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Review of alkali laser research and development

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Abstract. In this review we present an analysis of optically pumped alkali laser research and development from the first proposal in 1958 by Schawlow and Townes to the current state. In spite of the long history, real interest in alkali vapor lasers has appeared in the past decade, after the demonstration of really efficient lasing in Rb and Cs vapors in 2003 and the first successful power scaling experiments. This interest was stimulated by the possibility of using efficient diode lasers for optical pumping of the alkali lasers and by the fact that these lasers can produce a high quality and high power output beam from a single aperture. We present a review of the most important achievements in high power alkali laser research and development, discuss some problems existing in this field, and provide future perspectives in diode pumped alkali laser development.

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1 Introduction

Historically, the first proposed laser was an alkali laser. Schawlow and Townes proposed a design of an optically pumped potassium vapor laser in 1958.¹ They called it “optical maser” as the word “laser” was invented by Gordon Gould only in 1959. Unfortunately, they didn’t experimentally demonstrate this laser at that time, and the first laser demonstration was performed by Maiman in 1961 with a ruby laser.² Laser gain in an optically pumped Cs vapor was demonstrated and measured in 1961,³ and the first laser action in alkali atoms (Cs) at 7.18 μm was observed in 1962 using an RF-powered helium lamp as a pump.⁴ The lasing efficiency in these experiments was very low, and the output power did not exceed 50 μW .

After these initial experiments with alkali atoms, there were various demonstrations of stimulated emission, gain, and amplified spontaneous emission (ASE) in alkali vapors over the next 40 years (e.g., see Refs. 5–13). Numerous theoretical and experimental studies of energy transfer, energy levels mixing, and a three-level lasing in alkalis were performed during that time,^{14–27} but an absence of powerful enough narrowband tunable pump laser sources did not allow efficient lasing in alkali vapors until the beginning of the new millennium. The first really efficient lasing in pulsed and continuous wave (CW) operation in Rb and Cs vapors was observed in 2003 to 2005,^{28,29} using a Ti:sapphire laser for optical pumping. The first diode pumped alkali laser (based on Cs vapor) was demonstrated in 2005,³⁰ and the first optically pumped Potassium laser was realized in 2007.³¹

After these first demonstrations of efficient alkali lasers operation, several research groups in the United States and abroad started extensive experimental and theoretical studies of all aspects of diode pumped alkali laser (DPAL) operation such as collisional processes, line broadening,

DPAL modeling, etc. (e.g., see Refs. 32–39). Experiments performed during the past decade demonstrated high efficiency of alkali lasers and their potential for power scaling. The best result obtained with a Ti:sapphire laser pump was an 81% slope efficiency and 63% total optical efficiency for a CW operating Cs laser.⁴⁰ (The “slope efficiency” is the slope of the curve obtained by plotting the laser output power versus the pump power after threshold. The “optical efficiency” is the ratio of the laser output power to the pump power.) The first DPAL based on a Cs-ethane mixture with a buffer gas pressure of 600 torr demonstrated a slope efficiency of 41% and an overall optical efficiency of 32%. But the output power in all these experiments didn’t exceed the 1 W level. The way to significantly increase the output power of alkali lasers and, at the same time, the total wall plug efficiency is to use high power laser diode arrays (LDAs) or stacks of arrays for optical pumping of alkali lasers. There are, however, some problems in using diode lasers for alkali lasers pumping, mainly connected with the relatively broad spectral linewidth of diode lasers and their poor beam quality. There are several publications^{41,42} devoted to techniques for using LDAs for alkali laser pumping. The linewidth of the LDA in these experiments was narrowed to about 0.2 to 0.3 nm using a volume Bragg grating (VBG), but it was still much broader than the alkali absorption line broadened by a buffer gas with a pressure of several atmospheres. The relatively broad linewidth of the pump sources in these experiments limited the absorption efficiency. The slope efficiency for the Rb laser⁴¹ was about 10% and 1.8% for the Cs laser.⁴² Both of these lasers were pulsed, and the peak power did not exceed 1 W and 0.27 W for the Rb and Cs lasers, respectively. Another line-narrowing approach for LDA developed in,⁴³ allowed demonstration of an efficient CW operation of Cs laser with 10 W output power, a slope efficiency of 68% and a total optical efficiency of 63%.⁴⁴ The same approach applied to a Rb laser resulted in demonstration of 8 W of output power with a slope efficiency of 60% and a total optical efficiency of 45%.⁴⁵ Using this narrowbanding technique

the same authors performed a series of scaling experiments with longitudinal^{46,47} and transverse^{48,49} pumping using multiple LDAs and both stable and unstable^{49,50} configurations of the laser cavity. This allowed for an increase of the demonstrated output power of these alkali lasers to a level of tens of Watts. Recent experiments with high power diode laser stacks pumping reported in Ref. 51 demonstrated output power of a Cs laser close to 1 kW.

