Diode Pumped Alkali Laser - Current Status and Prospects

Masamori Endo (endo@tokai.ac.jp)
Tokai University School of Science Graduate School of Science: Tokai Daigaku Rigakubu Daigakuin Rigaku Kenkyuka https://orcid.org/0000-0002-4290-0985
Hiroki Nagaoka
Kawasaki Heavy Industries
Fumio Wani
Kawasaki Heavy Industries

Research Article

Keywords: DPAL, alkali laser, gas laser

Posted Date: October 22nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-998610/v1

Diode pumped alkali laser - current status and prospects

Masamori Endo[1*], Hiroki Nagaoka[2] and Fumio Wani[2]

[1*]Department of Physics, Tokai University, 4-1-1 Kitakaname, Hiratsuka, 259-1292, Kanagawa, Japan.

[2]Aerospace Systems Company, Kaswasaki Heavy Industries, 1 Kawasaki-Cho, Kakamigahara, 504-8710, Gifu, Japan.

*Corresponding author(s). E-mail(s): endo@tokai.ac.jp; Contributing authors: nagaoka_hiroki@khi.co.jp; wani_f@khi.co.jp;

Abstract

The historical aspect, present status, and future prospects of diode-pumped alkali lasers (DPAL) are discussed. DPAL is a relatively new laser, first reported in 2003. It is characterized by extremely high scalability, good beam quality by virtue of its gaseous laser medium, and intrinsically high efficiency because it is a three-level laser with a small Stokes defect. Because of these features, DPAL is being studied as a directed energy weapon and is also expected to find applications in industry and space. We propose the use of DPAL for space debris removal. Some of the research results of our group are also introduced.

Keywords: DPAL, alkali laser, gas laser

1 Introduction

If you want an extremely high-power laser that is capable of megawatt-class average output with near-diffraction limited beam quality, what might be your choice? In general, it is pretty difficult to achieve high average power and high beam quality simultaneously, especially for those exceeding 10 kW of output power. One obvious application of such a laser is a laser weapon.

In the past, there were such lasers that were capable of shooting down hostile missiles from hundreds of km away. They were called “chemical lasers” because the laser medium, such as excited oxygen gas, was generated by chemical reactions. However, although they were intensively studied in the last century, expectations soon turned into disappointment because the logistics that could keep such lasers in operation were tremendously cumbersome.

At the beginning of the 21st century, there was revolutionary progress in fiber laser technology. Now, commercially available fiber lasers reach 100 kW. The military section also eyed this progress, and a number of defense laser prototypes based on fiber lasers have been developed. Some of these lasers are now under the deployment phase.

However, there is a fundamental limitation in fiber lasers in terms of the diffraction-limited output power. Dawson *et al.*[1] have theoretically shown that the output of a single-mode (diffraction-limited) fiber laser cannot exceed 36 kW no matter how the structure of the fiber is elaborated. The existing defense laser prototypes are bundling the multiple fiber laser incoherently, and their beam quality is far from diffraction-limited.

At the same time as the high power fiber laser boom, a new concept of gas laser appeared. It was named "diode-pumped alkali laser (DPAL)." This laser has scalability comparable to the chemical lasers with diffraction-limited beam quality, yet pumped by a highly efficient electrically driven laser diode (LD). In this paper, the principle, history, current situation, and proposed applications of DPAL are discussed.

2 Principle of DPAL

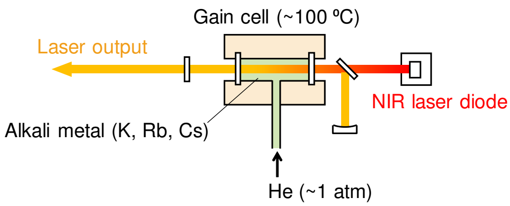

Fig. 1 Schematic drawing of a DPAL

Figure 1 shows the schematic drawing of a DPAL. It is composed of a heated gain cell, an optical resonator, and an LD module for pumping the medium. The laser medium uses gaseous alkali metal vapors such as potassium, rubidium, and cesium. These elements are easily vaporized by heating at 100 to 200 °C. Helium is added at nearly atmospheric pressure as a buffer gas. Helium plays two main roles. The first is that it broadens the absorption linewidth of the alkali atoms by pressure broadening to match that of the pumping LD. However, the pressure broadened absorption linewidth is still on the order of 0.1 nm, so the LD needs to be specially designed. The second role is to facilitate mixing between the two upper levels of alkali atoms by collisional energy exchange. However, the mixing enhancement by He is less effective for

Rb and Cs, so light hydrocarbon gases, such as methane, are added to the buffer gas.

