Abstract Recent developments in semiconductor disk lasers (SDLs) generating visible or ultraviolet light are reviewed. After an introduction on potential applications, we discuss how the combination of vertical-emitting semiconductor GaAs-based structures and intra-cavity nonlinear conversion techniques can be successfully exploited to uniquely meet demands for continuous-wave radiation in the visible and ultraviolet spectral range. To do so, an overview of the device operating principles and performance is presented highlighting the underlying material considerations, semiconductor structural designs, thermal management techniques and suitable cavity configurations. This summary is completed by a presentation of new developments in the field, with a particular focus on the trends towards miniaturization.

Semiconductor disk lasers for the generation of visible and ultraviolet radiation

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1. Introduction

1.1. Background

Semiconductor Disk Lasers (SDLs) also known as Vertical External-Cavity Surface-Emitting Lasers (VECSELs) form a category of lasers whose concept is based on the use of an optically-pumped semiconductor platelet as the gain medium inside a bulk optics cavity (see Fig. 1). As such, its origin can be traced back to 1966 [1]. Although this approach was used on various other occasions [2–4], it was only in the late 1990s, in the light of advances in diode-pump sources and semiconductor epitaxy, that the potential of this laser configuration was re-assessed and recognized as a valuable practical format [5]. Indeed, SDLs appeared to the semiconductor laser community as a means to obtain power-scaled, high-quality output beams from the closely-related vertical-cavity surface-emitting lasers (VCSELs) [6, 7]. They also became attractive to the diode-pumped solid-state laser community as they constitute a variation on the doped-dielectric thin-disk concept [8, 9], with the advantage of a bandgap engineered emission wavelength and a simplified pumping scheme. Since then, this combined interest and application-driven developments have made this technology the subject of vibrant topical research [10–13]. In this review, after an overview of potential applications, we provide a tutorial on the design and engineering of visible and ultraviolet (UV) emitting SDLs as well as an up-to-date summary of their performance.

1.2. Applications

To help understand why SDLs have attracted such an interest as visible or UV sources, this section presents an overview of potential applications highlighting the associated desirable characteristics.

The application for visible sources which currently receives the most attention is their use as light engines for laser televisions or projectors [14–16]. In such systems, the image to be displayed is produced either using a micro-display element or a laser-scanning technology. In the former, one combined red green blue (RGB) source provides a constant or frame-rate illumination of an array of elements (micro-mirrors [17], liquid crystal display) which defines sequences of image frames to be subsequently relayed using an optical lens system. In the laser-scanning approach, a single combined beam of RGB light raster-scans the display area and each pixel is produced by appropriate intensity modulation of each of the individual colour beams. In both cases, to offer the best image quality, the preferred RGB wavelengths are respectively 620, 532 and 460 nm as they enable maximum colour gamut coverage [18]. To ensure the use of lasers over competing illumination sources (LEDs, lamps), the key requirements to be met by the developed devices are suitability for mass-production at low cost, high efficiency (to limit power consumption, cooling), small volume (typically of <1 cm³) and stability (fixed polarization, low noise, absence of wavelength shift while ageing, longevity of ≈10,000h). Furthermore, output beams with close-to-diffraction-limited characteristics are desirable as they allow the projection of sharp points in laser scanning systems [16] and easy homogenization in the micro-display case [15]. Finally, direct modulation capability at ≈100MHz frequencies to enable high-definition television standard image projection is deemed essential in laser scanning projection/display [16].

The second most prominent field of application envisaged is spectroscopy. In this sector, the number of units to be sold is generally small but the devices require more refined performance. In the area of atomic physics for instance, the general consensus is that, to be useful, the laser sources should generate beams of high lateral mode quality and that they should be continuously wavelength-tuneable around the considered atomic transitions with narrow (<1 MHz) linewidth. Low amplitude and frequency noise characteristics are also desirable [19]. In the visible and UV part of the spectrum, the most relevant atoms include lithium (670.8 nm), neon (640 nm), calcium (657 and 672 nm), strontium (689 nm), iodine (503 nm), copper (327 nm), silver (328 nm) and sodium (589.5 nm) [20]. It should be said that the laser requirement will vary widely depending on the intended specific use. For instance, the spectroscopic study of the hyperfine structure of sodium could be performed with a 589.5 nm, 10 nm-tuneable source producing <100 mW of light, while use in astronomy as a laser guidestar requires powers in excess of 20 W [21, 22].

In the topical area of biophotonics, applications of continuous-wave or pulsed visible or UV laser sources are many and varied. In particular, the development of small form factor, efficient lasers with emission wavelength in the UV or blue spectral regions could be conveniently used as replacements for the current bulky excitation sources.

Figure 1 (online color at: www.lpr-journal.org) Schematic setup of an SDL.
Figure 2 (online color at: www.lpr-journal.org) Laser rear-projection television. The laser source is framed in the red box [14]. Image courtesy of Coherent, Inc.

used in fluorescence-based bio-imaging (microscopy) [23]. Similarly, in forensics, the fluorescence-based search for fingerprints in ambient/day light illumination would benefit from multi-watt portable green (∼510 nm) sources [24]. In medicine, the ability to produce reliable, watt-level red (630–690 nm) lasers is of great significance for photodynamic therapy especially as red lasers are the only viable option to provide sufficient illumination for the treatment of malignant tumours only accessible using optical fibres [25, 26]. Finally, in ophthalmology, yellow emitting (577 nm) sources are in high demand for the treatment of retinal vascular diseases [27, 28].

One further application area where low-noise high-brightness lasers would be considered as valuable components is laser engineering. Indeed, in the spectral range of interest to this paper, Ti:sapphire [29] and Pr:fluoride lasers [30] are two specific examples of sources which can take full advantage of stable, high-power good beam quality pumps emitting respectively at 532 and 480 nm, as may be provided by SDLs.

2. SDL concept description

2.1. Semiconductor chip design

As described in Sect. 1, the SDL concept is based on a semiconductor region providing gain to the laser in a direction normal to the wafer surface. Although in the original devices, bulk semiconductor platelets were used as gain elements, modern SDL semiconductor structures include four sub-sections (see Fig 3): a mirror, a gain section with quantum-wells (QWs) or planes of quantum-dots (QDs) as active elements, a carrier-confinement window and a cap layer to protect the latter layer and those underneath from oxidation. The compositions and thicknesses of the different layers composing the SDL multilayer are typically chosen based on the lattice-bandgap energy diagram of Fig. 4 and on calculated reflectivity and E-field patterns evaluated using thin-film matrix methods [11, 31].

The relevant alloys under consideration here are all based on GaAs, with AlGaAs being used for the passive sections (i.e. mirror and confinement window), AlInGaP for the gain section of direct red emitters and InGaAs(N) or GaAsSb for near infrared emitters to be frequency-doubled to the visible region. Although the use of GaN technology can be envisaged for blue emitters and subsequent frequency-doubled operation to the UV, the absence of high-power (Watt-level) UV laser diode pumps and difficulty

Figure 3 (online color at: www.lpr-journal.org) Layout of a 13QW 1060 nm SDL, representative of a typical SDL gain structure.
in producing semiconductor mirrors with sufficient reflectivity and bandwidth [32] presently reduces the technical and commercial attractiveness of this approach. Similarly, though II–VI semiconductors have been used to produce visible VCSELs [33], SDLs have not yet exploited these alloys due to fast degradation issues [34] and the lack of appropriate pump laser diodes.

High performance SDLs require high quality semiconductor growth, hence homoepitaxy i.e. choosing alloy materials such that their lattice constant is identical to that of the chosen semiconductor substrate (a_{subs}, GaAs here), a rule also known as lattice-matching. Layers with relative deviations in lattice parameter up to ~ 3.5% can be grown under compressive (a > a_{subs}) or tensile (a < a_{subs}) strain, provided that their thickness is lower than the critical thickness where the structure mechanically relaxes [35]. This limit can be overcome by alternating the growth of materials with larger and smaller lattice constants than the substrate at the expense of relatively high interfacial strain. This technique is generally used to provide mechanical stability of multi-QW structures where the thickness of a layer with strain of opposite sign is adjusted to exactly cancel the in-built energy induced during the QW growth, a method known as ‘strain-compensation’ [36].