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. These lasers have a number of positive features as compared to other high power lasers (chemical, solid state, fiber lasers) and do not have the problems that exist in other high power laser systems and limit their applications. The most important features of alkali laser systems are the following.

- (1) *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 is also important for minimizing heating problems since the energy defect is usually converted into heat released into the gain medium.
- (2) *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 centers, and refraction index fluctuations. Generally, laser beams generated in gas gain medium have excellent quality and diffraction limited divergence.
- (3) *Reduced thermal problems* is one more advantage of a gas gain medium. The thermal effects existing, for example, in solid state lasers cause 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.
- (4) 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.
- (5) *CW operation* is possible for DPALs, which is important when a high average power is required for the specific application.
- (6) *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 fiber lasers. Operating at lower intensities suggests that nonlinear optical effects and optical damage will probably not be limiting factors for alkali lasers. In addition, recently performed intensity scaling experiments for the Rb laser^{52,53} at pump intensities as high as 1000 times threshold demonstrated linear scaling of output intensities.
- (7) *Operating wavelengths* of all DPALs lie within atmospheric transmission windows (e.g., see Refs. 54 and

55), which is essential for any directed energy application of DPALs in atmosphere.

- (8) *No hazardous expendable chemicals* are required for DPAL operation, which 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.

2 Experiments with Titanium-Sapphire Laser Pump and Other Surrogate Pump Sources

2.1 First Demonstration of an Efficient Alkali Laser

The first demonstration of an efficient lasing in alkali vapor gain medium was performed by Krupke et al. in 2003,²⁸ and their work introduced a new concept in alkali lasers R&D: the concept of a high power DPAL. A standard for all alkali lasers, the three-level pump scheme (Fig. 1) described by Konefal²⁷ was used to create population inversion on the D1 transition of Rb atoms (795 nm). As a pump source they used a 500-mW Ti:sapphire laser resonant to the rubidium D2 line (780 nm). The ethane buffer gas (at a pressure of 75 torr) provided effective collisional transfer from the $P_{3/2}$ state to the $P_{1/2}$ state.

A slope efficiency of 54% and an optical-to-optical efficiency of 16% were demonstrated in this experiment. The same authors repeated this experiment with a Cs laser²⁹ in 2004 and obtained a 59% slope efficiency and 34% optical efficiency. 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 linewidth of the pump laser (30 to 50 GHz) was broader than the absorption line of the alkali vapors (about 10 GHz). These experiments also showed the importance of narrowbanding the diode laser pump source to match its linewidth to the alkali atom absorption line.

2.2 Demonstration of a Cs Laser with 81% Slope Efficiency

To demonstrate the potential of alkali lasers to operate with extremely high efficiency, we performed an experiment⁴⁰ in which all important parameters affecting the Cs laser efficiency were optimized. As a pumping source, we used a Coherent MBR 110 Ti:sapphire laser operating at 852 nm

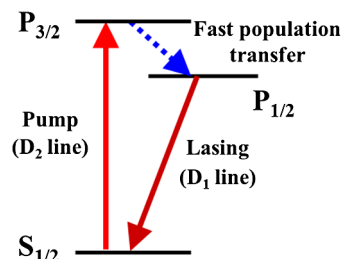


Fig. 1 Alkali laser energy level diagram.

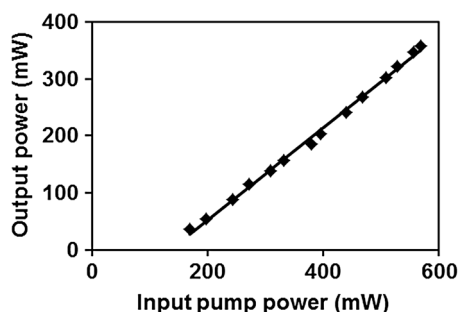


Fig. 2 Output power of the optimized Cs laser versus incident pump power.

