Optically pumped VECSELs: review of technology and progress

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Abstract
Vertical-external-cavity surface-emitting lasers (VECSELs) are the most versatile laser sources, combining unique features such as wide spectral coverage, ultrashort pulse operation, low noise properties, high output power, high brightness and compact form-factor. This paper reviews the recent technological developments of VECSELs in connection with the new milestones that continue to pave the way towards their use in numerous applications. Significant attention is devoted to the fabrication of VECSEL gain mirrors in challenging wavelength regions, especially at the yellow and red wavelengths. The reviewed fabrication approaches address wafer-bonded VECSEL structures as well as the use of hybrid mirror structures. Moreover, a comprehensive summary of VECSEL characterization methods is presented; the discussion covers different stages of VECSEL development and different operation regimes, pointing out specific characterization techniques for each of them. Finally, several emerging applications are discussed, with emphasis on the unique application objectives that VECSELs render possible, for example in atom and molecular physics, dermatology and spectroscopy.

Keywords: vertical-external-cavity surface-emitting lasers, semiconductor disk lasers, optically pumped semiconductor lasers, VECSEL, SDL

(Some figures may appear in colour only in the online journal)

1. Introduction
Vertical-external-cavity surface-emitting lasers (VECSELs), also referred to as semiconductor disk lasers (SDLs), have emerged at the frontier between solid-state and semiconductor laser technologies [1–3]. These high-brightness light sources combine the most important advantages of semiconductor and solid-state lasers: the possibility of engineering the emission wavelength of semiconductor gain media is combined with the high beam quality and functionality offered by external cavity architectures. These features facilitate the coverage of a wide range of emission properties, which has not been possible using other laser technologies. The VECSEL’s versatility in its wavelength coverage is illustrated in figure 1, which shows the generic trend for power levels demonstrated in various wavelength regions. In general, the unique combination of wavelength coverage from the visible to the mid-IR range, high output power up to the 100 W level, high brightness, single-frequency operation, efficient intracavity frequency conversion, ultra-short pulse generation down to the sub-picosecond range with GHz repetition rates, and low noise operation have given VECSELs the status of the most versatile laser technology platform. These features have also triggered an intense development activity, aiming to meet the
demands of a wide range of applications in spectroscopy, life science, laser cooling, laser projection, microscopy, and optical frequency comb generation, to name just a few of the fields where VECSELs are expected to gain even more momentum and trigger new developments.

A number of reviews have been published in recent years to emphasize the role and progress of VECSEL technology. The general concepts have been covered for example in [2, 4, 5], while the fundamentals and initial developments of mode-locked VECSELs were presented in [6]. A more recent review outlining progress in pulse duration, wavelength coverage, repetition rate, and power scaling of ultrafast VECSELs was published by Tilma et al [7]. In our review, we take a different route and focus primarily on recent key technological developments of semiconductor gain mirrors and the breakthroughs in laser operation that they have brought about. Section 2 summarizes the fundamental operation concepts of VECSELs and introduces the latest trends in thermal management and cavity design. Section 3 is a discussion of the main approaches to wavelength tailoring and gain mirror fabrication, covering monolithic and wafer bonding alternatives. Section 4 is an attempt to provide the first comprehensive summary of the most representative characterization methods that are used in developing and assessing the material quality and operation of VECSELs. Recent breakthroughs in emission properties are covered in section 5, and recent developments of mode-locked VECSELs are covered in section 6. Finally, an outline of VECSEL applications is given in section 7, emphasizing the unique properties they render possible.

2. Fundamental concepts

2.1. Operation principles

The distinctive features of VECSELs can be easily understood by analysing the architectures of the main types of semiconductor lasers. In edge-emitting laser diodes (LDs), the lasing action takes place via reflections between the two cleaved surfaces of a semiconductor waveguide that provides the gain. The thickness of the waveguide is typically in the range of hundreds of nanometres, whereas the width of the emitter can vary from a few microns (for single-transversal-mode laser diodes) to hundreds of microns (for high power multi-mode laser diodes). However, the relatively small gain volume and high optical intensity at the facets (responsible for catastrophic optical damage) limit the power scalability, particularly in single transverse-mode operation. Higher output powers in the range of tens of watts can be obtained with multi-mode diodes that have relatively wide emitter sections and therefore highly asymmetric output beams with poor $M^2$ values [8, 9]. This beam quality issue can be somewhat solved by integrating a single-mode laser diode and an adiabatically tapered amplifier section. Power levels as high as 10 W for single transverse-mode output have been reported for such compact amplified systems [10], though at the expense of larger beam asymmetry.

Vertical cavity surface-emitting lasers (VCSELs) avoid the problem of asymmetric output beams by emitting in a surface-normal direction through a symmetrical aperture on top of the device [11]. VCSELs contain a highly reflective bottom distributed Bragg reflector (DBR) and a partially reflective top DBR, so that the gain material is located in a micro-cavity between the two DBRs. The optical thickness of the micro-cavity is typically in the order of the emission wavelength with some hundreds of nanometres, while the diameter of the emission aperture ranges from a few $\mu$m in single-mode VCSELs to over 100 $\mu$m in multi-mode devices. The single-mode VCSELs typically exhibit very low threshold currents due to their small mode volume and low mirror losses, but also relatively low output power of a few mW. Nevertheless, their low power consumption and tens of GHz modulation capability have made single-mode VCSELs particularly suitable for high-speed telecom and datacom applications. Higher output power can be obtained by increasing the aperture area, but again at the expense of degraded beam quality. In multi-mode operation, large arrays of multi-emitter VCSELs can produce several kW of output power [12, 13] and are used in infrared illumination and industrial applications, for example.

The architecture of the laser resonator in VECSELs was borrowed from thin-disk solid-state lasers [14] and is typically formed between a thin semiconductor gain mirror and an external-cavity mirror; hence the alternative name of semiconductor disk lasers (SDLs). Conceptually, the idea of an optically-pumped semiconductor laser with a vertical geometry was suggested as early as 1966 by Basov et al in a paper
Figure 2. Example of a band-gap profile of a VECSEL mirror employing an RPG design with monolithic DBR and strain compensation layers. The picture on the right represents a scanning electron microscope (SEM) image for a mirror with GaAs pumping region and AlGaAs window layer. For clarity, only a few DBR layers are shown.

describing lasers with radiating mirrors [15]. However, it was not until the early 1990s that the concept was acknowledged and the first working devices were reported [16, 17]. It took several more years before the benefits of this laser architecture could be fully exploited and a surge of new developments was triggered, with the demonstration of the first high power, room temperature operated VECSEL [1, 18].

Structurally, the VECSEL gain chip comprises a highly reflective mirror and a semiconductor gain region. The gain region usually includes several quantum-well (QW) or quantum-dot (QD) layers that are separated by spacer or barrier layers. The typical mirror structure is a semiconductor DBR, although metallic, dielectric, or hybrid mirrors [19–21] have also been used in some specific cases. In general, the single-pass gain of a vertical cavity QW device is quite small due to the short interaction length between the laser mode and the gain material. The small gain is usually compensated by using a large number of QWs and by maximizing their coupling with the laser mode. The latter is achieved by placing the QWs periodically at the antinodes of the optical standing wave that is formed in the semiconductor DBR and the semiconductor top surface. Such resonant periodic gain (RPG) architecture has historically been employed in light-emitting devices with vertical geometry [22, 23] and is schematically shown in figure 2.

Depending on the design constraints, such as strain and pump absorption, one or two QWs are placed at the antinodes of the optical field [24]. If the QWs introduce large strains into the structure, strain compensation layers are usually placed at the nodes of the optical field. These strain compensating layers can also act as barriers, confining the pump-generated carriers to a specific QW (or group of QWs); the effect of the strain compensation strategy has been described in [25], for example. Finally, the gain mirror structure is covered with a thin window layer of high band-gap material to prevent carrier recombination at the surface. The total thickness of such a gain mirror structure is usually less than 10 µm. For optimal performance, the QW peak gain wavelength, the centre of the DBR stopband, and the micro-cavity resonance (in case of resonant gain mirror design) should all coincide at operational conditions. This also means that the optimal performance is obtained at a specific combination of pump power and VECSEL temperature. It should also be noted that the micro-cavity resonance narrows the gain bandwidth and introduces significant group delay dispersion. This can be detrimental for mode locking [26, 27], wavelength tunability [28] and single-frequency operation [29]. Consequently, the VECSEL gain structures are sometimes designed to be anti-resonant at the emission wavelength; such an approach inevitably reduces the gain and makes the laser operation less tolerant to cavity losses [26, 27, 30].

VECSELs are usually optically pumped with low-brightness multi-mode laser diodes, although electrical pumping can also be employed [31, 32]. However, the progress in electrically pumped VECSELs has been lagging well behind optical pumping schemes owing to the requirement for high-quality doped DBRs and the difficulties in injecting carriers uniformly over a large area. These limitations are avoided in optically pumped VECSELs, which permit the use of undoped materials and uniform carrier excitation over a large area. Moreover, VECSELs can absorb pump radiation in a broad wavelength range. This is in contrast to the operation of solid-state lasers, where variations in the pump wavelength would typically impair the operation. Consequently, VECSELs can utilize cheaper pump diodes due to the larger wavelength tolerance that is linked to the broad absorption range in semiconductors. VECSELs also avoid the catastrophic optical damage of high power edge-emitting lasers due to the large emitting area, even though the intracavity power in VECSELs can routinely reach several hundreds of watts.

Another important benefit of VECSELs, which is borrowed from solid-state lasers, is the possibility of using intracavity elements [2] such as nonlinear frequency conversion crystals that enable efficient frequency conversion and extension of the wavelength coverage down to the UV spectral region [33] or the generation of terahertz radiation [34]. Moreover, the external cavity architecture permits the use of semiconductor saturable absorber mirrors (SESAMs) that have been used in demonstrating various mode-locked VECSELs [6, 7]. Altogether, these properties open up a range of new applications that foster the intense development of VECSEL technology in power scaling, wavelength tailoring, and ultra-short pulse generation.
spreaders can also be reused, at least in a research environment, and simple to implement in laboratory conditions. The heat intracavity heat spreader approach has proved to be very quick and the semiconductor sample is cooled down after bonding. Fortunately there are several alternative bonding methods, such as InAu [45], Au–Au [46, 47] and sol–gel [48] bonding, which provide a combination of high reliability and relatively low bonding temperatures. It should also be mentioned that for high volume VECSEL chip production (whether flip-chip or intracavity heat spreader), one can also use direct optical contacting of the gain mirror.

Figure 3. Generic description of the OP-VECSEL concept emphasizing the common strategies used for heat extraction. Left: gain chip with intra-cavity heat spreader. Right: flip-chip device with substrate removed.

2.2. Thermal management

The early VECSEL experiments required very low temperatures for high power operation, which made the devices impractical for general use. To a large extent, this was caused by the lack of adequate heat dissipation techniques to manage the pump-induced heating (only a portion of the pump energy is converted into useful photons, while a significant part of it is transferred to phonons via non-radiative recombination and the quantum defect related thermalization). These effects can lead to excessive heating with increasing pump power, which then reduces the emission efficiency even further via increased non-radiative recombination and carrier leakage. The VECSEL heating also red-shifts the emission wavelength, which can lead to a mismatch between the emission wavelength and the resonant periodic gain structure [35, 36]. Consequently, the output power of a VECSEL exhibits a thermal roll-over with increased pump power. As a general strategy for achieving high power operation, one should seek to maximize the heat transfer away from the gain region and, at the same time, minimize the heat generation by reducing the quantum-defect and non-radiative processes [37, 38].