The semiconductor mirrors, referred to as distributed Bragg reflectors (DBRs), are stacks of N repeats of quarter-wavelength-thick layers of two lattice-matched alloys with respectively high (low) and low (high) refractive index (bandgaps). The constituent materials are chosen to be transparent at the fundamental emission wavelength with the highest index contrast so as to limit the number of repeats N and obtain broadband reflectivity. The alloys are also selected to be as thermally conductive as possible to facilitate heat dissipation from the active region (see Sect. 2.2). Typically, a 25.5-pair AlAs/GaAs mirror is used to provide R > 99.9% for SDLs emitting in the 920–1250 nm range.

The SDL gain is provided by QWs or QDs embedded in barrier material. Their composition and size are chosen based on transition energy and gain characteristics calculations [37–39]. Compressively-strained QWs are usually preferred as, in addition to a reduction in threshold (enabled by energy splitting of the valance bands), this type of strain favours the required TE-polarized gain [37]. To maximize gain extraction from these small thickness gain elements, it is beneficial to locate them at the antinodes of the standing-wave of the electric-field pattern established by the semiconductor mirror, a configuration known as resonant periodic gain (RPG - see Fig. 3 for an illustration). This arrangement avoids spatial hole burning effects and leads to a wideband gain enhancement around the design wavelength, \( \lambda_{RPG} \). We note that, contrary to QWs for which the gain peak corresponds to the ground state transition (i.e. between the lower level of the conduction band and the highest level of the valence band), the discrete nature of the density of states in QDs allows gain to be extracted not only from the ground state transition but also from excited states transitions (between higher levels of the conduction band and the highest valence band level).

The final part of the SDL structure that merits discussion is the confinement window. This layer is generally added to prevent pump-generated carriers from reaching the surface where they would be lost to non-radiative recombination. As such, it is chosen to be pump (and signal) transparent and to provide a sufficient electronic barrier for the carriers. The selection of a highly-thermally-conductive material is favoured to help with heat dissipation [40]. Thickness adjustments of this layer are also often used to suitably tailor the sub-cavity resonance(s) resulting from the Fabry-Perot interference between the semiconductor chip surface and the DBR. The presence of such a resonance (surface positioned at the antinode of the field) provides a wavelength-selective enhancement of the semiconductor chip effective gain around the design wavelength. An illustration of this effect is shown in Figs. 5 and 10. SDL structures using this feature are known as resonant devices. They are commonly used in frequency-doubled SDLs as the resonance helps with the wavelength selection. However, for wide laser tunability, anti-resonant (E-field node at air/semiconductor surface) structures are generally preferable.

For optimum performance, the wavelengths corresponding to the centre of the stop band, sub-cavity resonance and RPG should all be matched. However, the QW (QD) gain
Operation of the devices is obtained by optical pumping with the pump photon energy most often chosen to be larger than the barrier bandgap to benefit from carrier generation in the continuum states of this bulk material. This pumping scheme, known as barrier-pumping, benefits from a relative wavelength insensitivity and short absorption length (typically 1–2 μm), both of which simplify greatly the pumping arrangements compared to traditional doped-dielectric solid-state lasers. The Beer-Lambert absorption profile of the pump will however provide a graded carrier distribution, a factor that is somewhat mitigated by carrier diffusion but is given further attention at the design stage to obtain uniform pumping of the different QWs or QD planes (and low threshold). Non-uniform spatial distribution of the QWs (QD planes), as well as the insertion of pump dividers to obtain constant average carrier density (see Fig. 3) and/or the use of extensive modelling [38, 41–43] for gain element positioning have been explored as routes to ensure more even carrier distribution. An alternative method is to use a pump of lower photon energy than the barrier bandgap, an arrangement known as in-well or in-dot pumping. The weak (typically 1%) absorption of individual QWs (or QD planes) enables fairly uniform pumping of the different gain elements but requires more complex pump recirculation schemes to be used to exhaust the pump [9, 44]. This can for instance involve the modification of the semiconductor mirror to reflect at both signal and pump wavelengths [9, 44, 45].

2.2. Thermal management

Given the short pump absorption lengths (∼1–2 μm), the reduction in gain peak (see Fig. 5) and increase in non-radiative recombination associated with increased temperature, the choice of an effective thermal management technique is vital for SDL high power operation. The two heat removal approaches that have been deployed successfully to date are illustrated in Fig. 6. The first, so called “thin-device” technique, consists of transferring the thin (∼6 μm-thick) epitaxially-grown semiconductor gain mirror structure onto a heatsink [46–48]. In practice, the semiconductor growth starts with an etch-stop cap, followed by the active section and finishes with the mirror. A piece of the wafer is then soldered to the heatsink and the semiconductor substrate removed by a combination of mechanical/chemical etching. The second approach to SDL thermal management introduced by Sandia National Laboratories [49] and subsequently refined by the University of Strathclyde and collaborators [50, 51] uses an unprocessed epilayer, grown mirror first, onto which a high conductivity platelet, referred to as a heatspreader, is bonded directly using liquid capillarity [52]. This composite is then clamped in a heatsinking mount using indium foil (although solder could also be used). To be effective, the heatspreader must offer a much greater thermal conductivity than the semiconductor substrate and be sufficiently thick (typically >100 μm for diamond) to allow unconstrained heat dissipation to the contact ring (see Fig. 6) [40]. As an intra-cavity element, it also needs to be transparent with low scattering loss at the emission and pump wavelengths [53] and preferably of controlled birefringence to avoid unwanted polarisation loss [42, 44]. This restricts the potential material candidates and, in practice, only diamond [39, 42], SiC [38] and to some extent sapphire [37, 38] have been used in SDLs with fundamental
emission in the 640–1250 nm range. Further considerations regarding the spectral influence of the heatspreader will be discussed in the next section.

A number of finite-element analyses and experimental studies have been performed to assess the virtues of both approaches [40, 48, 54]. In the main, the results highlighted the fundamental difference in heat path between the two thermal management techniques. For SDLs with highly thermally resistive mirrors such as the direct red emitters reported hereafter, the heatspreader approach effectively by-passes the mirror and thus will provide more efficient heat extraction. For 920–1250 nm SDLs, the heatspreader technique will cool the device better at small pump spot sizes \((w_p)\) for the same reason as above, while the thin-device mounting technique should work better at larger pump spots as the radial heat transfer inherently associated with heatspreaders becomes less effective. These trends are illustrated in Fig. 7 for a typical 1060 nm device (see [48] for structural details) where the modelled device thermal resistance, \(R_{th}\), defined as the change in average temperature over the pump mode area per unit of absorbed pump power, is represented as a function of pump spot size. We also note that all SDLs exploiting a single gain chip will have a thermally-constrained maximum output power as neither thermal management method produces the desired perfect one-dimensional heat flow. Indeed, to be truly power-scalable, the SDL chip temperature would have to stay constant at constant absorbed pump intensity or equivalently the thermal resistance should present a \(1/w_p^2\) dependence which is simply not the case \((1/w_p^{7.7} \text{ for the thin-device approach and } 1/w_p^{1.2} \text{ for the heatspreader technique})\) as shown in Fig. 7.

The heat generated inside the structure will induce an expansion and a positive refractive index change of the different semiconductor/heatspreader layers creating an overall positive thermal lens. The strength of this lens is very much dependent on the chosen pumping conditions and on the effectiveness of the thermal management method [55]. Practically, it only plays a significant role in compact SDL cavity arrangements as discussed in Sect. 6 of this document.

### 2.3. Laser cavity arrangements

Once grown and adequately mounted, the semiconductor chip is used as an optically-pumped active end mirror in a laser cavity. For fundamental emission, this cavity is gener-
ally completed with at least one curved mirror that may also be the output-coupler (OC), as shown in Fig. 1. The mirror radius of curvature and distance to the semiconductor chip are chosen to provide mode-matching i.e. a cavity mode at the semiconductor identical to the gain aperture size, itself controlled by the pump mode size and power. However, three-mirror cavities (see Fig. 8) are commonly used as they provide additional setup flexibility with, in particular, an ability to reach mode-matching condition with first-order independence from the thermal lens incurred in the semiconductor chip, an arrangement known as a dynamically stable cavity [56].