(corresponding to the D2 line of Cs atom) in a single longitudinal mode with a linewidth less than 1 MHz, which is much narrower than the Cs vapor absorption line broadened by a 1-atm of ethane buffer gas (10 GHz). The density of the Cs vapor (or its temperature), the output coupler reflectivity, and the pump beam size were also experimentally optimized. Lasing occurred on the Cs D1 transition with a wavelength 895 nm. Figure 2 presents 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 low pump power (570 mW), but the slope efficiency demonstrated in this experiment is still a world record for optically pumped alkali lasers.

2.3 First Potassium Laser Demonstration

The first demonstration of an optically pumped potassium laser³¹ was performed in the USAFA lab using the same pumping Ti:sapphire laser as mentioned above. The pumping scheme was identical to one presented in Fig. 1: pumping the D2 line (766.7 nm) and lasing on the D1 line (770.1 nm). The K laser has a quantum efficiency of 99.6%, but the small separation of the pumped ($P_{3/2}$) and lasing ($P_{1/2}$) energy levels (57.7 cm^{-1}) decreases the population inversion on the lasing transition and, hence, leads to higher threshold and lower gain.

The experimental setup is presented in Fig. 3. The 2-cm-long sealed cell with K vapor and 500 torr of ethane buffer gas had windows AR coated on both sides (external and internal) and was kept at 98°C. The pump and lasing beams were orthogonally polarized and separated using polarizing beam splitter. The lasing threshold in this experiment appeared to be about 5 times higher than for Cs laser and

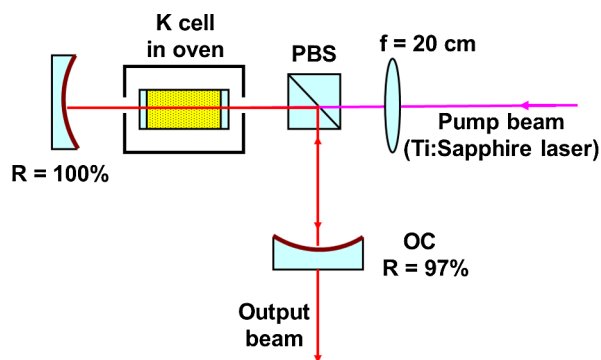


Fig. 3 Schematic diagram of the K laser experimental configuration.

the maximum output power of 14 mW was again limited by the power of the pumping source.

2.4 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 vapor lasers. Using of a pulsed alexandrite laser for pumping the alkali vapors can demonstrate alkali laser operation under conditions of a high intensity pump, which could not be achieved with CW Ti:sapphire laser. Such experiments were performed by Zweiback et al.⁵⁶⁻⁵⁸ for both Rb and K vapor lasers using a pulsed alexandrite laser as a pump source. This pump laser had a bandwidth of 0.15 nm and 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 buildup 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.⁴⁷

In these experiments authors used a longitudinal pumping geometry or the so-called end pump (similar to presented in Fig. 3) and stable resonator. Optical-to-optical efficiencies of 64% for Rb and 60% for K lasers were demonstrated, promising efficient operation of alkali lasers when scaling to high power levels.

3 Experiments with Diode Laser Pump

All of the experiments described above demonstrated high potential of alkali lasers as a novel light source, which can be useful for many applications. However, the average output power of alkali lasers pumped by a Ti:sapphire laser and other surrogate (non-diode laser) pump sources does not usually exceed the 1-W level because of the limited power of a pump laser. In addition, the total wall plug efficiency of such devices is very low because of a low efficiency of the pump sources. That is why, from the very beginning of alkali laser research and development, a lot of effort was devoted to using efficient and high power diode lasers as a pump source for alkali lasers.

3.1 First Diode Pumped Alkali Laser

The first alkali laser operating with a diode laser pump was demonstrated in 2005 by USAFA research group using a Cs-ethane mixture.³⁰ We used a narrowband diode laser operating at 852 nm (SDL-8630, linewidth is less than 1 MHz) and a 5-cm-long Cs vapor 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 match the laser cavity mode.