There are two commonly used methods for avoiding thermal issues in VECSELS. Both rely on placing a highly conductive heat spreader element between the gain mirror and the heat sink. The so-called ‘intracavity heat spreader’ method (shown on the left in figure 3) is technically simpler to implement and involves placing a transparent heat spreader element onto the gain mirror [39]. Diamond is by far the best material for this purpose [40], owing to its high thermal conductance (up to ~2000 W m\(^{-1}\) · K\(^{-1}\)) and wide transmission window, although optical quality diamond heat spreaders are significantly more expensive than polycrystalline industrial diamonds. Other suitable materials include sapphire (crystalline Al\(_2\)O\(_3\)) [39] and silicon carbide (SiC) [41]. The transparent heat spreader and the semiconductor sample are commonly mounted using capillary bonding [42] with deionized water or another suitable liquid. In our work, the intracavity heat spreader approach has proved to be very quick and simple to implement in laboratory conditions. The heat spreaders can also be reused, at least in a research environment, which overcomes their high initial cost. However, the intrinsic disadvantage of the intracavity heat spreader is that it introduces a birefringent loss element into the cavity and can act as an etalon. This etalon effect modulates the optical spectrum, thus affecting the mode-locking mechanism and making continuous wavelength tuning difficult. The etalon effect can be suppressed by using a wedged heat spreader with an anti-reflective (AR) coating [43]; but the wedge usually increases the intracavity losses and therefore decreases the output power.

Another option for efficient heat dissipation is schematically shown in figure 3 (right) and was described in the seminal paper of Kuznetsov [18] demonstrating the first room-temperature VECSEL. This process is often referred to as the ‘flip-chip’ process or the ‘thin-device’ process. It involves growing the Bragg reflector and the gain structure in a reverse order and bonding the component upside down onto a heat spreader element, after which the substrate is removed by wet etching. The heat spreader is usually a low-cost polycrystalline diamond, since there is no need for an optical-grade quality diamond as with the intracavity heat spreader approach. For GaAs substrate removal, one can use InGaP or Al(Ga)As etch stop layers and NH\(_4\)OH:H\(_2\)O\(_2\) based etchants. For InP-based structures, the etchants are often based on HCl [44], which may limit or hinder the use of indium solder for flip-chip bonding. For GaSb-based compounds, good etchant–etch stop combinations are less developed, but successful flip-chip VECSELs based on this material system have been reported [45].
and the heat spreader on a wafer scale [49, 50]. In any case, it is crucial to prevent formation voids at the bonding interface, because they will likely result in physical damage to the gain mirror under pumping. In fact, the bonding process is commonly performed in a vacuum to remove air bubbles and voids from the bonding interface. The presence of voids can be monitored prior to substrate removal using a scanning acoustic microscope (SAM), for example.

To date, the intracavity diamond and flip-chip heat management strategies have both successfully achieved over 10 W of output power from standard InGaAs/GaAs gain structures. The highest output powers have been achieved with flip-chip gain mirrors of around 1 µm with several tens of watts via intracavity frequency-doubling and >100 watts at the fundamental frequency [51, 52]. This level of output power should also be possible with the intracavity diamond approach with similar gain structures. Moreover, by increasing the DBR thickness (due to a longer operation wavelength or lower index contrast of the materials) or decreasing the thermal conductance of the DBR, it may be more advantageous to use the intracavity heat spreader technique. This is particularly true for InP- and GaSb-based VECSELs. A more detailed view of the heat flow in VECSEL assemblies can be found in [53–57], which provide finite element simulations for various configurations and VECSEL structures.

In addition to minimizing the thermal resistance, one should also minimize the heat generation in the gain mirror that arises from non-radiative processes and the quantum defect. The non-radiative processes can be minimized using high crystalline quality semiconductor structures (i.e. a reduced number of defects/non-radiative centres), whereas quantum defect optimization can be undertaken with a proper choice of pump wavelength and barrier material or, in the extreme case, by using direct ‘in-well’ pumping [58, 59]. In the latter case, the spacer layers between the quantum wells are transparent to the pump radiation and the pump wavelength is closely matched to the band-gap of the QWs. In an in-well pumped gain structure, the mirror section should provide high reflection for the unabsorbed pump light and therefore a double-pass for the pump radiation through the gain region. However, due to the short light–matter interaction length, it is difficult to absorb the pump light effectively even in a double-pass configuration; the typical QW is only a few nanometers thick, so the total absorptive path length is rather small in a typical VECSEL gain mirror having 5–15 QWs. To some extent, the pump absorption can be improved by adding more QWs into the structure, but usually a resonant pumping scheme [60] or external pump recirculation optics are required to attain high output powers [61]. In addition, the selection of the pump laser (wavelength) for in-well pumping is more critical (and possibly more expensive) than for spacer pumped lasers, where low-cost 808 nm diodes can be used for pumping gain mirrors covering wavelengths in the 900 nm to 2 µm range.

To summarize, efficient heat removal is instrumental for high power operation of VECSELs. The use of high thermal conductance heat spreader materials, such as diamond, ensures efficient heat extraction from the gain element. The distance from the gain region to the heat spreader can be minimized by optically contacting the heat spreader onto the sample or by flip-chip bonding the component onto a heat spreader or heat sink. The application and the type of gain material will determine which process is more suitable. To maximize output power, one should also optimize heat conduction in the material boundaries and ensure appropriate geometry of the heat sink and cooling elements. Furthermore, heat generation can be minimized by reducing the quantum-defect [37] and by using high crystalline quality epitaxial material that has a low number of defects and high internal quantum efficiency [38].

2.3. Cavity design and power scaling considerations

The VECSEL cavity design depends on the desired laser functionality, such as single-mode operation, narrow spectrum, mechanical stability, pulse repetition rate, etc. The typical design approaches follow from solid-state lasers with external cavities [62] and are schematically presented in figure 4. In general, since the gain mirror is essentially a very thin planar mirror, it can be placed into the laser cavity either as an end mirror or a folding mirror. When the gain chip is used as a folding mirror, the multiple passes through the gain element increase the round-trip gain [63], but also enable control of the intracavity dispersion with the folding angle of the gain element [64]. Moreover, a multi-pass configuration can also be useful in low repetition rate mode-locked lasers [65, 66], where the cavity round-trip time approaches or exceeds the upper state lifetime of the gain material (typically ~1–2 ns).

In the simplest form, the external cavity is formed between the gain mirror and an external output coupler, as shown in figure 4(a). Such a cavity of ~5–30 mm in length can be beneficial for single-frequency operation with extremely narrow spectral widths [67]. The V-shaped cavity shown in figure 4(b) is formed between the gain mirror, a curved folding mirror, and a planar output coupler. An advantage of the V-shaped cavity is that planar output couplers are often cheaper and more widely available from stock than equivalent curved couplers. In addition, the nonlinear crystal in frequency-doubled VECSELs is often placed at a location near or at the mode waist, while SESAMs in mode-locked VECSELs typically require tight focusing of the intracavity beam. These requirements are easier to fulfill in a V-shaped or Z-shaped cavity than in an I-shaped cavity, as illustrated in figures 4(b) and (c).

The design of the cavity and the pump optics is also inherently related to power scaling, provided that the thermal management is efficient enough to provide 1D heat flow within the gain element [68, 69]. First, the external cavity design enables modification of the properties of the transverse laser mode, so that the VECSEL beam quality does not need to be compromised with the increased pump area and the consequent increase in the output power. Second, power scaling can be obtained by introducing multiple gain elements (figure 4(d)) into the same cavity [69–71]. In effect, such an approach divides the pump-induced heat load between multiple gain elements, though the increased number of gain elements can also introduce higher intracavity losses that limit the power scalability [50, 72, 73]. A third power scaling approach...
Topical Review

utilizes double-side cooling, where the gain element is used as a transmissive element, as illustrated in figure 4(e). The benefits of such ‘DBR-free VECSELs’ consisting solely of the gain region have been recently explored in [74, 75]. Another more exploratory design was demonstrated in [76], where the gain element was contacted onto a prism and total internal reflection was used instead of a DBR. Besides allowing double-side cooling, such gain structures eliminate the need for lattice matching between the gain section and the DBR section, which may significantly simplify epitaxial fabrication. This could be particularly useful when working with InP-based materials or directly emitting red VECSELs, where it is difficult to find DBR materials with sufficient index contrast.

In addition to various external cavity configurations, VECSELs have also been demonstrated with semi-monolithic cavities with a plane–plane design (see figure 4(f)) stabilized by a thermal lens [77]. Such a laser may be more limited in power and brightness, but it does possess an extremely rugged design without need for active component alignment. Furthermore, the semi-monolithic cavity can be processed to have curved surfaces with mirror structures, thus avoiding the need for cavity stabilization by a thermal lens [78]. Finally, VECSELs can also employ ring cavities, as demonstrated in [79]. In addition, for the sake of generality, we also note that VECSELs have been demonstrated with coherently coupled arrays [80] and beam combining [81].

3. Gain mirror technology

3.1. Wavelength coverage; material systems for gain region

To date, VECSELs emitting at their fundamental wavelengths have been demonstrated from 393 nm [82] to beyond 5 µm [83]. This range of wavelengths can be reached by direct emission with the various compound semiconductor materials listed in table 1. In addition, depending on the wavelength and the active region design, VECSELs have demonstrated tuning ranges as large as 43 nm at 1 µm [28], 50 nm at 1.03 µm [84], 69 nm at 1.18 µm [84], 156 nm at 1.96 µm [85], and 900 nm at 5 µm [86]. Generally, wavelength tunability can be enhanced using different composition QWs [85], special RPG designs [28], or inhomogeneously broadened QD-based gain regions [84].

The shortest fundamental emission (360–540nm) can be reached with InGaN/GaN compounds. In principle, this material system could make use of monolithic AlGaN/GaN mirrors, but the large lattice mismatch between AlN and GaN leads to highly strained structures that are susceptible to...
cracks and dislocations [87, 88]. Thus, the GaN-based DBRs are usually fabricated using GaN/GaN layers, as demonstrated at 420 nm [89, 90]. InGaAs-based gain chips have also been demonstrated with dielectric mirrors using a microchip design at 413 nm [91] and with external cavities at 392 nm [82, 92] and 440–445 nm [93]. However, the overall concepts of such VECSELs and their feasibility for practical applications remain questionable, owing to the early stage of development for GaN-based vertical structures. Moreover, although one could use blue laser diodes at 405 nm for optical pumping, their power levels are still far from what is available for 808 nm diodes.

Moving up in wavelength, there is a green-yellow wavelength gap that cannot be reached using directly emitting semiconductor materials. In particular, while green edge-emitting lasers have progressed significantly, the development of yellow-emitting gain structures has remained a challenge. Instead, emission at this wavelength window has been achieved via intracavity frequency doubling of infrared VECSELs emitting at ~1150–1200 nm.

The gain structures for 620–700 nm red emission are based on a GaAs material system using (Al)GaInP QWs [61] or InP QDs [94]. The longer wavelengths in the 700–800 nm band can be reached using GaAsP and AlGaInAs QWs [95] (although, to our knowledge they are not yet used successfully as VECSEL gain mirrors) or InP QDs [96]. The 800–920 nm wavelength range can be reached by using GaAs [41, 97], AlGaInAs [98] and InGaAsP [99] QWs. However, when integrated monolithically, these gain regions need to resort to AlGaAs/AlAs mirrors, which require a relatively high number of layer pairs due to the low index contrast.

