31

Diode-Pumped Alkali Lasers (DPALs)

Boris Zhdanov and Randall Knize

CONTENTS

31.1 Introduction ........................................................................................................................................................................441
31.2 Achievements in DPAL Research and Development.........................................................................................................443
  31.2.1 First Demonstration of Efficient Lasing of an Alkali Vapour Laser ................................................................. 443
  31.2.2 Demonstration of the Highly Efficient Optically Pumped Alkali Laser ......................................................... 443
  31.2.3 Experiments with Alexandrite Laser Pump ........................................................................................................ 444
  31.2.4 First DPAL Demonstration ....................................................................................................................................444
  31.2.5 DPAL Efficiency Increase with the Use of a Narrowband Pump .........................................................................444
  31.2.6 Power Scaling of Alkali Lasers .............................................................................................................................444
  31.2.7 Transverse Pumping ..............................................................................................................................................446
31.3 Conclusions ........................................................................................................................................................................447
References ....................................................................................................................................................................................447

31.1 Introduction

Diode-Pumped Alkali Lasers (DPALs) attract growing interest of researchers during the past 15 years because of their potential to produce high laser power in an excellent quality beam and, thus, they can compete with the best currently available high-power laser systems. But, the history of alkali laser started much earlier, in 1958, even before the first laser demonstration was performed (ruby laser, T.H. Maiman, 1960). In 1958, Schawlow and Townes published their paper “Infrared and optical masers” [1] in which they proposed an optically pumped alkali (Potassium) vapour laser. They called it “optical maser” as the word “laser” was introduced by Gordon Gould later in 1959. Unfortunately, they did not experimentally demonstrate proposed alkali laser at that time. Laser gain in an optically pumped Cs vapour was first demonstrated and measured in 1961 [2], and the first laser action in alkali atoms (Cs) at 7.18 μm was observed in 1962 [3] using an RF-powered helium lamp as a pump source. The lasing efficiency in these experiments was very low, and the output power did not exceed 50 μW. All these experiments were a kind of “prehistory” of DPAL because no diode laser pumping was used that time and output power and efficiency of these lasers were very low.

After these initial experiments with alkali vapours, there were various demonstrations of stimulated emission, gain, amplified spontaneous emission (ASE) and lasing with low power and efficiency in alkali vapours over the next 40 years (see, for example Refs. [4–8]). Numerous theoretical and experimental studies of energy transfer, energy levels mixing and a three-level lasing in alkalis were performed during that time (see, for example Refs. [9–15]), though, an absence of powerful enough narrowband tunable pump laser sources did not allow efficient lasing in alkali vapours and, thus, limited interest to such lasers. However, as a result of these initial research efforts in the field of optically pumped alkali lasers, the basic principles and techniques for creation of population inversion, gain and lasing on D1 transition of an alkali atomic vapour (nP_{1/2} → nS_{1/2}) using optical pumping of the D2 line (nS_{1/2} → nP_{3/2}) were developed. To provide fast population transfer from nP_{3/2} to nP_{1/2} and create population inversion on lasing transition (D1 line), a buffer gas has to be used (usually ethane, methane or He). That is a standard pumping scheme (see Figure 31.1) utilized in all DPALs nowadays.

Using this approach, a concept of DPAL was introduced by Krupke in 2001 [16], when high-power and highly efficient diode lasers appeared in the market. As a proof of this concept, the first really efficient optically pumped alkali laser based on Rb vapour [17] was demonstrated by Krupke and his co-workers in 2003 using a Ti:Sapphire laser for optical pumping, and then, in 2004, they successfully repeat this experiment for Cs vapour [18] with the same pump source. The first true DPAL demonstration [19] based on Cs vapour was performed in 2005.