As SDLs are inherently low-gain devices, laser action can only be achieved with high-Q cavities ($R_{DBR} > 99.9\%$ and $R_{OC} > 80\%$ but more typically $>97\%$). Re-circulating intra-cavity powers with hundred Watt levels are routinely achieved. This justifies the interest in intra-cavity frequency-doubled operation as a technique to expand the wavelength coverage to the UV-640 nm spectral window otherwise inaccessible to fundamentally emitting SDLs. This research activity started as early as 1999–2000 [57–59] once sufficiently powerful SDLs had been built.

Fig. 9 shows a standard 4-mirror configuration suitable for intra-cavity second-harmonic generation. The key additional component in this laser is the nonlinear crystal which facilitates the conversion of two photons at the fundamental wavelength into one photon at the second harmonic wavelength. This process is characterized by the requirement of momentum conservation, also known as phase-matching. Although three types of phase-matching (type I, II and quasi-phase matching) exist, the choice of the nonlinear crystal is generally based on the crystal presenting a single set of desirable parameters: a high nonlinear coefficient, $d_{eff}$ (to allow the use of short crystal length), collinear (non-critically phase-matched) or slowly divergent (low walk-off) fundamental and harmonic beams (to maximize the harmonic power and beam spatial quality), and large angular, spectral and temperature acceptance bandwidths (to, respectively, enable efficient conversion with tightly focused beams, with a broad linewidth fundamental spectrum and with weak temperature sensitivity). These guidelines for nonlinear crystal selection are justified in detail in reference [60] which models the influence of these parameters on the performance of frequency-doubled SDLs. Although not as essential to the conversion process, other factors such as high damage threshold, absence of hygroscopy and photo-refractive effects are considered as additional favourable features in the nonlinear crystal
selection. Once chosen, the doubling crystal is usually positioned at an intra-cavity mode waist as the conversion efficiency depends on the square of the fundamental power density (see Fig. 9). Mirrors 1 and 2 of the cavity represented in Fig. 9 are arranged to act as a telescope and allow the adjustment of both the waist and the beam divergence through the nonlinear crystal. Furthermore, to meet phase-matching criteria, the fundamental laser polarization state has to be controlled carefully and justifies the use of Brewster’s cut/positioned elements.

In addition to the nonlinear crystal, a spectral filter is generally inserted into the cavity due to wavelength acceptance bandwidth constraints or to meet the application requirements for wavelength stability or continuously-tuneable emission. In light of this observation, the influence of heatspreaders on SDL spectral characteristics should be assessed carefully.

We show in Fig. 10 how the addition of a plane-plane or anti-reflection-coated (AR) wedged 250 μm-thick diamond \(n = 2.42\) heatspreader modifies the gain of a resonant SDL active mirror [48]. The observed broadening of the resonance feature originates from the introduced index-adaptation \((1 < n_{\text{heatspreader}} < n_{\text{SDL chip}})\). In addition, should the heatspreader present parallel surfaces (i.e. be plane-plane), the gain spectrum becomes channelled as a result of the added etalon. Defined fixed-wavelength laser operation can however be achieved with heatspreaders of controlled low (typically < 50 μm) thickness but at the expense of a higher thermal resistance [61]. The use of an AR-wedged heatspreader restores the laser narrow-linewidth and continuous-tunability potential but trades-off these properties with a higher sensitivity to loss because of the reduced composite peak gain [54] (see Fig. 10). We also note that the broadening of the resonance means that the shift of the emission wavelength with temperature or pump power will be less stringently controlled by the sub-cavity and hence exhibits a more complex evolution [48].

3. Direct generation of visible radiation from an SDL

The demonstration of direct generation of visible radiation from an SDL has been achieved with the use of the quaternary alloy AlGaInP, lattice-matched to GaAs, which has a mature growth technology due to the extensive development of red laser diodes. High power visible operation has been demonstrated in a range of SDL formats and the design and optical-pumping arrangements of these lasers will now be discussed.

3.1. General issues related to material and pumping

While the GaInP/AlGaInP material system allows quantum well emission over much of the red spectral region, there are however a number of restrictions in red SDL gain structure design that come into play at short wavelengths. For example, the signal wavelength is now energetic enough to exceed the GaAs bandgap and therefore we must compromise in the design of the AlGaAs DBR. Rather than AlAs and GaAs for maximum refractive index contrast, AlAs and Al\(_x\)Ga\(_{1-x}\)As must be used to avoid absorption, hence increasing the number of DBR layers required to achieve 100% reflectivity and reducing the mirror stop band width. For a design wavelength of 670 nm, the required aluminium fraction in the high index layer is \(x = 0.45\), increasing further with decreasing wavelength.

In the gain region, compressively strained Ga\(_{1-x}\)In\(_x\)P quantum wells \((x < 0.52)\) provide TE-polarised emission from 640–700 nm [62], however at the short wavelength end of this range, the reduction in carrier confinement leads to increased temperature sensitivity. Fig. 12 shows the tuning curves of three different SDLs operating around 645, 665 and 675 nm using 6 nm Ga\(_{0.46}\)In\(_{0.54}\)P QWs, 5 nm
We have since reported Watt-level CW operation at room temperature with the visible diode lasers, such as GaN laser diodes, being not available and therefore the laser of choice was a frequency-doubled Nd:YVO4 laser operating at 532 nm. This is an available and therefore the laser of choice was a frequency-doubled Nd:YAG laser. Richter et al. were the first to take advantage of these as pump sources with the demonstration of a diode-pumped Pr3+-doped LiYF4 laser.

For a red optically-pumped SDL we require a visible pump laser. Lasers are conventionally diode-pumped lasers, however when the red SDL was first investigated, high power visible diode lasers, such as GaN laser diodes, were not available and therefore the laser of choice was a frequency-doubled Nd:YVO4 laser operating at 532 nm. This is an ideal wavelength for pumping the red SDL as it allows us to achieve close to the minimum quantum defect tolerated in this material system while still pumping the QW barriers. The more recent availability of high power GaN laser diodes and their application to red SDLs is discussed in the next section.

The first high power CW red SDL [65] had a relatively simple gain structure design with the bandgap constraints described in the previous section. Grown by MBE on an undoped GaAs substrate, it consisted of a 40 pair AlAs/Al0.45Ga0.55As DBR, 20.6 nm-thick Ga0.45In0.55P quantum wells grouped in pairs positioned at the antinodes of the laser standing wave for resonant periodic gain and separated by (Al0.8Ga0.2)0.51In0.49P barriers. With no suitable material available for a confinement window, the structure was capped with 10 nm of Ga0.51In0.49P. The design wavelength set for the centre of the DBR stopband and RPG peak was 670 nm with a room temperature QW emission offset at 660 nm. At the high operating temperature of the laser, the peak output wavelength was 674 nm. The maximum output power with 2% output coupling was 0.4 W for ∼ 3.2 W input power and the slope efficiency was 17% [65]. This result was later improved with an MOCVD grown structure and increased pump power and output coupling to achieve 1.1 W output power with a slope efficiency of 20% [66].

A potential application for a tuneable red SDL with high beam quality is in the field of atomic spectroscopy, with the 2s-2p transition of the neutral lithium atom in particular falling within the current tuning range (670.8 nm). These applications require stable narrow-linewidth single frequency operation – not usually the natural state of the free-running SDL without additional intra-cavity spectral filtering. Single frequency-operation was demonstrated with the red SDL with the insertion of an intra-cavity tilted etalon and Brewster birefringent filter. Active stabilisation was achieved by mounting the laser output coupler mirror to a piezoactuator in an active feedback loop with locking to a low-finesse Fabry-Perot interferometer. In this way, the laser operated on a single longitudinal mode, linewidth 145 kHz relative to the reference cavity [67].