VECS ELs emitting in the wavelength range 920–1100 nm benefit from the most mature gain mirror technology, i.e. InGaAs/GaAs QWs and AlAs/GaAs DBRs. The maturity of this material system is reflected in many of the leading results in terms of output power, spectral features, and ultrafast operation. However, generating emission at wavelengths above 1100 nm is challenging due to the increased strain in InGaAs QWs with increasing In composition. While a certain amount of compressive strain per QW is favourable for increasing the differential gain [100, 101], VECSELs require a relatively large amount of QWs (typically 10 or more) so that the accumulated strain from individual QWs can lead to the formation of misfit dislocations, which reduces their efficiency and lifetime. The net strain arising from the use of multiple QWs can be reduced by strain compensation, i.e. employing layers which have a strain opposite to the one arising from the desired structure [102]. More precisely, in this wavelength range the compressive strain associated with InGaAs QWs is compensated by tensile GaAsP layers that are typically placed at the nodes of the optical field of the RPG mirror (see figure 2). A comparative study revealing the effect and optimization procedure for strain compensation of 1120 nm gain mirrors has been described in [25]. Such advanced strain compensation has also led to output powers as high as 50 W for a VECSEL emitting at 1180 nm [103]. However, we should note that while the strain compensation can to a certain extent reduce defects related to misfit dislocations, the incorporation

| Wavelength range | Gain region | DBR | Pump | Main challenges |
|------------------|-------------|-----|------|----------------|
| 360 nm–540 nm    | InGaAs/GaAs QWs | AlGaAs/AlAs | Dye lasers | Not diode-pumped. DBR highly strained. Low optical quality. |
| 630 nm–700 nm    | AlInP/GaAs QDs | AlGaAs/AlAs | Blue/red LDs | Poor carrier confinement for wavelengths below 670 nm. |
| 700 nm–800 nm    | GaAs/GaAs QDs | AlGaAs/AlAs | Red LDs | Low reflectivity of DBRs, high strain. |
| 800 nm–920 nm    | AlInP/GaAs QDs | AlGaAs/AlAs | Red LDs | Low reflectivity of DBRs, high strain. |
| 920 nm–1200 nm   | GaInAs/GaAs QWs | AlAs/GaAs | 808 nm LDs | Short wavelengths: poor carrier confinement. |
| 1000 nm–1300 nm  | InAs/GaAs QDs | AlAs/GaAs | 808 nm LDs | Low modal gain, lower power. |
| 1150 nm–1550 nm  | InGaAs/GaAs QWs | AlAs/GaAs | 808 nm LDs | Nitrogen related point defects. |
| 1250 nm–2100 nm  | InGaAs/GaAs QWs | AlAs/GaAs | 980 nm LDs | Process complexity, poor thermal conduction of quaternary AlGaNAs. |
| 1.9 µm–3 µm      | GaInAsSb/GaSb QWs | AlAsSb/GaSb | 980/1550 nm LDs | Auger recombination. Poor thermal conduction of DBR materials. |
| 3.3 µm–6.5 µm    | PbSe or PbTe QWs | PbEuTe/BaF2 | 1550 nm LDs | Fiber lasers. |

Table 1. Summary of major semiconductor material systems used for VECSEL gain mirrors (SHG = second harmonic generation, LD = laser diode).
and makes possible emission wavelengths added N lengthens the emission wavelength of InGaAs QWs content, i.e. typically less than 2%, into the InGaAs QWs. The in long-wavelength InGaAs/GaAs QWs is to alloy a small N such as As antisites, or increased surface roughness. [104], which in turn leads to the incorporation of point defects, of higher In content also requires lower growth temperatures [104], which in turn leads to the incorporation of point defects, such as As antisites, or increased surface roughness.

Another approach for reducing the high compressive strain in long-wavelength InGaAs/GaAs QWs is to alloy a small N content, i.e. typically less than 2%, into the InGaAs QWs. The added N lengthens the emission wavelength of InGaAs QWs and makes possible emission wavelengths > 1.2 μm without introducing excessive amounts of strain into the structure. These so-called dilute nitrides alloys have emerged as very promising candidates for generating emissions above 1100 nm [105]. This material system has been used to demonstrate a VECSEL with 11 W of output power at 1180 nm [106] and to cover emission all the way to the 1.3–1.55 μm range [107, 108]. However, incorporation of N is generally associated with the formation of point defects requiring careful optimization of the growth parameters and extensive knowledge concerning RF-plasma assisted molecular beam epitaxy [109]. Alternatively, one can use InAs/GaAs QDs or GaAsSb/GaAs QWs to extend the wavelength range of VECSEL emission beyond 1100 nm. Yet, both of these approaches introduce other limitations. InAs QDs generally suffer from low modal gain, though relatively high output powers have been demonstrated from these structures, i.e. >8 W at 1.04 μm [110], >7 W at 1.18 μm [111] and >4.5 W at 1.25 μm [112]. On the other hand, GaInSb suffers from low confinement of carriers (holes) [113], though this issue has recently been mitigated by employing type-II GaInAs/GaAsSb QWs for emission at 1.2 μm [114].

Typically, VECSELs emitting at the telecom wavelengths of 1.25–1.6 μm are realized using InP-based AlGaInAs QWs [115]. The drawback of this material system is the lack of high index contrast for lattice-matched InP-based DBR layers that can be monolithically integrated with the gain structure. Consequently, the recent development of InP-based VECSELs has utilized metamorphic growth with hybrid mirror technology [116], or wafer bonding techniques which enable the integration of InP-based gain structures with GaAs-based DBRs [117, 118]. These approaches will be described in more detail in the next section. Nevertheless, it should be noted that, while InP-based AlGaInAs active regions suffer from poor thermal conductance, they can make use of 980 nm pump lasers and therefore have lower quantum defects than 808 nm pumped GaInNAs VECSELs.

VECSELs emitting in the 1.9–3 μm range are based on GaSb/GaInAsSb material systems. These gain mirrors benefit from utilization of AlAsSb/GaSb DBRs that offer an outstanding index contrast, but they possess poor thermal conductance. At wavelengths beyond 3 μm, VECSELs have been fabricated using PbSe or PbTe active layers grown on BaF₂ [83] or Si [119] substrates; the wavelength coverage of these gain structures extends from 2.65 μm to 6.5 μm [120–122]. However, they usually need low operating temperatures for lasing, though lasing at temperatures as high as 52 °C has been demonstrated [123]. The DBRs for this wavelength range benefit from the very high refractive index of PbEuTe and the very low refractive indexes of BaF₂ or EuTe. Consequently, a high reflectivity is obtained with just two or three layer pairs.

3.2. Approaches for the integration of gain media and reflectors

The main approaches for the integration of the gain and reflector regions are presented schematically in figure 5. Due to the relatively low round-trip gain of only a few percent, the intracavity losses of VECSELs should be kept to a minimum and the reflectivity of the DBR should approach unity (in practice, values are around 99.8%). Ideally, the DBR materials and the gain region materials will have similar lattice constants that enable monolithic fabrication in one epitaxial step. The DBR should comprise layers of quarter-wavelength thickness, with relatively high refractive index contrast in order to minimize the overall thickness and, therefore, ensure effective heat transport. Unfortunately, not all of these features can be met for all material systems that are relevant for VECSELs. Thus, alternative techniques such as wafer bonding or hybrid DBRs have also been employed.

The main features of the most common monolithically grown DBR materials are summarized in table 2. A favourable material combination for the DBR section is GaAs/AlAs, because it provides an exceptionally high thermal conductivity and a high refractive index contrast. Unfortunately, the high performance of GaAs/AlAs DBRs is not available outside the 900–1200 nm wavelength range; at shorter wavelengths the signal absorption in GaAs becomes an issue, and at longer wavelengths difficulties arise from the lack of gain materials that are lattice-matched to GaAs. In particular, AlGaAs/AlAs DBRs operating below 800 nm [4, 126] and

![Figure 5](image-url). Main approaches for integration of gain and reflector regions. (a) Monolithic (b) hybrid (c) wafer-bonded and (d) DBR-free.
In principle, the thermal conductance of the DBR can be increased by reducing the number of DBR pairs and compensating the consequent reflectivity loss with a highly reflective semiconductor-metal mirrors can also ensure increased reflectivity to residual pump if the hybrid mirror increases when the thickness of the dielectric layer approaches the Bragg mirror thickness of $\lambda/4$. In practice, however, the maximum reflectivity is obtained at a slightly smaller dielectric layer thickness of about 0.22 $\lambda$, because the phase shift that occurs in the final metal layer [138, 139]. This final metal layer can be any highly reflecting metal, but the highest reflectivity above ~600 nm is obtained with Au.

The trade-off between the thickness of the DBR section and the thickness of the dielectric layer is illustrated in figure 6 for GaAs/AlAs–Al$_2$O$_3$–Al and GaAs/AlAs–MgF$_2$–Al$_2$O$_3$ mirrors. The simulated reflectivity data is obtained using the 1.32 $\mu$m flip-chip VECSEL structure described in [131]. Figure 6 also shows the reflectivity data for a similar VECSEL structure that is assumed to operate at a longer wavelength of 1.6 $\mu$m. In both cases, most of the reflectivity benefits are realized with dielectric layers of about 100 nm in thickness. Specifically, a reflectivity $>99.8\%$ can be achieved using 100 nm thick layers of MgF$_2$ and Al$_2$O$_3$ with 10.5 and 15.5 GaAs/AlAs DBR pairs, respectively. Interestingly, such dielectric layers of 100 nm thickness are also sufficiently thin to produce a negligible contribution to the overall thermal resistance of these structures [21]. Finally, as already mentioned, the concept of reducing DBR thickness can be taken to its extreme by omitting the DBR [76] and making the implementation of double-side cooling more beneficial [74].

3.2.1 Use of hybrid mirrors with reduced thickness of DBRs. To date, semiconductor-dielectric-metal VECSEL mirrors have been realized with GaAs/AlAs–Al$_2$O$_3$–Al structures [21, 131, 132]. The benefits of these materials include high adhesion, high mechanical stability and limited diffusion between the layers [133]. But the use of oxide dielectrics also has certain clear drawbacks; namely, they exhibit poor thermal conductivity [116, 134] and poor adhesion to Au [135]. One possible way to circumvent these drawbacks could be to use fluoride dielectrics, due to their higher thermal conductivities [136] and better adhesion to Au [137]. Such progress would be beneficial for semiconductor-dielectric-metal mirrors, because the number of required DBR pairs is mostly determined by the thickness of the dielectric layer and the reflectivity of the metal layer. In particular, the reflectivity of the hybrid mirror increases when the thickness of the dielectric layer approaches the Bragg mirror thickness of $\lambda/4$. In practice, however, the maximum reflectivity is obtained at a slightly smaller dielectric layer thickness of about 0.22 $\lambda$, because of the phase shift that occurs in the final metal layer [138, 139]. This final metal layer can be any highly reflecting metal, but the highest reflectivity above ~600 nm is obtained with Au.

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1 µm has not led to improvement in VECSEL performance. In particular, the highest output power of 106 W has been obtained with a pump-absorbing 22.5 pair GaAs/AlAs DBR [52], while pump-transparent AlGaAs/AlAs DBRs have been shown to possess inferior thermal properties [57]. Moreover, the number of GaAs/AlAs DBR pairs has been found to have a negligible effect on VECSEL output power [21]. In all, these findings indicate that the high performance of thin GaAs/AlAs DBRs at 1 µm has reached a milestone that is difficult to improve further, as also mentioned in [20]. Nevertheless, long-wavelength VECSELs would benefit from thinner DBR structures with less strain and hence a lower number of misfit dislocations [140], but also from reduced growth times and less material use. Moreover, semiconductor-dielectric-metal mirrors could provide benefits for VECSELs emitting at wavelengths <800 nm, where one has to resort to AlGaAs/AlAs DBRs with lower refractive index contrast and higher thermal resistance [141].