The first successful demonstration of efficient alkali vapour laser operation convinced several research groups in the United States and abroad to start extensive experimental and theoretical studies of all aspects of DPAL operation and its potential for scaling to high powers (see, for example Refs. [20–26]). Experiments performed during the past decade brought very positive and promising results. A slope efficiency of 81% and an optical efficiency of 63% were demonstrated for a CW operating Cs laser [27] with a Ti:Sapphire laser pump.
There are, however, some problems in using diode lasers for alkali lasers pumping, mainly connected with the relatively broad spectral line width of diode lasers (~1 THz) compared to the absorption line of the alkali vapour gain medium (~10GHz at atmospheric pressure of buffer gas). To achieve an efficient coupling of the pump radiation into the alkali vapour gain medium, it is necessary to match the pump line width and the alkali absorption line width. This requires either spectral line narrowing of the pump radiation or alkali absorption line broadening, or both. Currently, there are two approaches for DPAL development explored by different groups. First approach utilizes low-pressure buffer gas (about 1 atm) and requires spectral narrowing of the pump diode laser emission line to the value about 10–20 GHz. Another approach, so called high pressure approach, requires moderate narrowingbanding of the diode laser pump to the value about 100–200 GHz but has to use high-pressure buffer gas (10–20 atm) and higher gain medium temperatures (200°C–250°C). Both approaches have their pros and cons and are under extensive study by researchers. Illustration of the first approach is presented in Ref. [28], where the authors used a Volume Bragg Grating (VBG) [29] to narrow the diode laser bar emission line width to about 0.2–0.3 nm that was still much broader than the alkali absorption line broadened by a buffer gas with a pressure of several atmospheres. The relatively broad line width of the pump sources in this experiment limited the absorption efficiency, and the slope efficiency for the Cs laser was only 1.8% [28]. There were several other experiments in which the authors used diode laser bars or stacks narrowbanded by VBG to the value of about 0.3–0.5 nm for DPAL pumping. The optical-to-optical efficiencies achieved in these experiments were less than 10% because of bad matching of pump and absorption line widths. Further research on VBG development [30] showed that VBGs can provide much better narrowbanding (below 0.03 nm) for LDAs with a power of several tens of watts. However, implementing VBGs for high-power diode laser stacks can meet technical problems because of their high thermal sensitivity.

Another technique for line narrowing of diode laser bars was developed (Ref. [31]) and provided line narrowing up to 0.03 nm. This allowed demonstration of an efficient CW operation of the Cs laser [32] with 10 W output power, a slope efficiency of 68%, and a total optical efficiency of 63%. Using this narrowbanding technique, the same authors performed a series of scaling experiments with longitudinal [33] and transverse [34,35] pumping using multiple LDAs and both stable [35] and unstable [36] configurations of the laser cavity. This allowed for an increase of the output power of these alkali lasers to a level of tens of Watts, which was again limited by the available pump power. However, these experiments also demonstrated that at power level higher than several tens of Watts, the DPAL efficiency can be affected by such limiting issues as thermal effects [33] and/or photoionization [37]. These problems can, probably, be mitigated by flowing the gain medium through the laser cavity, what was studied in several publications [38,39]. Recent published experiments on power scaling DPAL with flowing gain medium demonstrated output power close to 1 kW for Cs DPAL [40] and about 1.5 kW for K DPAL [41].

Such an extensive research and development of DPALs during the past decade was stimulated by their potential to achieve high power in a high-quality beam as these properties are very desirable for various important applications in science, technology and national security areas. The DPALs have a number of positive features as compared to other high-power lasers (chemical, solid-state and fibre lasers) and do not have the problems which exist in other high-power laser systems that limit their applications. The most important features of alkali laser systems are the following:

**FIGURE 31.1** A standard three-level pump scheme for all optically pumped alkali lasers (a). Table (b) shows operating wavelengths and quantum efficiencies for corresponding alkali atoms.
High quantum efficiency: 95.3% for Cs, 98.1% for Rb and 99.6% for K as compared to 76% for a 1.06 µm Nd:YAG laser.

High quantum efficiency is not only a promising factor for the high overall laser efficiency but also important for minimizing heating problems since the energy defect is usually converted into heat released into the gain medium.

1. Gaseous gain medium is a very important feature because it can be very homogeneous and has excellent optical quality with reduced aberrations, absorbing and scattering centres and refraction index fluctuations. Generally, laser beams generated in a gaseous gain medium have excellent quality and diffraction limited divergence.

2. Reduced thermal problem is one more advantage of a gaseous gain medium. The thermal effects existing, for example, in solid-state lasers and causing aberrations and thermal lensing that degrade the beam quality. The thermal problems in a gaseous gain medium can be significantly reduced or even eliminated by flowing the gain medium.

3. Use of diode laser pumping of the alkali gain medium allows an increase of the total wall plug efficiency of the DPAL system because of very high efficiency of the diode lasers as compared to other pump sources.

4. CW operation is possible for DPALs which is important when high average power is required for the specific application.

5. Scalability to high power is possible by increasing the volume of the gain medium and number of pump diode laser sources. Thus, scaling to high power does not necessarily lead to the high light intensity inside the gain medium, like in fibre lasers. Operating at lower intensities suggests that non-linear optical effects and optical damage will probably not be limiting factors for alkali lasers.