In most cases, the pump light is irradiated from the axial direction so that there is as much overlap as possible with the resonator mode. For larger systems with a large number of LD modules, lateral pumping is also used. In large systems, gas circulation is generally implemented to mitigate thermal lensing of the laser medium, although this is not depicted in Fig. 1.

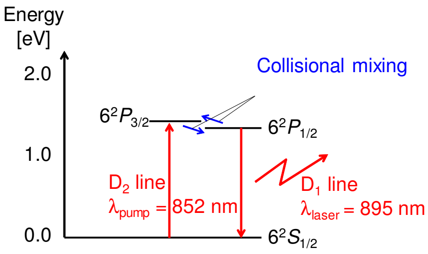

Fig. 2 Energy level diagram of a Cs DPAL

Figure 2 shows the energy diagram of Cs DPAL. The lowest electrically excited levels of the alkali metals are ^2P states, and they lie in the near-infrared energy level above the ground state. The ^2P states of the alkali metals are split into sublevels due to the spin-orbital interactions. These are termed as $^2P_{3/2}$ and $^2P_{1/2}$. Table 1 shows the energy gap of these ^2P states of the alkali metals. As shown, they are very small compared to the $^2P_{1/2} -^2 S_{1/2}$ transition. That is the reason for the high intrinsic efficiency of DPAL. Transition between these sublevels to the ground states are termed as D_2 line ($^2P_{3/2} -^2 S_{1/2}$) and D_1 line ($^2P_{1/2} -^2 S_{1/2}$), respectively, for a historic reason.

Table 1 $^2P -^2 S$ Transition of the alkali metals

Atom	D_1 transition (nm)	D_2 transition (nm)	Quantum defect (%)
Na	590	589	0.1
K	770	767	0.4
Rb	795	780	1.8
Cs	895	852	4.7

DPAL is optically pumped by a narrow-band LD tuned at the D_2 transition of the alkali metal. The atoms excited to $^2P_{3/2}$ level are sent to $^2P_{1/2}$ level by collisional energy exchange with the buffer gas. This reaction is very fast, and the population of $^2P_{3/2}$ and $^2P_{1/2}$ are thermally equilibrated in less than a nanosecond. Because the small energy gap of the two ^2P states is still larger than k_BT of the operating temperature, the equilibrium is inclined to the laser upper level, $^2P_{1/2}$. So, population inversion between $^2P_{1/2}$ and $^2S_{1/2}$

is established immediately; then, lasing action occurs continuously. To summarize, DPAL is an optically pumped three-level CW gas laser. Bravely to say, it is one of the simplest lasers discovered to date.

It should be noted here that the degeneracy of the $^2P_{3/2}$ level is twice as much as that of the ground state. This means that most of the alkali atoms could be optically pumped to $^2P_{3/2}$ state. Therefore, the efficiency of optical pumping in DPAL is intrinsically high. The highest slope (optical-to-optical) efficiency reported was 81%[2], and more than 50% is common. Considering the high electro-to-optical efficiency of LD, the wall-plug efficiency of DPAL is expected to be 30 to 50%.

3 History and current status

The idea of using alkali metals as a medium for gas lasers dates back to more than 60 years ago, i.e., before the first laser oscillation by T. H. Maiman. In a historical paper by Schawlow and Towns[3], sodium atoms were mentioned as a candidate for an "optical maser." Not long after that, a continuous wave laser operated by Cs vapor was reported in 1962. However, scientists would have to wait another 40 years to obtain the last piece of the puzzle that would make possible the unique "optically pumped three-level continuous oscillation" of DPAL.