3.2.2. Wafer bonding techniques for long wavelength infrared gain mirrors. Simply put, wafer bonding enables the integration of materials that cannot be grown monolithically without introducing an excessive number of defects due to mismatched lattice constants and coefficients of thermal expansion [142]. This technique has been applied earlier in the development of infrared VCSELs [143] and recently also to multi-junction solar cells [144]. It also appears to be the optimal solution for combining GaAs-based DBRs with InP- (or GaSb)-based active regions [145], since the results obtained from monolithically grown metamorphic structures have been modest in comparison [146–148]. The possibility of integrating GaAs-based DBRs onto InP- and GaSb-based active regions also brings more significance to the use of semiconductor-(dielectric)-metal compound mirrors, for several reasons. First, GaAs/AlAs DBRs are transparent to the 980 nm radiation that is usually used for pumping long-wavelength VECSELs. Thus, the benefits of residual pump reflection in semiconductor-(dielectric)-metal compound mirrors can be exploited without resorting to thermally inferior AlGaAs/AlAs DBRs. Second, increasing the pump absorption in the active region via recirculating the residual pump absorption has already been shown to enhance VECSEL performance (when using pump-transparent DBRs) [149, 150]. Third, the benefits of reducing the number of DBR layers by using metal reflectors become more obvious with increasing wavelength, because the thickness of the λ/4 DBR layers increases with the emission wavelength [20, 21, 37].

The most common wafer bonding methods are schematically summarized in figure 7, as adapted from [151–155]. The first category contains direct bonding methods that are divided into fusion, hydrophobic, hydrophilic and ultra-high vacuum bonding. By definition, these bonding processes are performed without resorting to intermediate layers. In fusion bonding, the distinctive features are high pressures and temperatures that promote material diffusion at the bonding interface. In hydrophobic and hydrophilic bonding, the wafer surfaces are treated to become either repellent or attractive to water, respectively. In practice, hydrophobic surfaces are often terminated with hydrogen or fluorine and hydrophilic surfaces with reactive oxides. In both cases, the wafers are bonded via chemical reactions between the surfaces. Finally, the wafer bonding can also be carried out with clean surfaces that are free of adsorbents, but such conditions can only be realized in an ultra-high vacuum (UHV). All these direct bonding methods have been applied to III–V semiconductors [156–160], although hydrophilic bonding of III–V semiconductors can be problematic, since their surfaces are prone to roughening upon wet chemical cleaning and the III–V oxides tend to be unstable [161, 162].

The bonding methods via intermediate layers are categorized based on the materials that are used for the bonding. Variations of these processes have also been used in several VECSEL developments, such as flip-chip bonding and
photonics assembly, as summarized in table 3. In particular, metal layers are often used for integrating flip-chip VECSELs onto their sub-mounts [46], though metal layers are obviously not suitable for integrating DBRs with VECSEL active regions due to their opaqueness. Moreover, glass frit and adhesive bonding are usually associated with relatively thick bonding layers, which can adversely affect the operation of the resonant periodic gain structures [5]. Therefore, for wafer-bonded VECSELs, this leaves the use of thin (~nm) dielectric layers and monolayers as suitable options for fabricating the gain mirrors. These approaches also have certain distinctive benefits when compared to the direct wafer bonding methods. Namely, they avoid the requirement for an ultra-high vacuum and the problems related to III–V oxides, but also enable relatively low processing temperatures and therefore low residual stresses in the assembly [159, 163–165]. In addition, the use of monolayers and/or hydrophilic dielectric layers can relax the requirements for surface smoothness of the wafers [166, 167]. Finally, we note that III–V wafer bonding can also be accomplished using sulphide-treated surfaces [168–170], but these methods are not covered here.

### 3.2.2.1. Wafer bonding of GaAs-based DBRs with VECSEL active regions

The first wafer-bonded VECSEL was demonstrated with a GaAs-based DBR and an InP-based active region using wafer fusion [118], but a similar procedure had been demonstrated as early as the 1990s for optically pumped VCSELs [143, 181]. This bonding process uses compressive pressures of 3 kPa–3 MPa and temperatures over 500 °C, which induce bonding via slight plastic deformation and atomic diffusion [145, 156]. For this reason, the process has also been termed ‘bonding by atomic arrangement’ [182, 183]. It also has a resemblance to hydrophobic bonding, because the surface oxides are removed prior to bonding and the bonding is carried out in oxygen-reduced atmospheres, such as hydrogen or nitrogen. Such wafer-fused VECSELs have exhibited output powers of 33 W at 1.28 µm [184], 5 W at 1.48 µm [185] and 4.7 W at 1.58 µm [186].

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### Table 3. Various bonding methods and their utilization in VECSELs.

| Bonding method                        | Materials                      | Application                      | Reference         |
|---------------------------------------|---------------------------------|----------------------------------|-------------------|
| Wafer fusion or hydrophobic bonding   | GaAs and InP                   | VECSELs @ 1250–1700 nm           | [117, 118, 145]   |
| Hydrophilic bonding with intermediate | GaAs and InP                   | VECSELs @ 1250–1700 nm           | [131, 132, 171]   |
| dielectric layers                     |                                 |                                  |                   |
| Hydrophobic bonding with intermediate | GaAs and InP                   | VECSELs @ 1250–1700 nm           | [131, 132, 171]   |
| monolayer                             |                                 |                                  |                   |
| Au–Au thermocompression bonding       | III–V semiconductors            | Flip chip bonding of VECSELs     | [46, 47, 172]     |
|                                       | Cu-diamond                     |                                  |                   |
|                                       | CuW submounts                  |                                  |                   |
| Eutectic AuSn bonding                 | III–V semiconductors            | Flip chip bonding of VECSELs     | [173–175]         |
|                                       | Cu-diamond                     |                                  |                   |
|                                       | CuW submounts                  |                                  |                   |
| Indium soldering                      | III–V semiconductors            | Flip chip bonding of VECSELs     | [176–178]         |
|                                       | CVD diamond submounts          |                                  |                   |
| Adhesive bonding                      | Optical components              | Photonics assembly               | [48, 179, 180]    |
|                                       | III–V semiconductors            | Flip-chip bonding of VECSELs     |                   |
|                                       | CVD diamond submounts          |                                  |                   |

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*Figure 7. A diagram of common wafer bonding methods.*
Wafer-bonded VECSELs with InP-based active regions and GaAs-based DBRs have also been demonstrated using intermediate Si-based layers and monolayers [171]. A schematic of the wafer bonding process with intermediate SiO2 layers is shown in figure 8. The nm-thick SiO2 layers are first activated using ammonia, which places hydrophilic OH and NH2 groups onto the wafer surfaces [187–189]. The surfaces are often also covered with a few monolayers of polar H2O molecules that provide room temperature adhesion via van der Waals forces. Covalent bonding is obtained when the wafers are contacted and the water is removed from the bonding interface, either through diffusion or reactions with the surrounding material. In essence, such a bonding process could also be categorized into direct hydrophilic wafer bonding using intermediate SiO2 layers. A cross-cut image of this type of wafer-bonded VECSEL is also shown in figure 8.

On the other hand, the wafer-bonded VECSELs using self-assembling monolayers utilize a thin SiO2 layer and a monolayer of (3-mercaptopropyl)trimethoxysilane (MPTMS) [171]. The bonding process is started by activating the SiO2-covered GaAs-based DBR with ammonia as before, after which the DBR is placed in a low-vacuum chamber with an open container of MPTMS [190]. As the MPTMS evaporates from the container, the hydrophilic MPTMS molecules react with the hydrophilic NH2 and OH groups on the DBR surface. Consequently, the DBR surface becomes covered with hydrophobic SH groups, which can be used for bonding onto a hydrophobic InP surface [165]. Next, the InP surface is rendered hydrophobic by dipping it into 0.5% HF [191]. The wafer bonding then takes place (possibly) via the chemical reaction given in [192]. Similar to hydrophilic bonding with SiO2 layers, this bonding process could be categorized into direct hydrophobic bonding between a thiol-terminated GaAs surface and a hydrogen (and fluorine) terminated InP surface.

In general, it is not straightforward to differentiate between direct bonding and intermediate layer bonding when the thickness of the bonding interface is in the range of a few nm. In particular, while direct hydrophobic wafer bonding can result in a bonding interface free of intermediate structures, as shown in [193], it can also be associated with an intermediate amorphous layer a few nm in thickness [194]. On the other hand, direct hydrophilic wafer bonding of silicon wafers usually comes with an intermediate oxide layer with a thickness of a few nm [164]. Therefore, the use of SiO2 a few nm thick and/or monolayers for III–V wafer bonding could be considered as direct bonding, although in the strictest sense they utilize intermediate layers for the bonding. As for their performance, wafer-bonded VECSELs with intermediate layers are considerably less studied than wafer-fused VECSELs. However, the reported output powers of 3–4 W at 1.32 µm [131, 171] correspond to the performance of similar wafer-fused structures [47]. Moreover, while being far from a definite comparison, this observation of similar performance is strengthened by the thermal simulations of wafer-bonded VECSELs [56]. These simulations indicate that an intermediate layer a few nm thick and with a thermal conductivity of 1 W m−1 K−1 introduces close to a negligible increase in the overall thermal resistance. Such a value also corresponds to the expected thermal conductivity of the intermediate bonding layers [195], so the presence of a very thin intermediate bonding layer is not expected to affect the performance of optically pumped wafer-bonded VECSELs.

4. Overview of characterization techniques

The increased popularity of VECSEL technology has triggered the deployment of specific characterization techniques. In this section we review the most common techniques used in the
development of VECSELs. These techniques are generically divided into two categories. Section 4.1 covers the characterization of VECSEL gain elements, while section 4.2 covers the characterization of VECSELs in lasing operation. The purpose of this section is to discuss in detail the most specific methods, while other techniques are summarized in tables 4 and 5.

4.1. Characterization of VECSEL gain elements

4.1.1. Structure quality. The crystalline quality of VECSEL structures can be evaluated using x-ray diffraction (XRD), which provides information about the composition and the strain of multilayer heterostructures [196, 197]. XRD measurements can also provide information on wafer bending, which occurs due to net accumulation of strain in the DBR and the active region [25, 198]. On the other hand, photoluminescence (PL) measurement is the most facile technique used in the process of optimizing the optical quality and emission features of the active region. As a subset of PL technique, VECSEL development benefits from wafer-level photoluminescence mapping, where the wafer is illuminated optically and the corresponding PL signal is collected with an IR camera [25, 127]. The measurement provides information on defect-related dark spots and dark lines in the structure and is particularly useful when developing strain compensated gain mirrors. Namely, PL mapping reveals dark lines that are formed due to strain-induced misfit dislocations when the critical layer thickness is exceeded [199], as illustrated in figure 9.