These results represent the best performance of red SDLs to date, although diode-pumped frequency-doubled GaInNAs SDLs offer an alternative “three-stage” route to short red wavelengths, albeit with lower efficiency [68] (see Sect. 4). Pr3+ fluoride lasers on the other hand offer much better efficiency [30], however these lasers operate on fixed discrete transition lines without the wavelength flexibility and tunability that are the main advantages of SDLs.

3.2. Green-pumped red SDLs

For a red optically-pumped SDL we require a visible pump laser. Lasers are conventionally diode-pumped lasers, however when the red SDL was first investigated, high power visible diode lasers, such as GaN laser diodes, were not available and therefore the laser of choice was a frequency-doubled Nd:YVO4 laser operating at 532 nm. This is an ideal wavelength for pumping the red SDL as it allows us to achieve close to the minimum quantum defect tolerated in this material system while still pumping the QW barriers. The more recent availability of high power GaN laser diodes and their application to red SDLs is discussed in the next section.

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3.3. Diode-pumped red SDLs

GaN laser diodes have recently become commercially available at powers sufficient for optical pumping of visible lasers. Richter et al. were the first to take advantage of these as pump sources with the demonstration of a diode-pumped Pr3+-doped LiYF4 laser [69]. Previously these lasers, which are capable of 4-level laser operation at several discrete emission lines in the visible region, were pumped by Ar ion lasers or frequency-doubled Nd:YAG lasers, however they performed with low efficiency due to the poorly overlap with the absorption peaks of Pr3+. An absorption line exists at 444 nm which is exploited for pumping with long wavelength GaN laser diodes, albeit with a
lower absorption cross-section than that at 479 nm. The alternative is in fact to pump with a frequency-doubled SDL which is tuned to this absorption peak [30].

While the SDL has no such restrictions in terms of spectrally narrow absorption, the main performance limitation for a GaN diode-pumped red SDL is the very short absorption length of the pump light in the red material system. For light of wavelength 445 nm the absorption length in (Al0.6Ga0.4)0.51In0.49P, the material used for the QW barriers, is only 367 nm. Thus we must confine our QWs to the first two antinodes of the laser standing wave (see Fig. 13). An SDL designed for diode-pumping at 445 nm and containing 7 strained QWs in the configuration shown in Fig. 13 has been demonstrated [70]. Output power of 12 mW in a TEM00 output beam with a beam spatial quality factor $M^2 < 1.1$ [71] was achieved for an input power of 600 mW. This was later increased to 18 mW using a similar structure with strain compensated QWs [72]. Interestingly this laser demonstrated a tuning range of 16 nm at these low powers (relative to the green-pumped SDL), most likely due to the short sub-cavity length and low longitudinal confinement factor resulting from such closely-packed QWs.

Frequency-doubled SDL lasers are now commercially available with multi-Watt output power at 532 nm providing the reasonable option of a visible SDL-pumped visible SDL, however we believe that for applications that require compact and efficient operation the further development of the diode-pumped red SDL is the most sensible route.

4. Visible radiation obtained through frequency conversion

As mentioned previously, since there is no commercially-viable and long-lived semiconductor to provide diode-pumped direct emission in the spectral range below 640 nm, the only viable option is to use a frequency-doubling scheme. This section reviews the development of the relevant near-infrared sources and second harmonic generation to the visible.

4.1. Development of high-power infrared SDLs

In the next sections, we will highlight the specific underlying semiconductor structure considerations to produce efficient SDLs emitting in the near-infrared. To ensure SDL commercial viability, high-power pump lasers need to be readily available at low cost and hence 780–810 nm pumps are generally selected. Furthermore, as AlAs/GaAs mirrors can be used in all the devices, the discussion will be essentially focused on the gain section designs and laser performance. Given the different associated challenges, this description has been divided into the following three wavelength bands 920–940, 960–1100 and 1150–1250 nm.

4.1.1. 960 nm–1100 nm SDLs

We start the discussion of near-infrared SDLs with the devices emitting in the 960–1100 nm band, for historical reasons and because of the relatively straightforward designs used here. Indeed, applications as pumps sources for erbium-doped fibre lasers ($\lambda = 976$ nm) and, once frequency-doubled, as replacement technology for the 488 nm-line emission of argon ion lasers were the prime original motivations for the development of these sources. Extension to 1064 nm and the associated frequency-doubled green version came later as the projection/display and other applications emerged (see paragraph 1.2) and the SDL benefits became more obvious.

The design of QW-based SDLs in this wavelength range is simplified by the availability of InGaAs/GaAs QWs, a technology which offers, in this spectral window,
predominantly-TE-polarized high gain at manageable compressive strain levels, as well as a low temperature sensitivity because of large band offsets ($\sim 180$ meV for the conduction band) and low band dispersions (large effective masses). The choice of GaAs as barrier material is also ideal for carrier generation using in-barrier 808 nm pumping. With an absorption coefficient $\alpha = 1.32 \times 10^4 \text{cm}^{-1}$ [73], an overall barrier length of 2.3 $\mu$m allows 95% of the pump photons to be absorbed in a single-pass and 15 antinodes of 1060 nm signal to be accessed for the insertion of QWs. The actual number of QWs and their distribution are then decided based on modelled performance [5, 38, 41–43]. As part of this design process, the QW width is usually varied to optimize the achievable gain. Narrow QWs are generally favoured for their larger subband separation and reduced number of populated subbands for a given band filling energy which results in high gain and lower threshold densities [74]. However, growth reproducibility and carrier thermalisation set a lower limit to the QW width. As an example, we use the model reported in [5], where the carrier distribution is assumed to be uniform, the thermal effects are neglected and an internal efficiency of 75% is considered, to predict the performance of a 808 nm-pumped 1060 nm SDL. Figs. 15 and 16 show that designs with 10 to 15 QWs should allow operation with optimum external mirror reflectivity of $\sim 93\%$, threshold powers of $\sim 0.75$ W and output powers reaching $\sim 2$ W under 10 W of excitation. The 13QW structure of Fig. 3 represents the final design resulting from these calculations. It includes carrier dividing layers and non-uniform distribution of QWs to define areas of constant average carrier density per QW.

After growth by MBE and bonding to a diamond heatspreader, laser performance was recorded for a mount temperature of 7 $\degree$C and an 808 nm pump spot size of 80 $\mu$m-diameter. Fig. 17 confirms that the device characteristics are comparable with the theoretical predictions (Figs. 15 and 16). More accurate numerical predictions should be obtained using more advanced self-consistent models [38, 41, 43] which include temperature dependence and carrier diffusion effects. Taking into account the 20% reflection losses at the front facet of the diamond heatspreader, a maximum net slope efficiency of 28% is achieved.

Using a similar design and thermal management approach, 1060 nm SDLs with 15 strain-compensated InGaAs/GaAs QWs distributed uniformly over 15 antinodes generated, from a $\sim 200$ $\mu$m excitation zone, pump-power limited output powers of 11 W with a slope efficiency of $\sim 50\%$ [75]. Applying similar design principles, but using a combination of large pump spot sizes (0.5–0.9 mm) and thin-devices on diamond submounts for heat removal, very impressive performance from $\sim 980$ nm and 1060 nm SDLs have been achieved [14, 46, 76, 77]. The highest powers recorded to-date reach 30 W at 980 nm with a multimode beam ($M^2 \sim 3$) [14] and 12 W at 1060 nm with TEM$_{00}$ emission [77]. From these results, it can be understood that for devices which present a low thermal resistance mirror, the two thermal management techniques have led to comparable single transverse mode performance but with very different mode sizes.