The first experiments on alkali pumping with high power LDAs were performed by Page et al.⁴¹ for Rb and by Wang et al.⁴² for Cs vapors. The linewidth of the LDAs in these experiments was narrowed to about 0.2 to 0.3 nm using a VBG, which was much broader than the alkali absorption line broadened by low pressure buffer gas. For this reason, the lasing efficiencies and output power demonstrated in

these experiments were low. The slope efficiency for the Rb laser⁴¹ was about 10% and 1.8% for the Cs laser.⁴² Both of these lasers were pulsed, and the peak power did not exceed 1 W and 0.27 W for the Rb and Cs lasers respectively.

Significant improvement in DPAL efficiency can be achieved by matching the pump spectral linewidth to the absorption band of an atomic alkali vapor broadened by buffer gas (about 10 GHz for 1 atm of buffer gas pressure). Our first experiment on pumping Cs vapor laser by narrowband LDA (linewidth about 10 GHz) demonstrated an optical-to-optical efficiency of 62% with a slope efficiency of 68%.⁴⁴ The LDA used in this experiment was narrowbanded using the line-narrowing technique, developed at the USAFA⁴³ and had a linewidth that nearly perfectly fits to the Cs absorption line broadened by a buffer gas with a pressure of about 1 atm. The laser cavity arrangement was similar to the one presented in Fig. 3 for the K laser. The L-shape 51-cm-long laser cavity consisted of a flat output coupler (20% reflectivity at 894 nm) and a highly reflective 50-cm-radius concave back mirror. A 2-cm-long cell with antireflective-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 incident laser diode array pump. These CW efficiencies and output power were about an order of magnitude higher than the previous results obtained for LDA pumped pulsed alkali lasers^{41,42} and was related to the total pump power, not to the “absorbed power.”

3.2 Diode Pumped Rubidium Laser

We implemented the technology developed for the LDA pumped Cs vapor laser⁴⁴ to a Rb vapor laser.⁴⁵ Using a narrowband LDA operating at 780 nm with maximum power of 17.8 W, we obtained efficient lasing in Rb vapor at 795 nm with maximum output power of 8 W and slope efficiency 60%. The overall optical efficiency was 45%. In this experiment we employed the laser cavity design identical to that described above for the Cs laser (Sec. 3.1) with a replacement of the Cs cell by a Rb cell with 600 torr of ethane. The cavity mirrors were replaced to ones suitable for a 795 nm lasing wavelength. The experimental dependence of the Rb laser output power on the pump power was measured for the output couplers with reflectivities 33, 21, and 11% (see Fig. 4). The corresponding measured values of the slope efficiencies for these output couplers are 40, 49, and 60%.

The optimal Rb cell temperature that provided the maximum output power in this experiment was determined experimentally and appeared to be in the range 103°C to 106°C, which is about 40°C lower than in previous experiments⁴¹ (about 150°C) because of the narrower pump radiation linewidth (10 GHz in our case, compared to 120 GHz in Ref. 41). The lower cell operation temperature is much preferable because of lower probability of the cell contamination by products of chemical reactions between the alkali atoms and a buffer gas (see below and Refs. 45, 59, and 60). In our experiments we did observe a decrease in the Rb laser output power after several hours of CW high power operation caused by windows contamination even at operating temperatures of 110 to 120°C.

There were several experiments on diode laser pumping of Rb laser performed by other research groups,^{41,42,61–64} which used diode laser arrays or stacks narrowbanded by

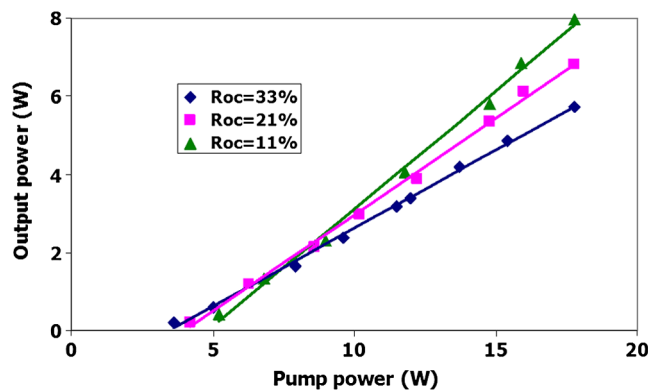


Fig. 4 Output power of the Rb laser as a function of input pump power for different output couplers (33, 21%, and 11%). For the optimal output coupler of 11%, the data shows 60% optical-to-optical slope efficiency, a 45% overall efficiency, and an output power of 8 W.

