to operate an OPO with a 2.5 GHz repetition rate [33] and signal and idler average output powers of 5 and 78 mW, respectively. In 2002, we demonstrated OPOs with 10 GHz and the added advantage of much higher signal output powers of up to 100 mW [34]. This became possible with the construction of low-loss OPO cavities and the use of the 10 GHz $Nd:YVO_4$ pump laser with 2.1 W average power as described in section 2. The first of these OPOs had a monolithic cavity (figure 4), consisting of a periodically poled $LiNbO_3$ crystal with dielectric mirror coatings evaporated on the curved end faces. Typical threshold pump peak powers are in the order of a few watts, even with a significant output coupler transmission of a few percent which allows for high power efficiencies. Therefore, the 10 GHz $Nd:YVO_4$ pump laser with >10 W peak power can be used to easily exceed the pump threshold. The latest published results [35] include a wavelength tuning range of up to 153 nm and an average output power up to 350 mW, and they show that the use of ring cavities has some advantages. It becomes apparent that multi-GHz OPOs can provide not only a much wider tuning range but also much higher output powers, compared with Er:Yb:glass lasers. An overview of multi-GHz pulse sources with high output power is presented in table 1.

A very recent result, to be published soon [36], is the demonstration of a 39 GHz OPO. For this high repetition rate, it was necessary to pump the OPO with the combination of a diode-pumped low-power 39 GHz laser (as described in section 2) and a fibre amplifier. The amplifier is based on an ytterbium-doped fibre, cladding-pumped with 20 W at 915 nm from a fibre-coupled laser diode. The threshold of the OPO ring cavity is reached at 1.76 W pump power,

Table 1. An overview of important laser performance results for multi-GHz pulse sources with relatively high output power. All lasers are diode-pumped, except for the first one which was pumped with a Ti:sapphire laser. Results of the 40 GHz OPO, pumped using a fibre amplifier, are preliminary but will be published soon.

Type of source	Wavelength (nm)	Repetition rate (GHz)	Average output power (mW)	Pulse duration (ps)	Ref.
Miniature Nd:YVO$_4$ laser	1064	157	45	2.7	[18]
Nd:YVO$_4$ laser	1064	10	2.1×10^3	14	[18]
Nd:YVO$_4$ laser	1064	40	50	2.7	[22]
Er:Yb:glass laser	1529–1569	10	15	3.8	[26]
Er:Yb:glass laser	1535	25	25	1.9	[6]
Er:Yb:glass laser	1535	40	18	4.3	[27]
Er:Yb:glass laser	1535	50	7.5	2	[27]
Sync-pumped parametric oscillator	1535–1578	10	100	6–13	[34]
Sync-pumped parametric oscillator	1466–1620	10	350	14	[35]
Sync-pumped parametric oscillator	1571	39	$>1 \times 10^3$	2 ps at 0.5 W	[36]
Optically pumped VECSEL	960	10	1.4×10^3	6.1	[46]

and preliminary results showed average output powers at 1.5 μm of over 1 W. We envisage that this approach should soon lead to repetition rates of 80 GHz or even higher.

Note that the round-trip time of the OPO can be an integer multiple of the pulse period, so that a longer crystal with correspondingly higher parametric gain can be used. In this situation, multiple pulses are circulating in the OPO cavity. In contrast to the situation of a harmonically mode-locked laser, here we do not need special measures to guarantee a constant spacing of the pulses, because this is defined by the pump repetition rate. The above-mentioned 40 GHz OPO has 55 pulses circulating in its cavity.

Another possibility would be rational harmonic pumping. For example, an OPO with a fundamental cavity frequency of, e.g., 3.333 GHz could be pumped at a repetition rate of 8 GHz, causing the OPO to operate at 40 GHz, the smallest integer multiple of fundamental cavity frequency and pump repetition rate. The lower pump repetition rate makes it easier to construct a pump laser which delivers the required average power. The disadvantage is that each pulse gets amplified only after a number of cavity round-trips (five in the given example), so that the pulse energy is not exactly constant. However, the variation of pulse energies stays small for low-loss cavities, which are preferable to keep the threshold low. We anticipate that this technique should make it possible to construct OPOs operating at 80 GHz and possibly even higher, directly pumped with diode-pumped mode-locked lasers without using an amplifier.