Two modifications to the strategy described above have been proposed to enhance laser efficiencies. The first technique replaces the GaAs-barriers with composition-graded...
AlGaAs layers to promote capture of pump-generated carriers by the QWs. Experimentally, a \( \sim 20\% \) improvement of the 15\% slope efficiency and of the \( \sim 360 \text{ mW} \) maximum output power was observed [78]. The added growth complexity and potential influence of other parameters (such as gain-cavity offset) on the results has meant that the scheme has not yet been widely adopted. The second approach looks to achieve better performance by reducing the quantum defect and associated pump-induced heating. This method relies on the availability of high-power pump lasers with longer emission wavelengths (940–980 nm) and exploits the in-well pumping scheme. In this case, to ensure sufficient pump absorption, the semiconductor structure is modified to embed a higher number of QWs, a pump retroreflecting mirror and the sub-cavity is tailored to present an additional resonance at the pump wavelength [44, 79]. The QWs can also be positioned at or close to both pump and signal resonances [80].

As a reduction of dimensionality offers prospects of benefits in terms of lower threshold densities, higher temperature insensitivity and potential for extended wavelength coverage, there is interest in developing SDLs with QD-based active regions. First and foremost, a proof-of-principle that QDs are viable gain elements for SDLs was needed. Investigations started with a target emission of \( \sim 1 \mu\text{m} \), a wavelength where proven high-performance operation of edge emitters and VCSELs had already been achieved [81–83]. The constraints imposed here are marginally different from the ones associated with the design of QW-based SDLs. However, the main difficulty is in fact to choose a type of QDs that can provide sufficient gain for operation in SDL format, a task somewhat more involved than for VCSELs (as SDLs typically include 10 QWs against \( \sim 30 \) QWs for VCSELs). More specifically, the parameters of importance to be met by the selected QDs include having a high TE-polarized sheet gain and a high-enough saturation fluence, be resilient enough to be operated at temperatures of \( \sim 50–80 \, ^\circ\text{C} \) and allowing for short minimum plane-to-plane separation.

Sub-monolayer QDs, obtained by stacking repeats of 0.5 monolayer (ML) of InAs and 2.3MLs of GaAs (see Fig. 18), were deemed the most promising since they offer a large ground-state gain and they can be grown with good size uniformity at high densities (\( \sim 10^{11}\text{cm}^{-2} \)) with a minimum stacking distance of 20 nm [82, 83]. Their true 3-dimensional confinement should also provide easy population inversion and good thermal immunity. The only potential drawback is that their columnar nature may favour TM-polarized gain, a subject under investigation [84]. A resonant-type structure including a 35.5 pairs \( \text{Al}_{0.99}\text{Ga}_{0.02}\text{As/Al}_{0.2}\text{Ga}_{0.8}\text{As} \) DBR and using 13 planes of these QDs distributed non-uniformly over 7 antinodes was grown by MOCVD. A diamond heatspreader bonded chip was then pumped over a 180 \( \mu\text{m} \)-diameter spot size using a 808 nm pump. It produced up to 1.4 W of output power with 12.4\% slope efficiency [85].

Another option is to exploit the somewhat more conventional Stranski-Krastanow QDs, but to use their excited-state transition to benefit from a three-fold increase in internal gain. Proof-of-principle of the viability of this approach has been demonstrated with a 1045 nm SDL. The epilayer structure was identical to the SML QD chip, except in this case the QDs were grown by deposition of 2.7ML of \( \text{In}_{0.65}\text{Ga}_{0.35}\text{As} \) followed by a 180 s growth interruption to lead to a QD density of \( \sim 10^{13}\text{cm}^{-2} \). The plane-to-plane separation also needed to be increased to 35 nm to produce layers of identical QDs. Using a heatspreader for thermal management, emission with a 6.7\% slope efficiency and a roll-over limited maximum output power of 0.28 W was achieved [86]. The compromised performance of this laser can, at least in part, be attributed to the effects of ground state recombination.

### 4.1.2. 920 nm–940 nm SDLs

The projection/display application with target blue wavelength in 460–470 nm region has been the main driver for the development of 920–940 nm sources, although other applications may also benefit from the availability of this technology.

The idea of using the same parts (pump, etc.) and design principles for the 920–940 nm devices as for the previously described 960–1100 nm SDLs was very attractive to the laser developers and manufacturers. However, the choice of a 780–810 nm pump turns out to be a real constraint for the design of 920–940 nm SDLs.

Indeed, following the standard approach (described above) suggests using InGaAs QWs with pump-absorbing GaAs-barriers. The resulting conduction band-offset is evaluated to be \( \sim 63 \text{ meV} \). Because of this low-confinement, as the device is pumped harder or as its temperature increases, a significant proportion of carriers would be thermalised to the barriers and be lost through further radiative or non-radiative recombination. To overcome this limitation, it is desirable to keep a low carrier density in the...
QWs and therefore include a high number (20–30) of QWs \[87, 88\]. The addition of AlGaAs carrier-blocking layers to prevent long-range diffusion of carriers in the barriers is also deemed advantageous \[87\] (see Fig. 19). Here again, strain-compensation using GaAsP layers should also be added. The latter would slightly hinder the drift of electrons from the GaAs-barriers to the QW and justify, together with the search for increased confinement, the recently introduced modification of the barrier composition to Al\(_{0.08}\)Ga\(_{0.92}\)As \[88\] (see Fig. 19). Using such an approach, 920 nm SDLs with a slope efficiency as high as 58% and pump-limited output powers of 12 W have been obtained \[88\].

An alternative method is to deliberately choose the barrier material to increase confinement, thereby converting the 780–810 nm excitation to an in-well pumping scheme (see Fig. 19). A 940 nm SDL that had 30 \(\times\) 6 nm-thick In\(_{0.09}\)Ga\(_{0.91}\)As QWs, strain-compensated using GaAs\(_{0.95}\)P\(_{0.05}\) layers and positioned in a uniform 5-\(\Lambda\) RPG active region using In\(_{0.49}\)Ga\(_{0.51}\)P barriers led to the demonstration of 2.9 W with 17.5% slope efficiency as shown in Fig. 20. The single-pass performance could be improved with the addition of a double-band mirror and a pump recycling scheme. Using a similar technique but with AlGaAs as the barrier material and an undisclosed in-well pumping arrangement, Lutgen et al. reported SDLs with up to 5 W of 920 nm emission and 48% slope efficiency \[89\].

### 4.1.3. 1150 nm–1250 nm SDLs

The third wavelength window of near-infrared SDLs under consideration here is the 1150–1250 nm range which, once
frequency-doubled, opens access from yellow to the orange/red part of the visible spectrum. These developments are aimed at bio-photonics applications and for the generation of the most vibrant red colour for projection/display.

From a material perspective, this corresponds to a regime where InGaAs/GaAs technology reaches its two-dimensional-growth critical-thickness limits because of the required amount of compressive strain. Operation of a thin-device-type InGaAs SDL with central emission of 1170 nm and 50 nm-tuning capabilities has nevertheless been demonstrated successfully with up to 7 W of output power and 32% net slope efficiency [90].

As the emission wavelength increases, in particular beyond 1200 nm, the use of alternative semiconductor alloys becomes necessary. Suitable compounds include GaAsSb/GaAs QWs [91], InGaAsN/GaAs QWs [92] and In(Ga)As QDs [81], all of which have been introduced and developed to push GaAs-based technology to 1300 nm for telecommunication applications.

Pioneering work in the 1200–1250 nm band was performed by Gerster et al. [93] who used GaAsSb/GaAs QWs to obtained 1220 nm SDL emission. Although the bulk bandgap of GaAsSb is similar to InGaAs for low antimonide content \((x < 0.5)\), the much lower conduction band offset means that, for the same strain level, slightly longer wavelengths can be obtained using GaAsSb/GaAs QWs [94]. The associated weak electron confinement also means that the developed devices will suffer from high temperature sensitivity. Experimentally, using the thin-device cooling method, a 6QW structure pumped at 808 nm produced up to 93 mW at 1220 nm when the chip temperature was maintained at −15 °C.

The alternative QW-based approach is to use the GaInNAs/GaAs material system. The addition of a small amount of nitrogen to InGaAs not only reduces the alloy lattice constant (see Fig. 4) but also introduces a large reduction in bandgap and a reduced temperature sensitivity [92]. This technique has been used to create diamond heatspreader-bonded SDLs with 10–12QWs with emission covering the 1150–1250 nm band under 780–810 nm pumping [68, 95, 96]. As shown in Fig. 21, performance has reached 3.5 W output power with 20% slope efficiency at 1220 nm with a 20 W, 160 μm pumped area [68]. Similarly, at the slightly shorter wavelength of 1180 nm, a GaInNAs SDL has demonstrated 0.79 W with a slope efficiency of 18.7% for 8 W pump power [96].