VBG to the value of about 0.3 to 0.5 nm. Such pumping linewidth is not narrow enough to match the absorption line of Rb vapor broadened by buffer gas with about 1 atm pressure. That is why the optical-to-optical efficiencies achieved in these experiments were less than 10%. Later research on diode laser line narrowing^{65,66} showed that VBGs can provide much better narrowbanding (below 0.03 nm) for laser diode arrays with a power of several tens of watts. But, implementing of VBGs for high power diode laser stacks can meet technical problems because of the high thermal sensitivity of VBGs.

The importance of pump diodes linewidth narrowing to fit the absorption band of alkali gain medium was demonstrated in experiments with extremely narrowband pump diode laser.⁶⁷ Authors of this work used diode laser with a linewidth about 1 MHz (Sacher Lasertechnik, Germany) for pumping Rb vapor with low pressure (50 to 400 torr) buffer gas and demonstrated the highest (for that time) DPAL slope efficiency: 69%. There is no one publication demonstrating such a high DPAL efficiency with a pump source having linewidth broader than the alkali gain medium absorption line.

4 Power Scaling of Alkali Lasers

4.1 Power Scaling Using Longitudinal Pump

Scaling of alkali lasers to higher powers requires using multiple diode laser sources for pumping. We performed several experiments on longitudinal pumping of alkali lasers with multiple LDAs. Figure 5 shows the experiment apparatus for longitudinal pumping of a Rb laser by two CW LDAs with a total power of 37 W.⁴⁶ The two pump beams entered the Rb cell from opposite sides collinear with the lasing beam (and the laser cavity axis). To separate the pump and lasing beams (which had orthogonal polarizations), we used two polarizing beam splitting cubes (PBS). The Π shape laser cavity had a length of 40 cm and was created by a highly reflective 50-cm-radius concave back mirror and a flat output coupler. The optimal reflectivity (11%) of the output coupler was determined experimentally. The maximum output power of 17 W was obtained in this experiment with a slope efficiency of 53% and maximum overall optical to optical efficiency of 46%.

As a next step in alkali laser power scaling using a longitudinal pump, we performed experiment on pumping a Cs

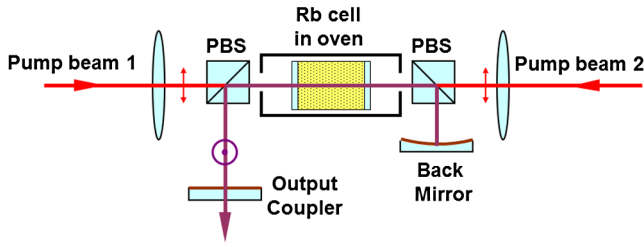


Fig. 5 Schematic of the experimental setup for longitudinal pumping of Rb laser.

vapor laser by four LDAs.⁴⁷ The experimental setup is presented in Fig. 6. The Cs cell and oven designs were the same as in previous experiments. The 40-cm-long Cs laser cavity, which had a “II” shape, was made by two mirrors: a 50-cm-radius concave back mirror with near 100% reflection at 894 nm and a flat output coupler with 20% reflection at 894 nm. The cavity included two dichroic mirrors (DM), which had high reflections (98.8%) at 894 nm for s-polarization and high transmissions (88%) at 852 nm for unpolarized light, both at a 45 deg angle of incidence. The dichroic mirrors were used for separating the lasing radiation (894 nm) from pumping radiation (852 nm), which entered into the Cs cell from both sides through these mirrors. Each of the four pump beams was focused into the center of the Cs cell by lenses (L) with a focal length of 20 cm. A pair of pump beams (#1 and #2, see Fig. 6) having orthogonal polarizations were combined in a PBS before entering the Cs cell from one side. The same was done for another pair of pump beams (#3 and #4), which entered the Cs cell from the opposite side. The pump beams were generated by narrowband LDAs with external cavities using techniques described earlier.⁴⁰ The maximum power of each pump source was about 25 W, and their linewidth was less than 10 GHz.