5. Surface-emitting semiconductor lasers (VECSELs)

Although passively mode-locked lasers based on ion-doped crystals, as e.g. Nd:YVO$_4$, have recently been pushed into a regime of extremely high repetition rate, the discussion in section 2

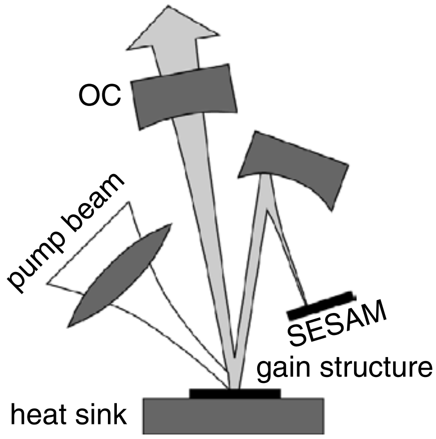

Figure 5. Cavity of a passively mode-locked VECSEL, containing the semiconductor gain structure (pumped with a high power laser diode) on a copper heat sink, a SESAM as modelocker, and an output coupler mirror (OC).

has shown that this approach has its limitations when a combination of high repetition rate, high power and short pulses is required. These limitations mainly result from the tendency for Q-switching instabilities, suggesting that one should look out for a gain medium with significantly lower saturation fluence. Although we have not found any ion-doped crystal or glass material with properties clearly superior to those of Nd:YVO_4, it is well known that semiconductor gain media exhibit strong gain saturation. Therefore, semiconductor lasers can be passively mode-locked or hybrid mode-locked at extremely high repetition rates of tens of GHz or even >1 THz [37]. However, the traditional approach of edge-emitting semiconductor lasers severely limits the mode-locked average power and even more the peak power. The mode areas are limited by the constraint to achieve single-transverse-mode operation (a prerequisite for mode locking), and strong non-linear effects arise for high peak powers.

In recent years, the concept of the optically pumped semiconductor vertical-external-cavity surface-emitting laser (OPS-VECSEL) has been introduced and shown to be capable of generating very high diffraction-limited continuous-wave output powers [38]. Such a laser consists of a very thin semiconductor gain structure, mounted on a heat sink, within an external cavity to define the transverse mode size. A large spot on the gain structure can be pumped easily with good spatial homogeneity, using the output of a high-power diode laser bar. Within a wide range of parameters, the output power can be increased by applying a higher pump power to a spot with a correspondingly increased area. Due to the very short pump absorption length, the pump beam quality is not critical, and the VECSEL can serve to convert up to about half of the incident power with poor spatial quality into a diffraction-limited beam. The highest output power published so far is 8 W [39], although in this case the beam quality factor M^2 was 1.8. The highest reported diffraction-limited continuous-wave power is currently 4.4 W [40]. With somewhat lower beam quality, higher powers of 8 W with $M^2 = 1.8$ [39] and recently even 30 W with $M^2 = 3$ [41] have been reported. All these results have been achieved in the wavelength region around 1 μm; 1.5 μm devices with currently lower power levels are under development [42]. This technology also has the potential to be realized in other important wavelength regions.