A further option to extend the wavelength coverage to the 1200–1250 nm region is to deliberately go beyond the InGaAs critical thickness limit and exploit QD technology. A structure including 27 planes of \(10^{11}/\text{cm}^2\) Stranski-Krastanow QDs distributed over 9 antinodes in groups of 3 with 40 nm separation was grown by MOCVD [97]. Fig. 22 shows the recorded ground state laser characteristics using the optimum 99.8% reflectivity external mirror and a 180 μm pump spot. Changing the mount temperature over the 10–30 °C range suggests that the wavelength of emission is controlled by the resonance of the device and approximately constant power-transfer curves are obtained. The observed low slope efficiency (≈ 1.7%) and thermal behaviour are attributed to the wide bandwidth but low-peak gain of the QDs in use.
4.1.4. Power scaling

The power-scalability of single chip SDLs is expected to be limited by thermal constraints as discussed in paragraph 2.2. and references [11, 76, 98] or by laser action in the semiconductor plane [76]. Heatspreader-bonded devices show reduced thermal resistance for small spot sizes compared to their thin-device counterparts with the difference increasing with mirror thermal resistance [54]. As a result, the heatspreader heat removal technique is to be favoured for devices where thick or thermally insulating mirrors are required (i.e. materials used for emitters in the 670–850 nm range, or those operating beyond 1500 nm) or for devices that are lossy (low growth quality) or require a high carrier density to reach transparency. However, heat extraction using heatspreaders is less power-scalable with spot size than the thin-device option (see Fig. 7 and paragraph 2.2). This means that for emitters in the range 900–1300 nm, where materials offer low thermal resistance, thin-device-cooled SDLs should ultimately reach higher powers than heatspreader-bonded devices, a trend yet to be confirmed experimentally. A survey of all the results published to-date establishes the current maximum power emitted by heatspreader-bonded SDLs to be greater than 12 W (≈ 0.2 mm cavity diameter, single transverse mode) [88] and greater than 30 W (≈ 0.9 mm cavity diameter, multimode) for thin-device SDLs [47]. The thermal limitation to power-scaling is illustrated in Fig. 23 which represents the power transfer characteristics of a 1060 nm heatspreader-bonded SDL recorded for a fixed cavity (TEM$_{00}$ mode size ≈ 60 μm) as the pump is defocused [99]. As expected the pump power required to reach threshold increases with pump area. However, in spite of possible gain extraction by higher order lateral modes, the slope efficiency is seen to degrade with increasing pump size, a characteristic generally associated with increased active region temperature. From this data, the maximum achievable output power is evaluated to be 7 W for this single chip SDL.

To overcome the above-mentioned limitations, the development of lasers with more than one gain chip, a concept originally introduced in doped-dielectric thin-disk lasers for brightness enhancement [8, 100], was investigated with SDLs. Independent reports of multi-chip SDL demonstrations were given by Coherent Inc. [98], by Tampere University of Technology [101] and the University of Arizona [102]. They all conclude (see Fig. 24) that the maximum output power scales linearly with the number of active regions used in the SDL. We note that to extend the concept to more than two chips, a periodic one-to-one image relay from one gain chip to the other with dynamic stability at each gain chip is recommended. Using this technique and a 3-chip frequency-doubled device, up to 55 W of TEM$_{00}$ emission at 532 nm were produced [98].

Alternatively, when the application does not require the laser to be operated in continuous-wave, emission under pulsed pumping is an advantageous way to benefit from “cold” laser characteristics. This is common practice in electrically-driven semiconductor devices and has been used in particular for devices used for micro-display-type projection/display applications [103, 104]. Recent pulsed pumping experiments [105, 106] have shown that this method improves the maximum output power achievable with a given SDL chip as long as the pulse duration is shorter than a few hundred nanoseconds, the typical transient time associated with SDL heating. It was also demonstrated that the use of a heatspreader has negligible impact on laser performance for these considered timescales [105].

4.2. Second harmonic generation from SDLs – covering the entire visible spectrum

Having presented the design and performance of near-infrared SDLs, the next section will focus on demonstrating how the obtained intra-cavity re-circulating powers of the order of a hundred Watts can be usefully exploited to produce visible light by intra-cavity frequency-doubling. The description is divided on a colour basis to match with the respective benefiting applications.
4.2.1. Blue (460–488 nm) emitters

The generation of high-power, high-quality-beam blue light is essential in applications including projection/display, computer-to-plate printing and fluorophore excitation in bio-photonics.

The first demonstration of second harmonic generation to the blue with an SDL was realised with a 2-mirror cavity and a 7.5 mm-long plano-concave KbNO₃ crystal where the concave surface was coated to provide anti-reflection at 490 nm and high-reflection at 980 nm. Up to 5 mW of blue light was obtained for 300 mW of 808 nm pump power. Since then, using the high-performance 920–980 nm SDLs described in paragraphs 4.1.1 and 4.1.2, lithium triborate (LBO) as the frequency-doubling crystal and 4-mirror cavity frequency-doubled doped dielectric lasers [121] and, for the very high powers, by intra-cavity second harmonic conversion of Yb-doped fibre lasers [122] or single-pass second harmonic generation of Yb-doped dielectric lasers [120] and, for the very high powers, by intra-cavity frequency-doubled doped dielectric lasers [121] or single-pass second harmonic conversion of Yb-doped fibre lasers [122].

4.2.2. Green (532 nm) lasers

With applications including projection/display, micro-machining, submarine communications, pump sources, forensics and other bio-photonics imaging, green lasers have received a great deal of attention over the years. In that framework, frequency-doubled 1064 nm InGaAs/GaAs SDLs correspond to a semiconductor-based analogue of diode-pumped doped-dielectric sources but with cost-saving potential and different noise and tuning characteristics.

In practice, intra-cavity second harmonic generation of SDLs to the green has been the most studied nonlinear conversion scheme. As such, demonstrations using a variety of nonlinear crystals have successfully been achieved. Table 1 summarises the different doubling materials used to-date, together with their properties, and the best laser performance that has been obtained.

Table 1 Single-chip green second harmonic SDLs: Nonlinear crystal properties and laser performance [54, 117]. LBO: lithium triborate; BBO: beta-barium borate; BiBO: bismuth triborate; KTP: potassium titanyl phosphate; ppLN: periodically poled lithium niobate; PM: phase-matching; I-c: type I-critical; QPM: quasi-PM; Δλ: wavelength bandwidth (FWHM); Δθ: angular bandwidth (FWHM); ΔT: temperature bandwidth (FWHM); BRF: birefringent filter.

4.2.3. Yellow (577–589 nm) sources

The development of yellow emitters is primarily driven by potential applications in ophthalmology, fluorescence-based biomedical diagnostic and astronomy (D₂ sodium line at 589 nm).

To date, all the reported SDLs emitting in that spectral range have been based on InGaAs/GaAs structures with thin-device thermal management and LBO nonlinear crystal. The latter material is chosen because it offers non-critical type-I phase matching at ∼1200 nm. Sources
emitting at 589 nm and 577 nm have been demonstrated with up to 5 W and 8.5 W output power respectively for 30 W pump power [123, 124].

Emission matched with the D$_2$ sodium line can also be obtained using more complex diode-pumped solid-state lasers for instance by frequency-doubling of Raman-shifted 1060 nm fibre [125] or crystal [126] lasers or by sum frequency mixing of the 1060 and 1319 nm lines of Nd:YAG [22, 127]. Reaching other yellow wavelengths would however really only be possible using frequency-doubling of the recently introduced bismuth-doped fibre lasers [128] or using optical parametric oscillators [129], both of which have their own disadvantages.