4.1.2. Optical properties. For the optical design, the correlation of PL and reflectivity measurements plays an important role. This is particularly true for resonant gain mirrors that require an optimized detuning between resonance and photoluminescence peak wavelengths [36, 149]. The detuning should eventually be zero at the targeted operation temperature and pump power. However, it should be noted that the photoluminescence spectrum measured from a VECSEL wafer is affected by the micro-cavity resonance and may be misleading. Therefore, the PL spectrum of the QWs should be measured from the edge of the sample [35] or by using a separate PL sample that does not contain a DBR or a micro-cavity. For a more detailed optical design optimization, gain measurements under optical pumping provide a clearer picture of

| Level | Feature assessed | Technique | Reference |
|-------|------------------|-----------|-----------|
| Optical | Peak gain wavelength | Photoluminescence | [35] |
| Optical | Gain dynamics | TRPL | [223] |
| Optical | Spectral reflectivity | Reflectivity (mapping) | [35] |
| Optical | Cavity resonance | Reflectivity (mapping) | [35] |
| Optical | Small-signal gain | CW probing | [200, 201, 203] |
| Optical | Radiative and non-radiative losses | Internal quantum efficiency at different pump densities | [35, 38] |
| Optical | Saturation fluence | Pulsed probing | [203] |
| Optical | Gain bandwidth and dispersion | Spectro-temporal measurement | [205, 206] |
| Optical | Nonlinear lensing | Z-scan, pulsed probing | [207–209] |
| Thermal | Temperature | Thermal imaging | [212, 225] |
| Thermal | Spatially resolved photoluminescence | | [213, 214] |
| Thermal | Thermal resistance | Shift in optical spectra | [116, 213, 215] |
| Thermal | Power: thermal-roll over point | [215–217] |
| Thermal | Thermal lensing | Interferometry | [51] |
| Thermal | Ray tracing of the output beam profile | [219, 226] |
| Thermal | Temperature measurement, calculation | [213] |
| Thermal | Average index change measurement, calculation | [227] |
| Thermal | Wavefront sensor measurement | [228, 229] |
gain mirror behaviour and have been used in the development of broadly tunable VECSELs [200, 201]. Recently, the effect of detuning between gain and resonant wavelengths has also been assessed by using an approach in which the resonant wavelength is changed by varying the angle of incidence of the laser beam on the gain chip [202]. This technique offers a dynamic way to assess optimal detuning for specific pump conditions and takes into account the exact thermal effects experienced by the gain chip. A lot of attention has also been given to characterizing the VECSEL properties that are relevant for mode locking. For instance, Mangold et al [203] determined the saturation fluence, induced absorption, small signal gain and the gain bandwidth under varying gain element temperatures and pump intensities. The measured values then enabled building of a numerical model for simulating mode-locked VECSELs [204]. Another study relevant to mode-locking was performed by Barnes et al [205]. The authors measured the spectral narrowing of a VECSEL gain structure at the onset of lasing, which was then used to determine the effective gain bandwidth and group velocity dispersion of the VECSEL gain structure. Similar spectro-temporal measurements were later performed by Head et al in [206] with increased resolution. The authors also applied efficient thermal management to the VECSEL and found that the gain bandwidth was narrower and the gain dispersion higher than observed by Barnes et al. This was seen as an indication that femtosecond pulses are most likely obtained at high VECSEL temperatures, when the intrinsic gain bandwidth is relatively broad.

The possibility of obtaining mode-locking via nonlinear lensing in the VECSEL gain mirror has also received notable attention and triggered the development of specific techniques. Quarterman et al [207] performed a reflection-type Z-scan measurement to determine the magnitude of nonlinear

| Level | Feature assessed | Technique | Reference |
|-------|------------------|-----------|-----------|
| Characterization of lasing features | Beam Transverse beam profile | CCD camera | [316] |
| | Spatial coherence M2 | | [317, 318] |
| | Wavefront sensor | | [228, 229] |
| | Speckle contrast | | [319–321] |
| Optical Intracavity losses | Caird plot | | [233, 234] |
| Lateral lasing | Findlay–Clay method | | [59, 205, 232] |
| Gain dynamics | CCD camera | | [231, 235] |
| | Optical spectrum | | [231, 235, 236] |
| Residual birefringence | Pulsed pumping, streak-camera | | [242] |
| | Loss modulation, fast photodiode | | [206] |
| | Beatnote between laser mode and cross-polarized ASE | | [239] |
| Noise Temporal stability, intracavity SHG | Chopper, fast photodiode, oscilloscope | | [246, 247] |
| Intensity noise | Relative intensity noise (RIN) | | [258, 259] |
| Frequency noise | Frequency discriminating interferometer | | [259–262] |
| Noise in dual-frequency operation | RIN, oscilloscope trace and calculation | | [286, 290, 291, 295] |
| Temporal stability, two-color operation | Streak-camera | | [214, 298, 299] |
| | Interferometry | | [299] |
| | RIN and joint-power spectral density | | [300] |
| Spectral Linewidth | Scanning Fabry–Pérot interferometer | | [268, 283] |
| | Self-homodyne and self-heterodyne measurements | | [29, 270–272, 274, 277, 278] |
| Characterization of THz radiation | Heterodyne measurement, two lasers | | [266, 279, 280] |
| | Calculation from frequency noise | | [227, 259, 281, 282] |
| | Heterodyne measurement | | [296] |
| | Interferometry | | [34, 297, 322] |
| Ultrafast Pulse shape | Autocorrelation, PICASO method | | [323] |
| Timing jitter and amplitude noise | von der Linde method | | [309–312] |
| Coherent artifact | Commercial analyzers | | [311, 313, 314] |
| Gain dynamics | Optical and radio-frequency spectra, time-bandwidth product, FROG | | [307, 308] |
| Dispersion | Pulsed probing | | [315] |
| Pulse evolution | White light interferometry | | [324, 325] |
| | Loss modulation, lasing onset measurements | | [326] |
Kerr lensing in a VECSEL. Interestingly, the measurements revealed that a sufficiently strong nonlinear lens could possibly induce mode-locking. Subsequently, Shaw et al performed additional measurements with an un-pumped antiresonant VECSEL [208], while Quarterman et al characterized the quantity of nonlinear lensing under optical pumping using a resonant femtosecond laser [209]. Again, it was found that measurable nonlinear lensing exists in VECSELs. However, whether this nonlinear lensing is strong enough to cause stable mode-locking is still under consideration [208, 210, 211].

4.1.3. Thermal effects. The effort to scale the output power has triggered interest in determining the gain element temperature under optical pumping. The early reports on temperature measurements were prepared by Jacquemet et al [212] who measured the top surface temperature of a flip-chip VECSEL using an infrared camera operating at wavelengths of 8–12 µm. However, the spatial resolution was only 60 µm and, therefore, suitable only for relatively large pump spots. Later on, Chernikov et al measured the VECSEL temperature by collecting the PL emission from the gain element using a large aperture lens [213, 214]. The main finding was that a uniform pump intensity distribution minimized the peak temperature in the VECSEL gain element, which permitted significantly higher output powers than were obtained with a Gaussian pump intensity distribution.

Measuring the thermal resistance of VECSELs has also received notable interest, because the maximum output power is directly linked to the ability to extract pump-induced heat. One method is to separately measure the shift rate of the longest wavelength component in the optical spectra as a function of pump power and heat sink temperature [116, 213, 215]. Another method was reported by Heinen et al, who showed that the thermal resistance can be determined from the thermal roll-over characteristics [215], because the thermal roll-over temperature of VECSELs is independent of the heat sink temperature [213]. It is noteworthy, however, that this model can lead to an underestimation of thermal resistance due to neglecting intracavity losses [216]. Consequently, Nakdali et al developed an expanded model that also takes into account the effects of intracavity (scattering) losses [217].

Increased VECSEL temperatures can also induce thermal lensing, where the refractive index of the gain element follows the pump-induced temperature distribution. This effect depends on the spatial temperature distribution [218] and can induce a significant amount of beam quality degradation and intracavity losses. The thermal lensing in VECSELs has been estimated, e.g. by using a Mach–Zehnder interferometer [51], measured temperature distribution in the gain element [213], and via ray tracing using the (measured) properties of the output beam [219]. However, VECSELs typically exhibit relatively low thermal lensing and therefore operate reliably over a large range of pump powers [51, 213, 220].

4.2. Characterization of VECSEL lasing features

4.2.1. Intracavity optical losses. The assessment of intracavity losses is relevant for VECSELs, because they are low-gain lasers and minimizing intracavity losses is crucial for efficient operation. The scattering losses associated with the gain mirror arise from its surface roughness [178, 222, 230] and intracavity heat spreaders [73, 100] and scale with the mode size on the gain element [222, 231]. Additional losses result from leakage through the cavity mirrors and intracavity components such as wavelength filters and SHG crystals. These intracavity losses have been evaluated using Findlay–Clay analysis [59, 205, 232] and Caird plots [233, 234]. The former is based on a linear relationship between the threshold pump power and the cavity losses, while the latter is based on a linear relationship between the inverted slope efficiency and the inverted output coupler transmission.

In addition to scattering and diffraction losses, lateral lasing can also induce significant optical losses in VECSELs. The presence of lateral lasing in VECSELs can be observed directly with a CCD camera, but also from the optical spectra, where lateral lasing is observed at longer wavelengths than the actual vertical lasing modes [231, 235, 236]. The initial reports on lateral lasing suggested that the temperature difference between the pumped spot and the surrounding colder area could contribute to this phenomenon. That is, if the relatively cold un-pumped areas are transparent to the spontaneous emission generated in the hot pumped area, lateral lasing could occur with minimal losses at high pump powers. However, Wang et al found that lateral lasing also occurs under pulsed pumping with negligible VECSEL heating [237]. In any case, the threshold for lateral lasing can be increased by using irregularly shaped VECSEL samples that have no parallel surfaces opposing each other, so that less feedback is provided to the spontaneous emission in lateral direction [235].
4.2.2. Residual birefringence. Attention has also been given to the quantification of residual birefringence in the VECSEL gain element. This work is related to the possibility of fabricating spin-injected VECSELs, whose performance was initially found to be limited by residual birefringence [238]. Consequently, an accurate measurement technique for quantifying the residual birefringence was developed by Frougier et al [239], which then led to the demonstration of a spin-injected VECSEL [240, 241]. The VECSEL utilized an intra-cavity perovskite lead lanthanum zirconate titanate (PLZT) electro-optic ceramic element with a controllable birefringence that enabled the offsetting of the residual birefringence of the VECSEL gain element.

4.2.3. Gain dynamics and intensity noise. Several authors have also characterized the dynamics of lasing onset in VECSELs. Such analysis has been performed via modulating intra-cavity power using a mechanical chopper [206] and pulsed pumping [242]. In the former study, a fitting parameter was obtained for determining the gain dispersion, while the latter study was carried out in order to gain insight into the modulation dynamics of frequency-doubled VECSELs that are essential, for example, in projection applications [243–245]. Characterization of (intracavity) frequency-doubled VECSELs has also been performed by Hartke et al with a focus on ‘green noise’ [246, 247], i.e. intensity fluctuations in the frequency-converted output that arise from longitudinal mode coupling via sum-frequency generation in the nonlinear crystal [248, 249] and spatial hole burning in the gain element [250]. In particular, when compared to solid-state lasers, green noise is expected to be minimized in VECSELs due to their fast carrier dynamics that prevent the intensity fluctuations from growing over several cavity round-trips and the resonant periodic gain structures that prevent spatial hole burning [248–251]. This conception was supported by the work of Hartke et al, who recorded the output of a frequency-doubled VECSEL using a fast photodiode (with a chopper in front) and an oscilloscope. The authors found that second harmonic output was stable when the optical spectrum was controlled with a birefringent filter [246] and the longitudinal modes were not spaced too far apart [247]. In fact, the overall noise properties of VECSELs have received considerable attention owing to their low values. Specifically, VECSELs exhibit relaxation-oscillation-free (class-A) operation due to the cavity photon lifetime exceeding the carrier lifetime, even though excess intensity noise can remain at low frequencies due to noise transfer from the pump laser, and at multiples of the cavity FSR due to mode beating [252, 253]. This excess intensity noise has also been used to observe phase locking between the lasing mode and spontaneous emission [254] and slow light effects [255] in VECSELs.

The intensity noise is typically characterized using relative intensity noise (RIN) measurements. RIN can be given as a single root-mean-square value for a given bandwidth, as often used in connection with commercial VECSELs [256], or as a power spectral density [257, 258], as often used in academic literature [259]. On the other hand, the frequency noise can be assessed using a frequency discriminating reference cavity, such as a Fabry–Pérot cavity, whose transmittance slope can be used to transform frequency fluctuations into intensity fluctuations [259–262]. The resulting signal is then detected with an electrical spectrum analyser to obtain the spectral density of noise. In all, the low noise behaviour of VECSELs has received attention especially with regard to single-frequency, dual-frequency and frequency-doubled operations, but also in highly coherent modeless broadband VECSELs encompassing an intracavity acousto-optic frequency shifter [263].