We studied the operation of the Cs laser in both CW and pulsed operation with pulse duration of 100 ms and repetition rate of 1 Hz. The results of the experiment are presented in Fig. 7. In pulsed mode, the Cs laser output power grows linearly with the pump power and reaches 48 W at 98 W pump power, which results in 52% slope efficiency and overall optical efficiency of 49%. In 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 behavior can be explained by thermal effects created by the heat released into the Cs vapor gain medium due to the energy defect ΔE between the D1 and D2 Cs lines (554 cm^{-1}). The

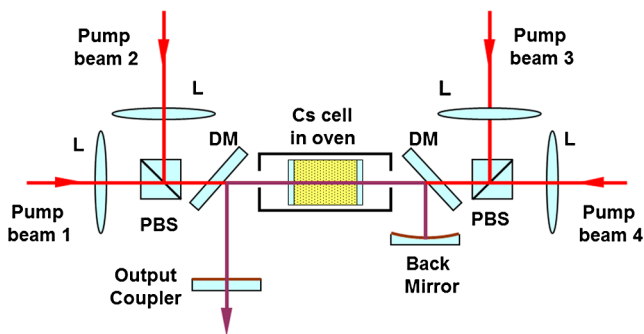


Fig. 6 Schematic diagram of the Cs laser configuration with four LDAs pumping.

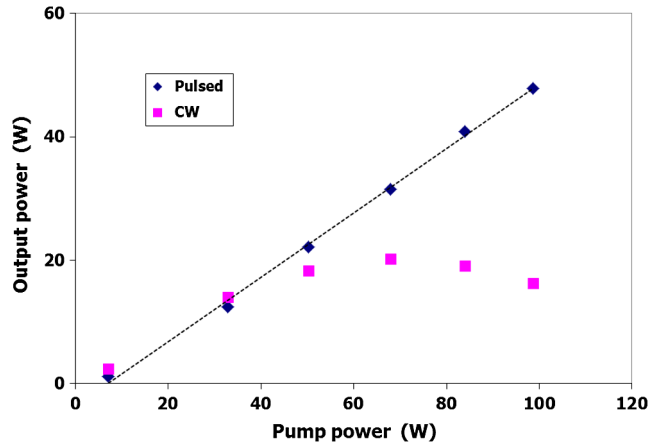


Fig. 7 Cs laser output power for pulsed (diamonds) and CW (squares) operation depending on the pump power. The dashed line is a linear fit to the pulsed operation data showing a 52% slope efficiency.

quantum efficiency of the Cs laser is $\lambda_{D1}/\lambda_{D2} = 95.3\%$, 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 beams⁶⁸ 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.

A recent experiment on lasing in the flowing Cs-CH₄-He mixture with high power pump⁵¹ demonstrated about 48% optical-to-optical efficiency at kW power level that showed effective mitigation of these limiting effects. The authors of this work used end pumping of the cell with flowing gain medium by multiple diode laser stacks with total power about 2 kW and obtained the output laser power close to 1 kW.

4.2 Transversely Pumped Cs Laser

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

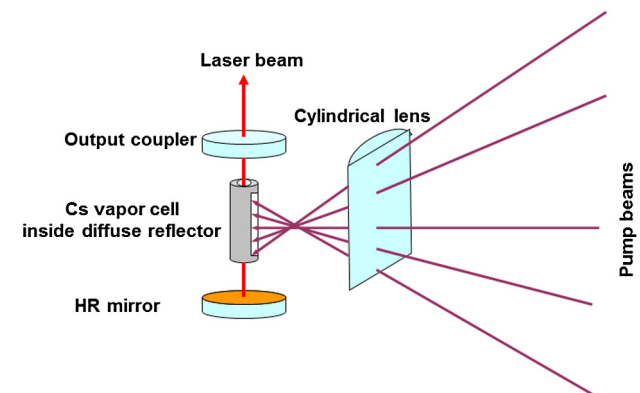


Fig. 8 Schematic diagram of the transverse pumped Cs laser configuration.