6. Operating wavelengths of all DPALs lie within atmospheric transmission windows (see for example Ref. [41]), which is essential for any directed energy application of DPALs in atmosphere.

7. No hazardous expendable chemicals required for DPAL operation that is a great advantage compared to chemical lasers. In addition, alkali lasers have no chemical waste as they can be constructed in a sealed cell or closed cycle flowing system, eliminating the need for vacuum pumping and discharge of chemicals.

All these properties and features of alkali lasers show that they can be a successful alternative to the most developed high-power laser systems and may even exceed them in many parameters.

There are numerous publications and reviews describing basic principles of the DPAL operation (see, for example Ref. [22,25,43]), which interested readers can study. In this chapter, we present the most important reported experiments and results achieved in the field of DPAL research and development in more detail.

31.2 Achievements in DPAL Research and Development

31.2.1 First Demonstration of Efficient Lasing of an Alkali Vapour Laser

The first experimental demonstration of a really efficient lasing in optically pumped Rb [17] and Cs [18] lasers was performed by W. F. Krupke et al. in 2003–2004. A standard for an optically pumped alkali laser three-level pump scheme (see Figure 31.1 above) with Ethane buffer gas was used in both experiments. An optical pump source was a tunable narrow-band Ti:Sapphire laser with an output power up to 500 mW. A laser cavity design utilized a widely used so call “L-shape” geometry (see Figure 31.2) with separation of the pump and lasing beams by Polarization Beam Splitter. A slope efficiency of 54% and an optical-to-optical efficiency of 16% for Rb laser and 59% slope efficiency and 34% optical efficiency for Cs laser were demonstrated in these experiments. The efficiencies reported in these experiments were “relative to the absorbed power”, and the real efficiencies (relative to the pump power) were several times lower because the line width of the pump laser (30–50 GHz) was broader than the absorption line of the alkali vapour (about 10 GHz for buffer gas pressure about 1 atm). These experiments also showed the importance of narrowing the diode laser pump source to match its line width to the alkali atom absorption line.

31.2.2 Demonstration of the Highly Efficient Optically Pumped Alkali Laser

To demonstrate the potential of alkali lasers to operate with extremely high efficiency, an experiment with Cs vapour laser, for which all important parameters affecting its efficiency were optimized was performed [27]. As a pumping source, a Coherent MBR 110 Ti:Sapphire laser operating at 852 nm (corresponding to the D2 line of Cs atom) in single longitudinal and transverse modes was used. A line width of this laser output was less than 1 MHz, which is much narrower than the Cs vapour absorption line broadened by a 1 atm of ethane buffer gas (10 GHz). The density of the Cs vapour (or its temperature), the output coupler reflectivity and the pump beam matching to the laser cavity mode were experimentally optimized. Lasing...
occurred on the Cs D1 transition with a wavelength 895 nm. Figure 31.3 presents the experimental setup diagram and the dependence of the Cs laser output power on the input pump power showing 81% slope efficiency and 63% overall optical efficiency for the output power relative to the input power.

The output power of this laser was not very high (about 360 mW) because of limited pump power (570 mW), but the slope efficiency demonstrated in this experiment is very close to the calculated value (86%) and is still a world record for optically pumped alkali lasers.

31.2.3 Experiments with Alexandrite Laser Pump

Tunable Alexandrite lasers can cover a spectral range that includes the pumping wavelength for Rubidium (780 nm) and Potassium (766 nm) alkali vapour lasers. Using of a pulsed Alexandrite laser for pumping the alkali vapours can demonstrate alkali laser operation under conditions of a high intensity pump, which could not be achieved with the CW Ti:Sapphire laser. Such experiments with a pulsed Alexandrite laser as a pump source were performed by Zweiback et al. [44] for both Rb and K vapour lasers. This pump laser had a bandwidth of 0.15 nm, produced about 300 ns pulses at 10 Hz repetition rate and provided a maximum peak power up to 75 kW. The pulse duration of 300 ns is long enough for the alkali lasers to operate as a CW laser because of a very short laser cavity build-up time. On other hand, the pulsed operation with low repetition rate allows to eliminate thermal effects, which can strongly affect laser operation at high average power (see, for example Ref. [33]). In these experiments authors used a longitudinal pumping geometry or, so called, end pump (similar to presented on Figure 31.2) and stable resonator. Optical-to-optical efficiencies of 64% for Rb and 60% for K lasers were demonstrated (see Figure 31.4), promising efficient operation of alkali lasers when scaling to high-power levels.