4.2.4. Red (620 nm) lasers

Short-wavelength red emission ($\lambda < 640$ nm) is mainly targeted for projection/display and photodynamic therapy applications.

The first demonstration of harmonic red emission was based around a GaAsSb/GaAs SDL structure and the use of LBO as the nonlinear crystal. There, 30 mW of 610 nm emission was produced [93]. The exploitation of GaInNAs technology and diamond heatspreaders for thermal management dramatically improved fundamental performance as explained earlier and, combined with a 4 mm-long BBO crystal, led to the generation of up to 2.7 W of red radiation in spectrally unconstrained operation (see Fig. 25) [68].

Frequency-doubled SDLs emitting in the 600–640 nm range are relatively free from competition. Low-power (<100 mW) edge emitting AlInGaP lasers with TM-polarisation [130] are the only direct III-V semiconductor devices working in that spectral band. Similarly, the 1200–1250 nm window is poorly served by doped dielectric media excluding the emerging bismuth-doped glasses/fibres [131]. Hence, only approaches based on doubled edge-emitting laser diodes as used for blue or green generation look to be likely alternative candidates.

5. UV Generation

The applications rich ultraviolet region of the spectrum has long required compact and tuneable sources not readily achieved for such high photon energies. As demonstrated in Sect. 4, SDLs are particularly suited to intra-cavity frequency-doubling due to their relatively low optimum output coupling of typically a few percent. Therefore the development of the high power red SDL led inevitably to the investigation of intra-cavity second harmonic generation to reach the ultraviolet [66] (see Fig. 26).

5.1. Second harmonic generation

In choosing a nonlinear crystal for frequency doubling the red SDL, the options were limited to those transparent at ultraviolet wavelengths. Beta barium borate (BBO) has transparency down to 190 nm with the advantage of a very high nonlinear coefficient. The main disadvantage of BBO is the high walk-off (see Table 1); after only a short distance through the crystal, the fundamental and second harmonic beams no longer overlap and generation ceases. Another
suitable candidate is LBO, however the low walk-off LBO comes at the price of a much lower nonlinear coefficient and therefore BBO was chosen for the first demonstration. BBO has the advantage of very low temperature sensitivity (FWHM of phase-matched SHG of 55°) so that temperature control of the crystal was unnecessary. A 7 mm-long crystal of BBO, Brewster-cut for type-I phase matching at 674 nm, was inserted at an intra-cavity mode waist of a 4-mirror red SDL cavity. A single-plate, 2 mm-thick quartz birefringent filter, placed in the cavity at Brewster’s angle, allowed wavelength tuning and narrowed the fundamental bandwidth for more efficient SHG.

The maximum UV power achieved in this demonstration was 120 mW at 338 nm, shared equally between two output beams with a maximum pump to second harmonic conversion efficiency of 2%. The output wavelength was tuned over a range of ∼5 nm, centred on 338 nm, by rotation of the birefringent filter (see Fig. 27).

This result demonstrates an all-solid-state system that shows promise as a compact, high-power continuous wave UV laser to rival nitrogen lasers which must operate in a pulsed regime at the fixed wavelength of 337.1 nm [132].

For emission at 320 nm only, the diode-pumped Pr$^{3+}$ laser offers a more efficient alternative via intra-cavity frequency doubling. However for wavelength flexibility, the frequency-doubled SDL offers tunable UV emission from 320–345 nm corresponding to the spectral range of the fundamental emission demonstrated with the AlGaInP material system thus far.

### 5.2. Higher order nonlinear conversion

To access the near-UV (∼340 nm), an alternative to second harmonic generation from direct red-emitting SDLs is frequency-tripled operation of near infrared SDLs. Technically, this is achieved by modifying the second harmonic SDL cavity of Fig. 9 to include a further cavity waist, where an additional nonlinear crystal is inserted to perform sum-frequency-mixing between the second harmonic and fundamental beams (see Fig. 28). This way, emission with output powers up to 1.1 W at 355 nm was obtained (see Fig. 29) from a 1064 nm chip pumped with two 30 W 808 nm diode laser arrays [133].

Emission in the deep ultraviolet was recently demonstrated by Kaneda et al by frequency-doubling the second harmonic output of a 978 nm SDL in an external bow-tie resonator. More than 200 mW continuous wave output power was achieved at 244 nm for 6 W of pump power from an 808 nm laser diode [134]. We note that a similar setup producing more than 1 W of output power at 244 nm has also been developed at Coherent Scotland Inc [135].

### 6. Compact SDLs

In this section, we turn our attention to the miniaturisation of both direct and frequency-doubled emitters. The approach adopted in this case generally consists of (i) limiting the length of the air spaces, (ii) simplifying the cavity and pumping arrangement by using as few and as small components as possible, and (iii) choosing an assembly
sequence involving a small set of robust and alignment-tolerant steps. The next three sections provide an illustration of the above approaches with the description of compact modules, the presentation of the microchip laser (a quasi-monolithic format of SDLs) and finally the introduction of pump integration schemes.

6.1. Compact modules

This section is dedicated to engineering solutions addressing the challenge of producing compact optically-pumped lasers with air-space cavities.

The first and most natural approach involves studying whether the Z-cavities used in the previous demonstrations can be shrunk to the desired size. As shown in reference [77], as long as the laser cavity is chosen to be longer than the Rayleigh range in the nonlinear crystal, it is possible to construct, using a Keplerian or a Galilean telescopic arrangement, a cavity which is dynamically stable at the semiconductor chip. The cavity length limited is thus related to the nonlinear crystal characteristics, in particular its damage threshold and acceptance angle. As a practical validation, a 486 nm SHG SDL using a 3 mm-long LBO crystal and a 15 mm-long cavity was built [77]. TEM$_{00}$ emission with up to 7.3 W of pump-power limited output was achieved. As expected, the cavity length reduction came at the expense of manageable shorter cavity stability ranges and more stringent alignment requirements.

We note that as the cavity length is reduced, it becomes more and more difficult to insert intra-cavity (birefringent, etalon) filters at Brewster’s angle. As a result, a number of techniques that would induce spectral and polarisation selection and still be suitable for compact cavities have been investigated. The first reported method used a combination of thin heatspreader and a short external cavity to produce single frequency operation from a fundamentally-emitting SDL [61]. Although successful, this arrangement does not ensure polarisation selection and imposes length requirements that may be too stringent to be applied in frequency-doubling schemes. The use of intra-cavity gratings was subsequently studied as an alternative technique. Volume Bragg gratings (VBG) [136] and high-reflectivity gratings [137] were demonstrated to stabilize and narrow the linewidth of SDLs but their effective reflectivity was found to be too low to enable efficient frequency-doubled operation. To overcome this limitation, the grating could be used extra-cavity [138] but with no real advantage in terms of footprint reduction.

A second aspect in the miniaturization of SDLs is concerned with the design of a manufacture-friendly small-volume pump assembly. Given the short absorption lengths involved in barrier-pumped SDLs, the pump energy from low-brightness edge-emitting laser diodes is delivered directly rather than via a fibre-coupled arrangement, as the latter pump geometry is not really compatible with very compact packages and introduces unnecessary coupling losses. In the case where the SDL is thermally managed using the thin-device technique, the pump has to be delivered to the top of the SDL chip. However, the mounting of the different elements on a single flat base plate using pick-and-place technique is also desirable. This means that the pump and SDL semiconductor chip can be bonded in a single step but also that beam lifters and deflectors have to be added to the focusing elements to relay the pump beam appropriately. Fig 30 shows a schematic and practical realization of such a pumping scheme as developed at OSRAM OS. Note that pump recycling optics can be also be implemented to use the pump power reflected by the SDL chip surface. With such a system and using a 3 W pump laser, up to 200 mW of green (520 nm) output was generated [139].

The use of an intra-cavity heatspreader to draw the heat out of the SDL chip is an enabling technique for the much simpler back end-pumping scheme illustrated in Fig. 31. Indeed, this thermal management configuration facilitates the use of a pump-transparent but slightly more thermally-resistive semiconductor mirror. Removal of the pump-absorptive substrate using mechanical and chemical etching opens access to the back of the structure for in-line pumping. Subsequent appropriate selection of the pump laser (facet size) and distance to the SDL active region allows the creation of a square pump spot with no need for further optics [140]. Using this arrangement, with a 7 W, 200*1 μm$^2$, 808 nm single laser diode, 535 nm emission with a pump-limited 1.1 W output was achieved [140].