4.2.4. Single-frequency linewidth. The linewidth of single-frequency VECSELs is not limited by fundamental physics but by technical noise, such as mechanical and pump-induced noise, as summarized in [259, 264]. The main frequency noise source at frequencies below 100 kHz is the pump intensity fluctuations that translate into thermal fluctuations in the VECSEL gain element. Consequently, the refractive index of the gain element fluctuates and creates cavity length fluctuations that lead to frequency noise. On the other hand, at frequencies above 100 kHz the main frequency noise source is the pump intensity fluctuations that induce intensity noise into the VECSEL [227, 229], which then transform into frequency noise due to the high Henry factor in semiconductor gain media [265]. Thus, the best performance is obtained by stabilizing both the cavity length and the multi-mode pump intensity fluctuations [264, 266], although single transverse mode pump lasers have also been used in some low power demonstrations [67, 267].

The linewidth of single-frequency VECSELs has been determined by various methods. A scanning Fabry–Pérot interferometer is often used to confirm and monitor single-frequency operation [268], but the resolution of these devices is typically in the MHz range, which is not sufficient for many single-frequency VECSELs. The linewidth can also be characterized using self-homodyne and self-heterodyne measurements [269], but these measurements are somewhat impractical for VECSELs due to the long fiber delay lines that are required [270, 271]. An alternative approach is to use fiber delay lines that are shorter than the coherence length of the laser, and then determine the linewidth via numerical fitting procedures [271–274]. However, the accuracy of this approach leaves room for improvement, as also mentioned in [29]. Nevertheless, such measurements with delay lines shorter than the laser coherence length have been used for determining a lower limit for the coherence length [275–277], which can then provide a rough estimate for the upper limit of the laser linewidth [278]. In practice, the VECSEL linewidth is typically determined using heterodyne measurements with two similar lasers [266, 279, 280] or from the frequency noise spectral density via calculation [227, 259, 281, 282]. In any case, the linewidth increases with the sampling time as more noise sources are taken into account [266, 268, 280, 283].

4.2.5. Dual-frequency noise properties. The class-A operation of VECSELs has also received significant attention in generating simultaneous dual-wavelength operation [284–287], i.e. producing two orthogonal frequency components that are spatially separated at the gain mirror, using an intracavity birefringent plate. This spatial separation should be only
partial (~50%) at the VECSEL gain mirror [288] so that the two frequency components still share correlated fluctuations and can generate high-purity RF beat notes via optical mixing [284]. The intensity noise correlations in these VECSELs were examined by De et al using time-domain oscilloscope data in [289, 290]. In a later work, De et al also investigated the phase noise of the generated RF beat note [291]. These measurements were performed by downshifting the RF beat note by mixing it with a local oscillator, recording the generated signal with a digital oscilloscope, and numerically processing the data. Similar to the single-frequency VECSELs, the measurements revealed that the RF phase noise was dominated by pump-induced thermal fluctuations at frequencies below 500 kHz and by pump-induced carrier fluctuations at frequencies above 500 kHz. It is also noteworthy that, while this work was performed with VECSELs emitting in the 1 μm wavelength range, it was later extended to the telecom wavelengths [286, 292] that are more suitable for microwave photonics [293, 294]. In particular, an investigation of both intensity and phase noise correlations for a telecom VECSEL can be found in [295].

In addition to RF beat note generation, two-wavelength VECSELs have been used to produce THz radiation via intracavity difference-frequency generation (DFG) [34, 296, 297]. The noise analyses of such lasers revealed that at low pump powers the intensities of the two colours undergo periodic anti-correlated fluctuations that arise from gain competition [298–300]. At higher pump powers, however, the absolute intensity fluctuations are reduced to a level of 0–20% and two-colour operation is obtained. Later on, this work was extended to THz generation via intracavity DFG from a two-chip cavity [301, 302]. Moreover, the potential intensity fluctuations in two-wavelength VECSELs could be addressed by using two separate gain chips in the same cavity [303] or two VECSEL gain elements in a coupled T-cavity configuration [304, 305]. In addition, the relatively low conversion efficiency with intracavity THz generation using two-wavelength VECSELs could be increased by using a dual-wavelength mode-locked VECSEL having a beat note in the THz range [306].

4.2.6. Mode-locked operation. The characterization of mode-locked VECSELs has also attracted notable attention. In particular, recent publications on SESAM-free passive mode-locking have raised questions concerning the sufficiency of the characterization involved. At minimum, the optical spectrum, RF spectrum, autocorrelation and a fast oscilloscope trace should be carefully characterized and correlated in order to avoid interpreting a coherent artifact as mode-locking [307, 308]. The noise properties of mode-locked VECSELs have also received attention. The early reports on amplitude noise and pulse timing jitter were published by Wilcox et al in 2006 [309] and Quarterman et al in 2008 [310]. These characterizations were performed using the von der Linde method, where the timing jitter and amplitude noise are extracted from the peaks of several harmonics in the RF spectrum: the 0 harmonic shows only amplitude noise, while the timing jitter increases with the square of the harmonic number [309–312]. Alternatively, the timing jitter has also been measured using commercial analysers [313, 314]. In all, the timing jitter of mode-locked VECSELs and MIXSELs has been found to be in the tens of fs range, which is comparable to mode-locked solid-state lasers [311, 314]. Finally, Barker et al [315] performed in situ measurements of VECSEL gain dynamics under mode-locked operation. The time-resolved reflectivity change of the VECSEL gain element was measured with a fiber probe laser that was phase-locked to the VECSEL cavity, with an adjustable offset to permit asynchronous optical sampling. The VECSEL gain was observed to deplete quickly in the time scale of the intracavity pulse, after which 80% of the gain was recovered during the next several ps.

5. Summary of achievements for CW operation and recent highlights for visible VECSELs

This section provides a summary of selected VECSEL milestones in terms of output power at various spectral bands. The main emphasis is on the yellow–red wavelength range, albeit a more comprehensive coverage is given in table 6. However, it should be noted that the values in table 6 cannot be directly compared, because the achieved results also reflect variations in the cavity design, cooling conditions, maturity levels of gain mirror technology, and the physical limitations and strengths of the available semiconductor materials. In general, the infrared wavelengths are mainly covered via directly emitting gain materials, as discussed in section 3, whereas the visible wavelength range has largely been tackled via intracavity frequency conversion.

The frequency conversion in a VECSEL is typically done by placing the nonlinear crystal within the cavity rather than using external cavity architectures. In this configuration, the nonlinear crystal acts in effect as the output coupler of the laser and provides certain distinct benefits. Namely, intracavity frequency conversion provides higher conversion efficiencies than the external cavity approach, because the intracavity powers are typically two orders of magnitude higher than the output power. Moreover, it enables the recycling of the nonconverted portion of the fundamental radiation, so that only a small fraction of the intracavity power needs to be converted in a cavity round-trip for efficient frequency conversion. In other words, efficient operation requires only that the frequency conversion efficiency reaches levels that are comparable to the optimal output coupling ratio of the given VECSEL, which is usually in the range of a few percent.

However, it should be noted that efficient frequency conversion requires controlling the optical spectrum of the VECSEL so that the fundamental wavelength is matched with the spectral acceptance bandwidth of the nonlinear crystal. This is usually done with an intracavity birefringent filter that narrows the optical spectrum and forces a linear polarization state. In some cases, an additional intracavity etalon is used for further narrowing of the optical spectrum to single-frequency operation. The nonlinear crystals are typically birefringent lithium triborate (LBO), owing to their relatively high nonlinear coefficient and high damage threshold, although periodically-poled lithium tantalate (PPLT)
and critically phase-matched barium borate crystals (BBO) have also been employed. Ideally, the output power in SHG operation is similar to the output power at the fundamental wavelength. For instance, an output power of 20 W of yellow light [327] was reached with a similar pump spot to that was used to generate 23 W of infrared light [328] using the same gain chip. However, additional intracavity losses brought by the wavelength selective elements and the SHG crystals can limit the frequency-converted powers to lower values than those which can be obtained via direct emission [329].

| Wavelength (nm) | Power (W) | Other features | Reference |
|----------------|-----------|----------------|-----------|
| 229            | 0.56      | 4th harmonic, serial intracavity and external cavity SHG, InGaAs/GaAs QWs | [330] |
| 244            | 0.2       | 4th harmonic, serial intracavity and external cavity SHG, InGaAs/GaAs QWs | [33] |
| 254            | 0.125     | Two serial external cavity SHG stages, InGaAs/GaAs QWs | [331] |
| 295            | 0.136     | 4th harmonic, serial intracavity and external cavity SHG, InGaAs/GaAs QWs | [332] |
| 330            | 0.26      | SHG, GaInP/GaAs QWs, cooled at −25 °C | [333] |
| 355            | 0.45      | 3rd harmonic, InGaAs/GaAs QWs | [334] |
| 460            | 7.5       | SHG, InGaAs/GaAs QWs | [335] |
| 488            | 15        | SHG, InGaAs/GaAs QWs | [336] |
| 505            | 8         | SHG, InGaAs/GaAs QWs | [51] |
| 532            | 30        | SHG, InGaAs/GaAs QWs | [337] |
| 532            | 64        | SHG, InGaAs/GaAs QWs, three gain chips | [51] |
| 559            | 1.1       | SHG, InGaAs/GaAs QWs, 300 KHz linewidth | [197] |
| 575            | 8         | SHG, InGaAs/GaAs QWs | [338] |
| 590            | 20        | SHG, InGaAs/GaAs QWs, cooled at 8 °C | [327] |
| 615            | 10.5      | SHG, InGaAs/GaAs QWs, cooled at 8 °C | [339] |
| 625            | 6.5       | SHG, InGaAs/GaAs QWs, cooled at 20 °C, compact prototype | [340] |
| 665            | 2.5       | GaInP/GaAs QWs, multi-pass in-well pumped, cooled at 10 °C | [61] |
| 740            | 0.05      | InP/AlGaInP QDs, cooled at 7 °C | [96] |
| 750            | 1.5       | SHG, AlGaInAs/InP QWs, wafer-fused, cooled at 15 °C | [342] |
| 785            | 1         | SHG, AlGaInAs/InP QWs, wafer-fused, cooled at 15 °C | [186] |
| 850            | 0.5       | GaAs/AlGaAs QWs, cooled at 10 °C | [41] |
| 850            | 1.6       | GaAs/AlGaAs QWs, in-well pumped, cooled at 10 °C | [58] |
| 920            | 20        | InGaAs/GaAs QWs | [51] |
| 980            | 40        | InGaAs/GaAs QWs | [51] |
| 1028           | 106       | InGaAs/GaAs QWs, cooled at 3 °C | [52] |
| 1064           | 60        | InGaAs/GaAs QWs | [337] |
| 1119           | 4         | InGaAs/GaAs QWs, 900kHz linewidth | [343] |
| 1140           | 12        | InGaAs/GaAs QWs | [344] |
| 1180           | 50        | InGaAs/GaAs QWs, cooled at −15 °C | [103] |
| 1200           | 1.6       | GaAs/GaInAs/GaAsSb QWs, cooled at 15 °C | [345] |
| 1228           | 4.4       | Raman conversion, InGaAs/GaAs QWs, cooled at 7 °C | [346] |
| 1255           | 4.6       | InAs/GaAs QDs, cooled at 10 °C | [112] |
| 1270           | 33        | AlGaInAs/InP QWs, wafer-fused, cooled at −15 °C | [184] |
| 1305           | 6.6       | AlGaInAs/InP QWs, wafer-fused, cooled at 7 °C | [341] |
| 1315           | 2.5       | Raman conversion, InGaAs/GaAs QWs, cooled at 10 °C | [347] |
| 1480           | 4.8       | AlGaInAs/InP QWs, wafer-fused, cooled at 8 °C | [185] |
| 1580           | 4.6       | AlGaInAs/InP QWs, wafer-fused, cooled at 8 °C | [186] |
| 2000           | 5         | GaInSb/GaSb QWs, cooled at −15 °C | [348] |
| 2020           | 17        | GaInSb/GaSb QWs, cooled at 20 °C, pumped at 1470 nm | [349] |
| 2020           | 20.7      | GaInSb/GaSb QWs, double-side cooled at −3 °C, pumped at 980 nm | [37] |
| 2360           | 3.2       | GaInAs/GaSb QWs, resonant in-well pumping, cooled at −15 °C | [350] |
| 2500           | 0.6       | GaInAs/GaSb QWs, cooled at 5 °C | [351] |
| 2800           | 0.12      | GaInAs/GaSb QWs, cooled at 20 °C | [352] |
| 3300           | 0.02      | PbSe/Si QWs, cooled at −20 °C, pulsed | [353] |
| 3500–4300      | 0.01–0.05 | PbTe QDs, cooled < −93 °C, pulsed | [354] |
| 4500           | 0.006     | PbSe/BaF2 QWs, cooled at 27 °C, pulsed | [355] |
| 5000           | 0.017     | PbSe/BaF2 QWs, cooled at −173 °C (1 W pulsed) | [119] |
| 5260           | 0.026     | PbSe/Si QWs, cooled at −173 °C, pulsed | [356] |
| 5400           | 0.005     | Difference frequency generation of 970 nm and 1170 nm, InGaAs/GaAs QWs | [302] |
Amongst the many developments concerning VECSELs, important milestones have recently been attained in producing yellow-orange radiation in the wavelength range of 570–650 nm. Development in this spectral window faced several challenges. First, there are no semiconductor materials that provide suitable band-gaps for direct emission at these wavelengths. Second, access via intracavity SHG requires developing high quality gain mirrors for the 1140 nm–1240 nm range, which has proved particularly challenging owing to the lack of well-developed lattice-matched alloys (see discussion in section 3.1). Despite these challenges, progress in these wavelengths is being made since the yellow–red wavelength range is instrumental for many high value applications, such as dermatology treatments and ion manipulation.