31.2.4 First DPAL Demonstration

The first real DPAL i.e. alkali laser operating with a diode laser pump was demonstrated in 2005 using a Cs-Ethane mixture [19]. A narrowband diode laser operating at 852 nm (SDL-8630 with a line width less than 1 MHz was used to pump a 5 cm long Cs vapour cell with 100 torr of Ethane buffer gas. The gain medium was longitudinally pumped through the one of the cavity mirrors. A maximum slope efficiency of 41% and a maximum output power of 130 mW were obtained in this experiment. The efficiency of this laser could be higher if the pump beam (which had an elliptical cross section) would better match the laser cavity mode. And output power of this DPAL was low because of the limited pump power. The way to increase DPAL output power is to use high-power diode laser bars and stacks with narrowbanded emission line.

31.2.5 DPAL Efficiency Increase with the Use of a Narrowband Pump

The first experiment on pumping Cs vapour laser by narrowband diode laser bar [32] (line width about 10GHz) demonstrated an optical-to-optical efficiency of 62% with a slope efficiency of 68%. The laser cavity arrangement was similar to the one presented in Figure 31.4. The L-shape 51 cm long laser cavity consisted of a flat output coupler (20% reflectivity at 894 nm) and a high reflective 50 cm radius concave back mirror. A 2 cm long cell with antireflection coated windows was filled with metallic cesium and 500 torr Ethane and placed in a heated oven with a temperature 92°C. An output power of 10 W was obtained using 16 W of an incident LDA pump. These CW efficiencies and output power were about an order of magnitude higher than the previous results obtained for diode laser bar pumped pulsed alkali laser [28] and were related to the total pump power, not to the “absorbed power”.

31.2.6 Power Scaling of Alkali Lasers

Scaling of alkali lasers to higher powers requires using multiple diode laser sources for pumping. First scaling experiments using longitudinal pumping of alkali gain medium from two sides of the alkali cell [33] were performed using two LDAs for Rb DPAL (see Figure 31.5a) and four LDAs for Cs DPAL (Figure 31.5b). In these experiments, an output power up to 17 W with slope efficiency 53% for Rb DPAL and 48 W with slope efficiency 52% for Cs DPAL were demonstrated.

It is worth noting that the experiment presented in Figure 31.5b also demonstrated for the first time that DPAL power scaling can suffer from some parasitic effects limiting their output power. Figure 31.6 presents results of measurement of the Cs DPAL output power for two modes of operation:
CW and pulsed with pulses duration of 100 msec and repetition rate of 1 Hz. In the pulsed mode, the Cs laser output power grows linearly with the pump power and reaches 48 W at 98 W pump power that results in 52% slope efficiency and overall optical efficiency of 49%. In the CW mode, the relationship between the pump power and output power is no longer linear as starting from 30 W pump power it rolls over and even drops at higher pump powers. Such behaviour can be explained by thermal effects created by the heat released into the Cs vapour gain medium due to the energy defect between the D1 and D2 Cs lines ($554 \text{ cm}^{-1}$). The quantum efficiency of the Cs laser is $\frac{\lambda_{D1}}{\lambda_{D2}} = 95.3\%$, which means that 4.7% of the pump power is released as heat into the gain medium. Another possible limiting effect that can cause the efficiency decrease is ionization of the gain medium in the high intensity pump and lasing beams [37], resulting in decrease of neutral alkali atoms density and, thus, the gain. To mitigate both these limiting effects, the flowing of the gain medium is required. The flow can both remove the excessive heat and replenish density of neutral alkali atoms required for gain and lasing.

An experiment on Cs vapour laser with flowing gain medium, performed by the Russian group in 2012 [40], demonstrated about 1 kW output power with 48% optical-to-optical efficiency that showed effective mitigation of the limiting effects mentioned above. The authors of this work used longitudinal pumping of the gain cell from both sides by multiple diode laser stacks (see Figure 31.7). The combined spectral width of the pump radiation from all diodes was about 0.7 nm (or about 300 GHz). The gain medium was a mixture of Cs vapour with He and Methane (CH4) at total pressure from 1 to 5 atm and it was kept at about 150°C. The partial pressure of methane varied in the range 0.1–1 atm. The gain medium
was flown through the cell with a flow rate about 20 m s\(^{-1}\). According to the data provided in this paper, matching of the pump spectral line width to the absorption band of Cs vapour broadened by buffer gas was not perfect because even at 5 atm pressure, the Cs absorption line width is about 80 GHz, which is four times less than the pump radiation band. At the lower pressures, this ratio is even worse. In spite of this, the optical efficiency demonstrated in this work was high enough, but, probably could be higher with better matching of the pump and absorption line widths.