The development of high-power LD from the end of the last century is the key. LD generates narrow-band coherent light in the visible and near-infrared wavelengths with a high efficiency that is unmatched by other lasers. However, it is inherently difficult for LDs to produce high output power, and an LD "module" with kW-level output power consists of thousands of chips arranged in parallel, with low coherence. Solid-state lasers and fiber lasers have made great strides by using them as pump lights.

Because ordinary LDs have a wide oscillation spectrum that spans several nm, they cannot be used as a pump source for gas lasers. However, by devising a special optical resonator, an LD can be made to oscillate in a bandwidth of 0.1 nm or less with almost no loss of efficiency. Among the several known techniques, volume Bragg grating (VBG) is a small reflector that can be directly bonded to an LD module, which has dramatically improved the usability of narrow-band LDs. Most of the DPAL systems use VBG-coupled LDs as a pump source.

Nevertheless, the absorption spectrum of the gas in the Doppler broadening region is several orders of magnitude smaller than the bandwidth of a narrow-band LD. To fill this gap, DPAL uses a buffer gas with a pressure of nearly 1 atm to extend the absorption bandwidth to the order of 0.1 nm.

The first oscillation of Rb DPAL was reported in 2003[4]. The output power was 30 mW, and the pump light was not a diode but a continuous-wave solid-state laser (Ti: Sapphire). Research has progressed rapidly, and the output power reached 140 W in 2010. Since then, the national defense agencies of some countries have begun to consider the possibility of DPAL for directed energy weapons. Now, the highest output power ever created by DPAL is 30 kW developed by Lawrence Livermore National Laboratory.

There is no doubt that DPAL research is most active in the United States. Other than that, there are research institutes in China, India, Israel, Japan, Russia, and South Korea. In most of these countries, DPAL is closely related to their national defense policies. On the other hand, we are doing DPAL researches for purely scientific purposes. The possible civil applications of DPAL are discussed in Section 5.

4 Works in Tokai University

In Tokai University, we have developed a cesium DPAL whose output is 12 W. It is relatively small compared to those of foreign national institutes. However, this scale apparatus tells us a lot about DPAL optics, physics, and chemistry. Together with experimental work, we also conduct theoretical work. We have developed a three-dimensional Navier-Stokes and wave-optics coupling numerical simulation model of DPAL that could predict the performance of the scaled-up devices.

4.1 10-W class Cs DPAL

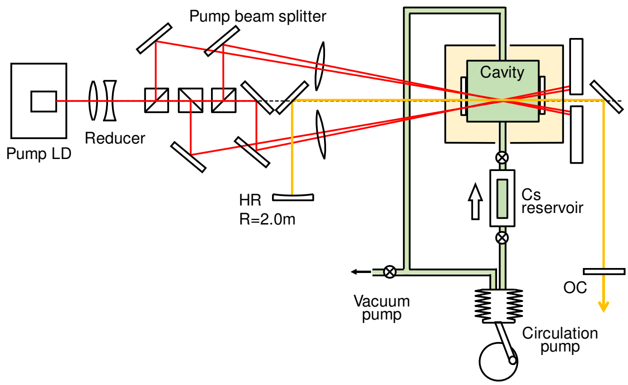

Fig. 3 Schematic diagram of the Tokai University's DPAL apparatus

Fig. 3 shows the schematic drawing of our 10-W class DPAL, and Fig. 4 shows its photograph. Since we have only one pump diode module, we split it into four sub-beams to emulate a scaled-up multi-beam pumping scheme. The pump beams come in at a grazing angle with the optical axis, surrounding it in a circle. It eliminates the dichroic optics to separate pump and laser beams, and a good overlap of each other is ensured at the same time. The numerical modeling result of this scalable pump beam arrangement has been reported elsewhere[5].