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 laser 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 we performed an experiment with a Cs vapor laser transversely pumped by 15 LDAs with total power of about 200 W.⁴⁹ The experimental diagram is presented in Fig. 8. A 5-cm-long and 3-mm-inner-diameter Cs vapor cell with ethane buffer gas was placed inside a cylindrical white diffuse reflector with inner diameter 10 mm. The reflector with the Cs cell was assembled inside a temperature controlled oven. Both the reflector and the oven had a 2×50 mm slit on their side, parallel to the Cs cell axis that was used for coupling the pump beams inside the cell. The 18-cm-long laser cavity was made by two mirrors: a 50-cm-radius concave back mirror with near 100% reflection at 894 nm and a flat output coupler with 20% reflection at 894 nm. The gain medium was transversely pumped by 15 pump beams, each of which was generated by a narrowband 852 nm LDA with external cavity, similar to described in Ref. 43. The LDA pump beams were individually collimated and then focused into the coupling slit by cylindrical lens with a focal length of 20 cm. The combined spot size of all 15 pump beams was about 2 mm by 5 cm at the slit.

To avoid thermal effects in cesium vapor that were observed previously,⁴⁷ we pumped Cs laser by pulses with duration of 500 μ s and repetition rate of 20 Hz (duty factor is 1%). It is worthy to note that the Cs laser operation with pumping by 500- μ s pulses is similar to the CW pumping when the thermal effects are eliminated, because the laser turn on/off time is less than 1 μ s (see Ref. 49). This method of laser pumping allows for a proof of principle of the CW Cs laser system operation where thermal contributions are better managed and hence, the efficiencies obtained in these experiments can show possible efficiencies of the CW pumped Cs laser not affected by thermal effects.

In this experiment we obtained a maximum output power about 28 W with a slope efficiency of 15% and maximum optical efficiency of 14%. The lower value of the slope efficiency compared to the longitudinally pumped Cs laser (68% in Ref. 44) can be due to a low pump coupling efficiency caused by the large difference between the cavity mode size inside the Cs cell (diameter is about 600 μ m) and the size of the diffuse reflector (diameter is 1 cm). As a result, the majority of the pump radiation does not illuminate the lasing volume and is not absorbed in it. To increase the pump efficiency (and hence the total laser efficiency), the laser cavity must be designed to have a mode size close to the illuminated volume inside the reflector filled with gain medium. This can be done by using an unstable laser resonator.

We explored a design of a Cs laser with unstable resonator and transverse pumping of the gain medium.⁴⁹ The design of the Cs cell and the pumping geometry in this experiment followed closely to the previous experiment utilizing transverse pumping described above (Fig. 8). The only difference was in the Cs cell diameter that was increased to 7 mm to better

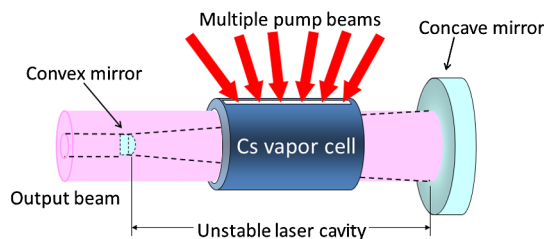


Fig. 9 Unstable resonator cavity.

fill the diffuse reflector volume. The unstable confocal laser resonator (Fig. 9) was constructed of concave and convex high reflecting at 894 nm mirrors and, in this geometry, the laser output is the light that escapes the cavity around the perimeter of the small concave mirror. The output laser beam has a doughnut shape cross section at the output mirror with external diameter about 7 mm (the Cs cell internal diameter) and the hole diameter about 2.8 mm (convex mirror diameter). The Cs vapor cell was placed near the concave mirror where the laser beams propagating in the cavity in both directions have maximum size. The mirrors and the cell are axially aligned, and this particular geometry has an effective output coupler reflectivity of approximately 16%.

In this experiment we obtained a maximum output power of 49 W when being pumped with 160 W with the slope efficiency of 43%. The maximum optical-to-optical efficiency obtained at 160 W pump power was 31%. The efficiencies achieved in this experiment are more than twice higher than in our previous experiment utilizing transversely pumped Cs laser with a stable resonator.⁴⁸ We attribute to this increase in performance to the better overlap between 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 pump⁴⁰ and 68% for diode laser pump).⁴⁴ This difference can be due to nonhomogeneous 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.