To potentially simplify mass-volume manufacture even further, a quasi-monolithic, self-aligned configuration of fundamental-emitting SDLs was introduced in 2003. As shown in Fig. 32, the so-called “microchip” approach builds on the use of a heatspreader for thermal management by mirror-coating the surface of the heatspreader not in contact with the semiconductor chip, thereby making an all-solid, monolithic laser cavity.
Successful operation at 850 [141], 980 [141], 1300 [142, 143], 670 [144] and 1060 nm [145] has been achieved since then. The red emitter was based on the 20 QW structure described in Sect. 3.1 and a 1% output-coupler-coated diamond heatspreader. When cooled to −5 °C and pumped using 3.3 W of 532 nm, it produced up to 330 mW of emission at 675 nm as shown in Fig. 33. The $M^2$ was measured to vary from $≈ 1.1$ near threshold to $≈ 2$ at full power.

The performance, stability and transverse mode selection in these plane-plane cavity microchip SDLs are inherently set by the pump-induced thermal lens [55], gain profile [55, 143] and the parallelism between the heatspreader surfaces (typically better than 0.33 μm/mm). To obtain more reliable and controlled properties from these lasers, microchip SDLs with plano-concave cavities have been introduced [145]. As illustrated in Fig. 34, they are made by fabricating an array of microlenses onto the outer surface of the diamond heatspreader by resist reflow/inductively coupled plasma etching followed by a mirror coating and bonding to the semiconductor chip. Of critical importance for the laser developer are the thickness of the heatspreader and the microlens radius of curvature (ROC), as these parameters define the cavity mode size (largely constant in these short cavities). In practice, the microlens focal length
is controlled by the thickness of the spun photoresist, the diameter of the disk pattern to be melted and the etching selectivity between the photoresist and heatspreader material [146].

In the first demonstration, it was shown that two methods can be applied to obtain single lateral mode emission from microlensed microchip SDLs [145]. The first approach exploits the finite size of the microlens as an aperture element to prevent higher order mode operation. In this case, compared to the plane-plane configuration, the microlensed emitter suffers from reduced slope efficiency as aperture losses also affect the fundamental mode. The second and more conventional technique to achieve single mode emission is based on mode-matching the pump and cavity modes in the semiconductor active region. In this situation, the microlensed devices showed improved beam quality over the plane-plane cavity lasers whilst maintaining similar power transfer characteristics. The formed microlenses (ROC < 1.7 mm) in 250μm-thick heatspreaders defined 1/e² cavity mode diameters of at most ~20 μm, restricting the achievable maximum power. Using a thicker (500 μm) diamond heatspreader and microlenses with larger ROC (up to 9.4 mm) allowed the investigation of the power-scalability of microlensed microchip SDLs (with cavity mode diameter up to 42 μm). With a nominally R=95% mirror coating and a 1060 nm SDL chip similar to the one used in the first demonstration, we have achieved TEM00 operation of microlensed microchip SDLs with output powers reaching 230 mW (see Fig. 35). We note that, by defocusing the pump, emission with up to 1 W of output could be achieved at the expense of mode-quality.

Given their planar nature, microchip SDLs are particularly suited to array operation. Both fixed [144,147] and dynamically addressable [144] arrays have been demonstrated to-date. Further opportunities in that area may arise with the use of devices with spatially-graded wavelength.
output or through some further power scaling exploiting beam combining techniques.

All the laser results discussed so far have been concerned with continuous-wave operation of the SDLs. Given the modulation requirements for laser display applications, we investigated the behaviour of the 980 nm plane-plane microchip SDL reported in [141] under 80 MHz ∼ 150 fs-pulse excitation from a Ti:sapphire laser operating at 800 nm. As shown in Fig. 36, laser action was obtained when the ∼ 60 μm-diameter spot was pumped with more than 880 mW of average power. The average output power reached 22 mW under 1 W of excitation. The temporal profiles of the produced pulses were then measured using an 18.5 ps recovery time photodiode detector and a 50 GHz oscilloscope which was triggered by a pick-off from the pump beam. As expected for any gain-switched semiconductor laser [148] and observed in Fig. 36 and 37, with increasing pump power, the emitted pulse width decreased to ultimately reach 3.45 ns and the turn-on time increased. The maximum pulse energy achieved is 0.275 nJ which is about half the energy of the best mode-locked pulses produced to-date [149]. This also demonstrates that the pulses produced by SDLs are ultimately controlled by a combination of the lifetimes of the cold-cavity (calculated to be 886 ps here) and gain (typically ∼ 1–2 ns for InGaAs QWs).

6.2. Electrically-injected devices

Returning to the topic of miniaturization, one might consider that the smallest package size will only be achieved with direct electrical injection of SDLs. The technological hurdles associated with this are essentially to create a uniformly-pumped 100-to-400 μm-diameter disk and to overcome thermal heating effects. In the main [103, 104, 150], the latter issue is addressed through the thin-device cooling approach and the use of pulsed pumping. As for the former challenge, two radically different approaches have been proposed to-date (see Fig. 38).

The first proposed injection scheme is an extension to a large area VCSEL pumping arrangement with a bottom disk and a top ring contacts. To obtain “top-hat” carrier distribution while minimizing carrier-absorption losses, the semiconductor chip includes a p-doped bottom DBR, a partial n-doped DBR and a 50–100 μm-thick low-n-doped (mid 1016 cm3) substrate. The latter mirror is added to further promote carrier lateral diffusion and to shield the gain section from some of the (carrier or band-edge related) losses incurred in the substrate. The number of pairs has however to be optimized to maintain a high enough intensity for efficient frequency-doubling in the external cavity. Devices with 100-μm-wide gain apertures, frequency-stabilized us-
ing a VBG and doubled using a 5 mm-long MgO:ppLN crystal were reported to emit up to 34 mW at 532 nm in CW mode [150]. Similarly, a 150-μm-wide device with 10 mm-long ppKTP crystal enabled up to 42 mW of 490 nm to be generated [151].

The second approach is based on the integration of the pump rather than a direct carrier injection scheme [104]. The semiconductor chip in that case effectively includes a standard undoped SDL structure coupled to an edge emitting laser structure also located inside the SDL external cavity (see Fig. 38). The facets of the edge-emitting pump laser(s) are defined by a lithographic/etching process while the carrier injection is accomplished using a transparent low-index p-contact layer. This layer ensures a good confinement of the pump mode in this part of the device while the evanescent coupling layer ensures effective uniform pumping of the SDL active region. Devices with a 400 μm-wide area pumped by 3 in-plane lasers have been demonstrated to emit up to 600 mW at the fundamental wavelength of 1060 nm [104].

7. Concluding remarks

To conclude, we have reviewed the key developments of SDLs and their state-of-the-art performance with a particular focus on frequency-doubled devices emitting in the application-rich visible and ultraviolet spectral windows. Current efforts towards miniaturisation have also been highlighted. The benefits of SDL technology are however not restricted to this wavelength range, as illustrated in the chart of SDL spectral coverage shown in Fig. 39, and in a recent review paper focussed on long-wavelength (λ > 1.2 μm) SDLs [13]. In the region around 1 μm, the engineered thin-device approach has been very successful in terms of power scaling, demonstrating record output powers. Away from
this region the thermal management of SDLs using diamond heatspreaders has enabled operation of devices with high thermal resistance mirrors and hence has extended the spectral coverage of fundamental emission. In addition, the use of the optically contacted heatspreaders has facilitated compact and novel device formats such as the microchip. These devices show very attractive performance in robust configurations with a great deal of versatility. The commercial viability of SDLs will of course depend on market uptake and technical and production-cost comparisons with alternative competitive technologies but, in any case, this will remain a vibrant research area for the foreseeable future.

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