When considering directly emitting orange–red VECSELs, moving to emission wavelengths below 650 nm becomes increasingly challenging due to poor carrier confinement in the AlGaInP QWs (which leads to poor efficiencies at elevated temperatures) and the low index-contrast of AlGaAs/AlAs DBRs. These issues were recently addressed in two new VECSEL configurations. In the first approach, the thermal load of the VECSEL was reduced via in-well pumping with a multi-pass pumping scheme (as illustrated in figure 10), generating 2.5 W at 665 nm [61]. In the second approach, the constraints regarding the DBR were circumvented using a double-side cooled ‘DBR-free’ gain membrane [74]. This barrier-pumped membrane external-cavity surface-emitting laser (MECSEL) produced an output power of 0.6 W at 657 nm. In general, both approaches could provide new opportunities for addressing the 630–650 nm range by providing enhanced cooling capability and reducing heat generation in active region.

When considering frequency-doubled VECSELs, the yellow–orange wavelength range can be accessed by extending the emission wavelength of GaAs-based VECSELs beyond 1140 nm using highly strained InGaAs QWs or GaInNAs QWs. The highest recorded power at 1180 nm is currently set at 50 W using highly strained InGaAs QWs [103]. This approach has also enabled output power of 20 W at 590 nm with an optical-to-optical slope efficiency of 36% [327], as already mentioned above. The corresponding output characteristics are shown in figure 11. The conversion to yellow was obtained in a V-shaped cavity that incorporated a non-critically phase-matched lithium triborate (LBO) crystal. The fundamental wavelength was set to the phase-matching bandwidth of the LBO using a birefringent filter and an etalon. In addition, we have demonstrated >10.5 W of output power at a longer wavelength of 615 nm from a frequency-doubled GaInNAs VECSEL emitting at 1230 nm [339]. Later, this VECSEL structure was also used to demonstrate > 6.5 W of output power from a compact, application-ready prototype emitting at a slightly longer wavelength of 625 nm [340]. When compared to the yellow VECSEL demonstration, the smaller output power at these red wavelengths is a reflection of the less mature GaInNAs-based technology and inherently higher number of defects associated with higher strain and/or higher N content. Nevertheless, with additional optimization of the epitaxy, a power level exceeding 10 W is deemed possible.

6. Frontiers in pulse generation: mode-locked VECSELs

This section will review briefly the recent developments of mode-locked VECSELs with a focus on pushing the frontiers in pulse generation. A more comprehensive open access review on the overall parameters and technology has been published in 2015 by Tilma et al [7]. Mode-locked VECSELs have also been the subject of an earlier review by Keller and Tropper [6].

6.1. Mode-locking mechanism

The most common mode-locking technique for VECSELs is the use of a semiconductor saturable absorber mirror (SESAM) [357]. This is not surprising since both the VECSEL gain material and the SESAM can utilize the same semiconductor fabrication technology and growth facilities.
To date, mode-locked VECSELs have been demonstrated in various configurations that include high harmonic mode locking with > 100 GHz repetition rates using coupled cavities [358–360], MIXSELs (mode-locked integrated external-cavity surface emitting lasers) where the SESAM is integrated with the VECSEL gain element [210, 361–364], and colliding pulse mode-locking in ring cavities [365, 366]. In addition, VECSELs have been mode-locked by synchronous pumping using a mode-locked Nd:YAG laser [367], mode-locked Ti:sapphire lasers [368, 369], and fiber-amplified pump diodes [370]. Mode-locking could also be obtained using a Kerr lens or a combination of an SHG crystal and a dichroic mirror, provided that the pump diodes are modulated at the cavity repetition rate [66, 371]. Recently, VECSELs have also been mode-locked using the saturable absorption in carbon nanotubes [372] and graphene [373]. In particular, Husaini and Bedford [374] reported a mode-locked VECSEL with 10 W average power and 353 fs pulse duration using a graphene absorber mirror. However, the RF spectrum in this publication did not indicate stable mode-locking, nor did the autocorrelation trace indicate single-pulse operation. Significant attention has also been devoted to the so-called ‘self-mode-locking’ that was first reported by Chen et al [375]. In these cases, the physical mechanism for the saturable absorption has been credited to a possible Kerr effect in the VECSEL gain material [376], but several reports have been published on the topic that both support and contradict self-mode-locking [207, 211, 307, 377–381]. Most notably, Quarterman et al [207] measured a sufficiently large Kerr effect in a VECSEL structure to support Kerr-lens mode locking. On the other hand, the long-term stability of self-mode-locking is still not unanimously resolved [211]. A review of the reported self-mode-locking results can be found in [382]. Our overall assessment is that, while the reliability of mode-locking and self-starting behaviour with SESAMs has been thoroughly proven and qualified in many industrial ultrafast solid-state laser products, this is not yet the case for alternative mode-locking methods.

6.2. Pulse width

The leading results of short pulse VECSELs are summarized in table 7, revealing that sub-ps pulses have been reported at most of the major wavelengths within the 665–1960 nm range. One should also note that, even though some of the wavelength domains are not extensively covered (as is the case for CW VECSELs), this is just a reflection of the lower number of active groups in this field, the need for more specific developments, and the early development stage rather than any fundamental limit.

Single pulses as short as 107 fs were obtained from a mode-locked VECSEL at 1030 nm by Klopp et al [388]. Similar pulse duration was later achieved by Waldburger et al [390]. In this case, the authors also utilized external pulse compression to obtain 96 fs pulses. Even shorter pulses of 60 fs have been reported by Quarterman et al [397], but the VECSEL operated in burst mode. The potential dynamics of such multi-pulse VECSEL and pulse break-up in the ultra-short pulse regime were discussed in detail by Kilen et al in [398]. The short conclusion of this computational work suggested that it will be difficult to achieve ultra-short pulses and high peak powers simultaneously from a mode-locked VECSEL. This is due to the fact that the pulses tend to break up if the net gain in the cavity is too high. Later on, in situ measurements of the gain dynamics in a mode-locked VECSEL were carried out, which also suggested the possibility of a pulse break-up if the cavity gain is not

![Figure 11. Top: output power characteristic of the yellow VECSEL (inset beam profile) and tuning range. Reproduced with permission from [327], 2014 The Optical Society. Bottom: photograph of the VECSEL in operation.](image-url)
In comparison to doped solid-state laser crystals and glasses, semiconductor gain materials exhibit much shorter carrier lifetimes, i.e. ns-scale as compared to the µs–ms upper-state lifetime typically found in conventional solid-state gain materials. This unique feature allows mode-locked VECSELs to operate at high repetition rates and average output powers without tendencies to Q-switching [404]. On the other hand, the short carrier lifetime also severely limits the capability to store energy in time. Thus, the typical mode-locked VECSELs operate at repetition rates of 0.5–5 GHz simply because lower repetition rates would lead to reduced efficiencies or harmonic mode-locking [174, 405], and higher repetition rates would require very short cavities that are difficult to realize with standard optomechanics. In any case, mode-locked VECSELs at low repetition rates have received attention recently due to their potential applications, such as fluorescence lifetime imaging, photo-acoustic imaging, LIDAR, and applications that require high pulse energies (micromachining, laser ablation).

Moreover, even higher repetition rates require very short cavities that are difficult to realize with conventional mode-locked VECSELs. MIXSELs have been demonstrated with harmonic mode-locking [407], generating 265 fs pulses [360] and average output powers of 1 W [358]. Finally, the MIXSEL concept [364] with an integrated SESAM in the VECSEL gain element has essentially overcome the mechanical difficulties that limit operation of conventional mode-locked VECSEL. MIXSELs have been reported with a fundamental repetition rate as high as 50 GHz has been reported [219]. Moreover, even higher repetition rates >100 GHz have been demonstrated with harmonic mode-locking [407], generating 265 fs pulses [360] and average output powers of 1 W [358]. Finally, the MIXSEL concept [364] with an integrated SESAM in the VECSEL gain element has essentially overcome the mechanical difficulties that limit operation of conventional mode-locked VECSEL. MIXSELs have been reported with a fundamental repetition rate as high as 100 GHz with 570 fs pulse duration and 127 mW average power by Mangold et al [362].

| Wavelength (nm) | Pulse width | Gain material | SESAM | $P_{avg}$ | Rep. rate | Reference |
|----------------|-------------|---------------|-------|----------|-----------|-----------|
| 489            | 5.8 ps      | InGaAs/GaAs (SHG) | InGaAs/GaAs (SHG) | 6 mW | 1.88 GHz | [383]     |
| 665            | 250 fs      | GaInP/AlGInP/GaAs | GaInP/AlGInP/GaAs | 1 mW | 836 MHz | [384]     |
| 675            | 5.1 ps      | GaInP/AlGInP/GaAs | GaInP/AlGInP/GaAs | 45 mW | 973 MHz | [385]     |
| 960            | 416 fs      | QD InAs on GaAs | QD InAs on GaAs | 143 mW | 4.5 GHz | [386]     |
| 960            | 784 fs      | QD InAs on GaAs | QD InAs on GaAs | 1.05 W | 5.4 GHz | [386]     |
| 960            | 28 ps       | InGaAs/GaAs | InGaAs/GaAs (MIXSEL) | 6.4 W | 2.5 GHz | [361]     |
| 1000           | 335 fs      | InGaAs/GaAs | InGaAs/GaAs | 120 mW | 1 GHz | [387]     |
| 1013           | 400 fs      | InGaAs/GaAs | InGaAs/GaAs | 3 mW | 1.67 GHz | [26]      |
| 1030           | 107 fs      | InGaAs/GaAs | InGaAs/GaAs | 100 mW | 1.63 GHz | [390]     |
| 1048           | 184 fs      | InGaAs/GaAs | InGaAs/GaAs (MIXSEL) | 115 mW | 4.33 GHz | [391]     |
| 1224           | 5 ps        | GaInNAs/GaAs | GaInNAs/GaAs | 275 mW | 840 MHz | [392]     |
| 1312           | 6.4 ps      | Wafer-fused, AlGaInAs/InP | Wafer-fused, AlGaInAs/InP | 100 mW | 910 MHz | [393]     |
| 1495           | 36 ps       | InGaAs/InP | Synchronously pumped | 260 mW | 100 MHz | [367]     |
| 1518           | 6.5 ps      | InGaAs/InP | Synchronously pumped | 13.5 mW | 1.34 GHz | [394]     |
| 1560           | 17 ps       | AlGaInAs/InP | GaInNAs/GaAs | 15 mW | 2 GHz | [147]     |
| 1560           | 902 fs      | AlGaInAs/InP | GaInNAs/GaAs | 10 mW | 2 GHz | [395]     |
| 1960           | 384 fs      | InGaSb/GaSb | InGaSb/GaSb | 25 mW | 890 MHz | [396]     |
6.4. Output power

While continuous wave VECSELs have already exceeded the 100 W mark [52] with optical–optical conversion efficiencies in the ~20–50% range, the power scaling of mode-locked VECSELs has been much more difficult [391]. Rudin et al. have reported the highest average power of 6.4 W with a conversion efficiency of 17.3% from a MIXSEL producing 28 ps pulses at 959 nm [361]. Other high power demonstrations include 5.1 W of average output power with 682 fs pulses at 1030 nm [389] and 3.3 W of average power with 400 fs pulses at 1013 nm [26]. These results are remarkable amongst mode-locked VECSELs, where the average power is typically less than 500 mW, and 1 W average power can be considered high.