The first passively mode-locked OPS-VECSEL has been demonstrated in the year 2000 [43]. Here, the external cavity contains a SESAM (figure 5). Although the performance of this first device was moderate with an average output power of 22 mW in strongly chirped 22 ps pulses at 1030 nm, the great potential of this new gain medium for passive mode locking soon became apparent. Apart from the potential for very high powers, the very low saturation fluence of the semiconductor gain medium basically eliminates the tendency for Q-switching instabilities [17] even for passive mode locking at very high repetition rates. In addition, the wide gain bandwidth (typically a few tens of nanometres) gives the potential for pulse durations below 1 ps, with the current record being 0.48 ps [44]. Therefore, this type of laser is ideally suited to offer the combination of multi-watt average output power, a multi-GHz repetition rate and short pulse durations of a few picoseconds or even <1 ps. These properties make it attractive for many applications, e.g. as a pump source for multi-GHz OPOs (section 4) or for optical clocking [8]. The landmark result of a mode-locked VECSEL with nearly 1 W of average output power is described in [45], and this paper also contains a discussion of thermal issues. So far, the highest reported mode-locked average output power has been 1.9 W [40]. In this case, the pulse duration and repetition rate have not yet been optimized and are 27 ps and 1.5 GHz, respectively.

Much shorter pulses of 6 ps duration, close to the transform limit, have been obtained with 1.4 W [46] and 10 GHz repetition rate. A soliton-like pulse shaping mechanism in the positive dispersion regime [47] helps to obtain short pulses with low chirp, although the details of the pulse shaping are complicated and so far not fully understood. A 10 GHz device generating 0.5 ps pulses has also been demonstrated [48], although with a moderate output power of 30 mW. We anticipate that OPS-VECSELs will soon operate in a regime of high repetition rate, high power and short pulse duration, which is hardly accessible by the more conventional types of lasers.

So far, most mode-locked VECSELs have operated in the 1 μm spectral region. However, a device in the 1.5 μm region has recently been demonstrated [42], and other interesting wavelength regions will become accessible. For example, the regions around 0.95 and 1.25 μm allow the generation of blue and red light by frequency doubling, with applications for laser projection displays.

Last but not least, it should become possible to fabricate passively mode-locked VECSELs with a highly cost-effective wafer technology as soon as the saturable absorber can be integrated into the gain structure. In this case, the cavity can consist of this semiconductor structure and a curved mirror mounted at a distance of a few millimetres or centimetres. Further integration would become possible with electrical instead of optical pumping [49]. Such kinds of lasers may in the future find large markets for various applications.

6. Conclusions

Various novel multi-GHz pulse sources have been introduced in recent years, which are all directly or indirectly based on passively mode-locked lasers and all can generate high-quality picosecond or even femtosecond pulses of higher powers than achievable with earlier approaches (excluding amplified sources). In the 1 μm spectral region, Nd:YVO$_4$ lasers have been pushed into the multi-GHz regime with up to 157 GHz [18], or with a high power of 2.1 W at 10 GHz [18], which enabled the construction of 10 GHz parametric oscillators [34]. A novel kind of passively mode-locked laser, the optically pumped VECSEL [43, 45], has a much larger potential for the combination of high powers, high repetition rates and short pulses and is expected to offer superior performance in the near future. It also has superior prospects for efficient mass production. Devices outside the 1 μm spectral regions are possible [42], although for the near future with lower power levels.

In the 1.5 μm region, diode-pumped Er:Yb:glass lasers appear to be the simplest approach for generating high-quality picosecond pulses at multi-GHz repetition rates and with relatively high powers, compared with edge-emitting semiconductor lasers or fibre lasers. So far, full C-band tunability of a 10 GHz [26] and a 25 GHz [6] laser have been demonstrated, or up to 50 GHz repetition rate with 7.5 mW average power [28]. If much higher power and/or an even wider tuning range is required, parametric oscillators in the multi-GHz regime can be employed. These are pumped either with Nd:YVO_4 lasers or (in the future) with OPS-VECSELs. So far, more than 1 W average output power in the 1.5 μm region has been achieved with a 40 GHz OPO, in this case using a fibre amplifier in the pump setup. Higher repetition rates and even higher powers appear to be feasible.

Note that all the pulse sources discussed in this paper exhibit a very high pulse quality. In contrast to many mode-locked edge-emitting semiconductor lasers, they deliver pulses with very high contrast (low pedestals), which is important, e.g., for applications involving pulse multiplexing, where pedestals have very detrimental effects. Also the pulse chirp is usually weak.

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