### 31.2.7 Transverse Pumping

A transverse pumping geometry, which is widely used in solid-state lasers, has many advantages for high-power lasers compared to the longitudinal pumping. First of all, it only has technical limitations on the number of pump sources used that allows coupling much higher pump power into a gain medium compared to the longitudinal pumping. Then, there is no problem with spatial separation of the pump and lasing beams because they use different windows of the gain cell. The downside of the transverse pumping is that it is more difficult to match the pump and laser mode volumes, especially when the stable laser resonator is used. An unstable resonator can solve this problem because the laser mode of such resonator can fill the whole gain medium.

To study the operation of DPAL with transverse pumping, an experiment [34] with a Cs vapour laser transversely pumped by 15 narrowband LDAs with total power of about 200 W through the side of the gain cell (see Figure 31.8a) was performed. A Cs vapour cell with 100 torr of Ethane and 500 torr of He mounted inside a cylindrical white diffuse reflector was placed inside a temperature-controlled oven. Both the reflector and the oven had a 2 mm × 50 mm side slit for coupling the pump beams into the cell. The stable laser cavity was made by a 50 cm concave back mirror and a flat output coupler with 20% reflection at 894 nm.

To avoid thermal effects in cesium vapour that was observed previously [33], the Cs laser was pumped by pulses with duration of 500 \(\mu\)s and repetition rate of 20 Hz. A maximum output power about 28 W with a slope efficiency of 15% and maximum optical efficiency of 14% were demonstrated in this experiment. The lower value of the slope efficiency compared to the longitudinally pumped Cs laser (68% in Ref. [32]) can be caused by a poor pump coupling efficiency: the laser cavity mode size inside the Cs cell was about 600 \(\mu\)m and the size of the diffuse reflector was 1 cm. To increase the pump efficiency, the laser cavity must have a mode size close to the illuminated volume inside the reflector filled with gain medium. This can be performed by using an unstable laser resonator.

A Cs laser with an unstable resonator and transverse pumping of the gain medium was explored in Ref. [35] (see Figure 31.8b). In this experiment, the Cs cell diameter was increased to 7 mm to better fill the diffuse reflector volume compared to design used in Ref. [34] (Figure 31.8a). The unstable confocal laser resonator was constructed of concave and convex high reflecting mirrors and the laser output beam, which was the light that escapes the cavity around the perimeter of the small concave mirror, had a doughnut shape with external diameter about 7 mm (the Cs cell internal diameter) and the hole diameter about 2.8 mm (convex mirror diameter). An effective output coupler reflectivity was approximately 16%.

In this experiment, a maximum output power of 49 W with the slope efficiency of 43% was obtained when being pumped with 160 W. The maximum optical-to-optical efficiency was 31%. The efficiencies achieved in this experiment are more than twice of that in the previous experiment utilizing the transversely pumped Cs laser with a stable resonator [34]. This increase in performance can be contributed to the better overlap between the lasing mode and pumped volume of the gain medium when using the unstable cavity geometry. However, the slope efficiency of this system is still lower than that for longitudinal pumping (81% for Ti:Sapphire pump [27]).
and 68% for diode laser pump [32]). This difference can be due to nonhomogenous pumping of the whole volume of the gain medium through the narrow slit. This assumption is supported by the observed output beam profile, which had elliptical doughnut shape instead of circular. In addition, there can be pump power losses because of multiple reflections of pump beams off the diffuse reflector. Improvements in the design of the transverse pumping system may result in an increase of the laser pumping efficiency.

### 31.3 Conclusions

We presented a historical prospective of DPAL research and development and a review of the main achievements in this field, demonstrating the high potential of alkali lasers as a scalable source of high-power laser radiation in the near-infrared range. The remarkable properties of these lasers, such as high wall plug efficiency, high beam quality, scalability and no consumables make DPAL systems very attractive for many important scientific, medical, technological and military applications. At the same time, we have to note that there are several challenges in DPAL high-power scaling, which need to be addressed and investigated. Among them, we can mention chemical interaction of alkali vapor with buffer gases and other elements of the DPAL system, damage of alkali cell windows, ionization of the gain medium and others.

### REFERENCES