7. Applications and future developments

Owing to intense development over the last decade and their unique features, VECSELs have reached a maturity stage that makes them very attractive for OEM and scientific applications. In particular, their ability to produce high-brightness radiation, initially at blue and green wavelengths and more recently at yellow wavelengths, has been the driving force for the establishment of an optically-pumped semiconductor laser (OPSL) product platform by Coherent Ltd. The success of OPSLs has led to the replacement of several types of established solid-state, ion, and metal-vapour lasers in various applications, such as ophthalmology, life science, Ti:sapphire pumping, and light shows [408–410]. The current estimations indicate tens of thousands of OPSL units already deployed, at the same time demonstrating excellent reliability and low maintenance costs as compared to competing high power laser technologies [409]. However, the unique technology of the VECSEL still offers various new opportunities and possibilities in practical applications. In particular, the possibility of low noise operation at narrow linewidths and ultrashort high-repetition rate pulse generation has prompted commercial interest. For instance, Innoptics SAS has built several early-stage prototypes for spectroscopic applications at 1 µm and 2.3 µm wavelengths [411–413]. In addition, M Squared Laser has provided the first commercial mode-locked VECSEL at 920 nm–1050 nm, namely the ‘Dragonfly’ platform that targets nonlinear spectroscopy applications with 1 W output power, 200 MHz repetition rate, and < 1 ps pulse duration [399, 414, 415]. From this general perspective, we focus on some specific applications areas of VECSELs that are seen as taking momentum in the near future.

7.1. Yellow VECSELs for dermatology

When considering life science applications, a very interesting development has recently emerged for yellow 590 nm VECSELs in dermatology that could potentially replace pulsed dye lasers (PDL) in the treatment of cutaneous vascular disorders, such as port wine stains and rosacea. The potential benefits arise from the combination of sufficiently high hemoglobin absorption and deeper penetration into skin than is obtained with the standard 532 nm and 577 nm wavelengths [416], therefore enabling the treatment of deeper vascular lesions. Interestingly, the 577 nm VECSELs have already been qualified in dermatologic medical products [417], and are expected to pave the way of VECSELs into an increasing number of medical applications. On a related note, we recently built a prototype of a VECSEL emitting at 585 nm (shown in figure 12) delivering about 6.5 W of power from a multi-mode fibre to a handheld scanner.

7.2. Sodium guide stars

Besides medical applications, yellow VECSELs could prove instrumental for developing more compact and affordable sodium guide stars, which are used in terrestrial telescopes equipped with adaptive optics. In these systems, a 589 nm laser beam is used to excite sodium atoms at ~90 km height in the atmosphere, and the resulting ‘artificial guide star’ is used as a reference point for the adaptive optical system, to compensate the image distortion that is caused by atmospheric perturbations. These guide star lasers should have a narrow spectral linewidth of a few MHz and be locked to the 589 nm sodium absorption line. Preferably, the laser should also produce an average output power ranging from several
watts or tens of watts [418]. To date, different technological approaches have been proposed, such as Raman-shifted fiber lasers [419], sum-frequency generation from Nd:YAG lasers [420], and dye lasers [421]. Again, as compared to these solutions, VECSELs could provide a relatively simple and low-cost alternative, and are already envisaged for creating polychromatic guide stars [344].

7.3. VECSEL-based laser systems for spectroscopy and quantum technology

Amongst the many applications fields, the versatility of VECSELs can probably be best exploited in scientific applications (as summarized in table 8) including quantum technology and spectroscopy. In these applications, the main focus has been on wavelength control, wavelength tailoring, cavity stabilization and noise aspects, as well as increases in output power. A recent example intended for spectroscopic applications includes a compact VECSEL module by Innoptics [413] that emits at the wavelength of 2.3 \( \mu \)m in a single transverse mode beam with a MHz linewidth. Other recent demonstrations include single-frequency UV generation for laser cooling of Cd atoms. In this case, the VECSEL utilized sequential intracavity and external cavity SHG stages, and delivered 0.56 W of output power at a wavelength of 229 nm [330].

VECSELs are also particularly suitable for atomic, molecular and optical (AMO) physics that require driving atomic transitions at specific wavelengths with linewidths in the range of hundreds of kHz to tens of MHz [430]. Some of most relevant transition lines and their coverage using VECSEL technology are summarized in figure 13. The possibility of tailoring the emission wavelength of single-frequency VECSELs provides a very attractive solution to these applications, because it enables the targeting of specific applications and transitions instead of relying on the discrete wavelengths that are available from existing dye or solid-state gain materials. Moreover, narrow emission linewidths and low intensity noise are a natural operation scheme for single-frequency VECSELs. This feature arises from the high-Q cavity and fast gain dynamics that result in ‘class-A’ laser operation intrinsically providing relaxation oscillation-free and extremely narrow ‘cold’ cavity lines, while the RPG gain structure provides spatially and spectrally homogenous gain without mode interactions [67, 259, 431]. This low-noise feature is very important in AMO applications [422, 430].

These attractive properties of VECSELs were recently exploited in an AMO experiment conducted by Burd et al who demonstrated two UV VECSEL systems for generating, cooling, and manipulating Mg ions [422]. The first system comprised two sequential external cavity SHG stages, while
the second system comprised sequential intracavity and external cavity SHG. A generic schematic of the transitions relevant to this demonstration is illustrated in figure 14.

First, photoionization was used to generate Mg$^+$ ions via a two-photon process at 285 nm. Such a procedure can be very efficient when compared to electron impact ionization, but it also reduces the probability of electrons charging the surfaces of the Mg$^+$ ions. The trapped Mg$^+$ ions were then illuminated with 280 nm light to perform Doppler cooling and fluorescence detection. Finally, the authors performed sub-Doppler cooling using two-photon stimulated Raman transitions that enabled the cooling of the Mg$^+$ ions close to their motional ground state. These experiments pave the way in making VECSELs a practical tool for quantum information experiments by providing wavelength flexibility, simplicity, and laser output features that have not been available so far.

7.4. Mode-locked VECSELs

For most short pulse applications, the optimal light source can be defined by its pulse duration, repetition rate, average power, and wavelength. The other key parameters may include features such as timing jitter and amplitude noise. To this end, mode-locked VECSELs do not compete in every category with other laser technologies. Namely, VECSELs are not expected to provide shorter pulses than mode-locked Ti:sapphire lasers at 650–1100 nm or fiber lasers in the 1550 nm range. Neither are VECSELs expected to provide higher average or peak powers than mode-locked solid-state thin disk lasers emitting at 1030 nm, which have broken the 200 W barrier in average output power [432, 433]. However, mode-locked VECSELs do provide certain distinct features when compared to other available technologies, particularly related to their versatility in customizing the emission wave-length and the repetition rate. Additional benefits include compact size, low cost, and intrinsically low noise. Moreover, VECSELs and MIXSELs are easily mode-locked at repetition rates of multiple GHz without Q-switching instabilities due to their fast carrier dynamics. This makes them particularly attractive for applications such as high-speed optical clocking, high-resolution optical sampling, and optical communications [311, 314, 362]. Other interesting developments include the demonstration of picoseconds pulses at red wavelengths [385] and sub-picosecond pulses at the mid-IR region [396].

The first commercial implementation of mode-locked VECSELs was made by M Squared with the launch of its ‘Dragonfly’ platform, specifically developed for users who are ‘apprehensive of using and maintaining traditional ultrashort laser systems’ [399]. These VECSELs provide a more compact system for nonlinear microscopy than diode lasers, because the latter requires several pulse compression and amplifying stages [414, 415]. The wavelength of the Dragonfly can be set in the range of 920–1030 nm to target nonlinear microscopy applications. These VECSELs operate at relatively low repetition rates of 200 MHz and, therefore, fill a range that typical mode-locked solid-state and fibre systems cannot reach; again, besides this, VECSELs could cover wavelength bands that are not attainable for solid-state gain media.

Mode-locked VECSELs and MIXSELs have also raised interest in generating optical frequency combs, e.g. for high-precision spectroscopy, frequency metrology, ultra-stable optical clocks, and ultra-high-speed optical communication (see [402, 434] and the references therein). Again, the specific interest arises from the possibility of fabricating compact and cost-effective ultrashort pulse sources [403]. In addition, the high repetition rates can prove useful in relation to frequency combs leading to lines with a larger frequency spacing and more power per mode, and in turn higher signal-to-noise ratios [362, 390]. In the same line, an innovative way to generate a synchronized dual-frequency-comb from a single mode-locked MIXSEL was demonstrated by Link et al [434, 435]. The authors used an intracavity birefringent element to divide the mode-locked intracavity beam into two separate beams with perpendicular polarizations. Recently, the same group also reported the use of such a source for dual-comb spectroscopy at 1 μm [436]. These developments are also expected to trigger demonstrations of high repetition rate mode-locked VECSELs at wavelengths above 2 μm, where spectroscopic applications have many needs.

Finally, mode-locked VECSELs have been demonstrated in relation to THz generation. Specifically, Wilcox et al demonstrated THz radiation using a mode-locked VECSEL and
a low-temperature-grown GaAsSb antenna [437]. This work was then followed by the first demonstration of a THz time-domain spectrometer by Mihoubi et al. [438], who utilized a mode-locked VECSEL in conjunction with a low-temperature-grown GaAs photoconductive antenna. However, the bandwidth and the signal-to-noise ratio of the THz spectrum were still limited by the pulse duration and average output power of the VECSEL. These issues were later overcome with the demonstration of a 1 GHz mode-locked VECSEL that produced 335 fs pulses and 120 mW of average power by Wilcox et al. [439]. Moreover, the authors argued that the signal-to-noise ratio could be improved even further by increasing the repetition rate, because the noise level increases with the square root of the number of pulses while the signal level increases linearly. Finally, the most recent demonstration related to THz time-domain spectroscopy comprises an intracavity antenna for THz generation in using a surface-patterned SESAM [440]. Such light sources could be particularly interesting, e.g., in pharmaceutical research, label-free readout of DNA sensors, gas spectroscopy and quality control (see in [441]).

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