4.3 Diode Pumped Cs Vapor Amplifier

Another way to increase an operating power of alkali lasers is to use a diode pumped alkali vapor amplifier or a chain of amplifiers, like it is usually implemented in high power solid state laser master oscillator power amplifier (MOPA)

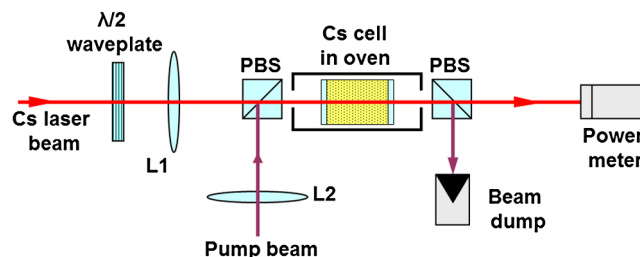


Fig. 10 Cs amplifier—experimental apparatus.

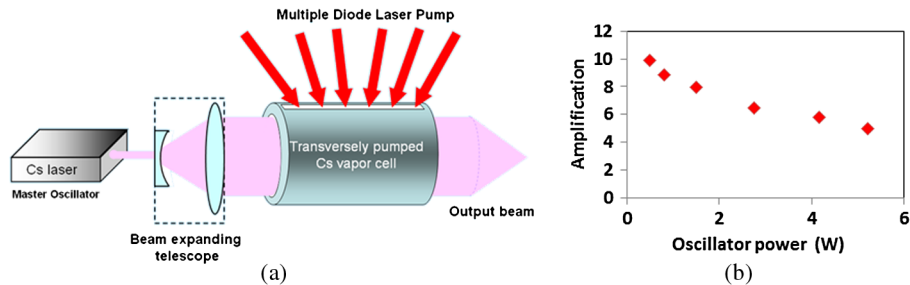


Fig. 11 Basic geometry of the (a) transversely pumped amplifier and (b) its amplification factor.

systems. A chain of amplifiers has many advantages compared to a single oscillator because the use of multiple pump sources can be simplified and handling of excessive heat released into the gain medium can be better managed. We have explored two different designs of diode pumped Cs amplifiers: with longitudinal⁶⁹ and transverse⁵⁰ pump.

The experimental setup for studying of the longitudinally pumped Cs amplifier is presented on Fig. 10. We used a Cs cell identical to one used in laser described in Ref. 44. The cell was pumped by a narrowband LDA with a linewidth less than 10 GHz and operating at 852 nm. The pump beam was focused into the center of the cell through the polarizing beam splitting (PBS) cube. The input signal beam with a wavelength 894 nm from the Cs laser identical to the described in Ref. 44 that had an orthogonal to the pump polarization, was also focused into the cell through the same PBS. We measured amplification factor $A = P_{\text{out}}/P_{\text{in}}$ for the low power input signal ($P_{\text{in}} = 10$ mW), which showed linear dependence on the pump power. The maximum value of this factor was about 145 at the pump power of 18 W, which gives a small signal gain of about 2.5 cm^{-1} .

The experiment on transversely pumped Cs amplifier was performed using the same Cs cell and pumping system as presented in Fig. 9 with any resonator mirrors absent [Fig. 11(a)]. Instead, the 894-nm output of an alkali master laser identical to described in Ref. 44 was used as a seed beam for the power amplifier. The seed beam was expanded to a 5 mm diameter before being allowed to pass through the pumped gain medium. Operation of the amplifier with a total pump power of 280 W is shown in Fig. 11(b), where the amplification factor as a function of the input power from the master oscillator is presented. We obtained a maximum power of just over 25 W with an amplification factor of ~ 5 when the seed beam is 5 W and a maximum amplification of 10 when the seed beam is ~ 5 W. The noticeable trends in the plot of Fig. 5 suggests that we are approaching the saturated regime where the seed beam will extract nearly all the available stored energy in the gain medium.

The similar results were demonstrated for DPAL MOPA system based on rubidium vapor.⁷⁰ A small signal gain of 0.91 cm^{-1} was observed, and the total amplification of 7.9 dB in a 2-cm-long gain cell was achieved.

5 Conclusion

We presented a review of the main achievements in the field of alkali lasers development, demonstrating the high potential of these 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, 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 cells windows, ionization of the gain medium, and others.

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