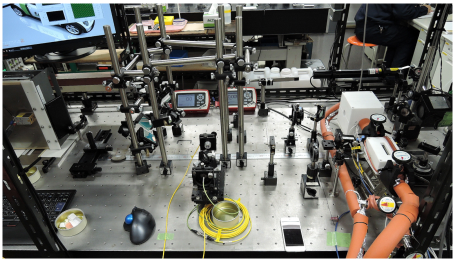

Fig. 4 Photograph of the Tokai University's DPAL apparatus

4.2 Numerical simulation code

Generally, three kinds of physics need to be handled when a gas laser is simulated. They are laser medium chemistry, fluid dynamics, and oscillation in the optical resonator. These three elements are closely coupled, but their characteristic time scales are different by orders of magnitudes. Therefore it is very difficult to handle them simultaneously. In general, one or two of the three elements are treated by simple approximate models to circumvent this difficulty. However, we have succeeded in handling these three elements in full detail. That enabled us not only to predict output power in a variety of operating schemes but also to predict the beam quality of the proposed DPAL with a variety of optical resonator configurations.

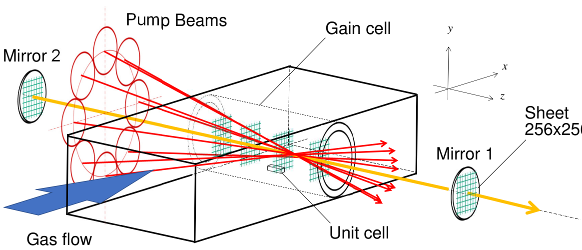

Fig. 5 Schematic diagram of the numerical simulation code

Fig. 5 shows the schematic drawing of our DPAL simulation code. The governing equation for the optical resonator is the two-dimensional Fresnel-Kirchhoff diffraction integral. We applied it to both pump beam and laser modes. The movement of the laser medium is modeled by the Navier-Stokes equation. As the medium velocity is of the order of 10 m/s, the incompressible fluid assumption is justified. On the other hand, buoyancy force plays a critical role in static-type devices, in which the laser medium is sealed off in a closed container. To model such conditions, we employed a modified Boussinesq approximation. The modification was necessary because the density variation of the laser medium sometimes exceeds 50%. The mathematical format of the modified Boussinesq approximation is described as follows[6];

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \boldsymbol{u} + \left(2 - \frac{T}{T_0}\right)\boldsymbol{g}. \tag{1}$$

The validity of this modification has been verified by comparing the flow field with a three-dimensional compressive Navier-Stokes simulation code for a convective flow problem.

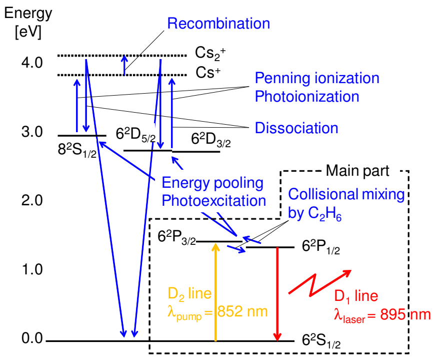

Fig. 6 More detailed energy level diagram and reaction paths of the Cs DPAL

Together with these optical resonators and fluid dynamics, the laser medium chemistry is coupled in the simulation code. Fig. 6 shows the energy level diagram of the cesium DPAL. Besides the principle reaction paths shown in Fig. 1, there are many levels and reactions that should be considered for the precise performance prediction.

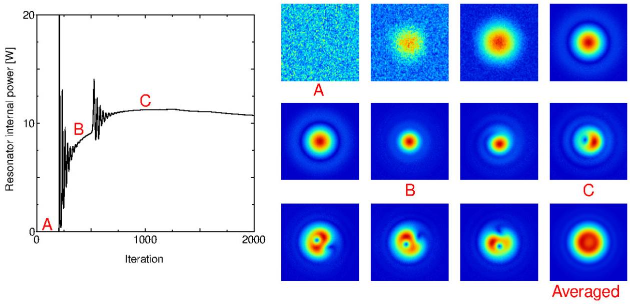

Fig. 7 Typical result of the simulation code: laser mode evolution

Fig. 7 shows the typical result of the simulation. The left graph shows the circulating power evolution in the resonator as a function of the number of iterations, and the 2-D images on the right-hand side show their transverse intensity profile. First, random spontaneous emission fills the resonator, and it gradually grows to one of the eigenmodes of the optical resonator. If the operational conditions allow the resonator to oscillate in multiple transverse modes, the simulation also oscillates in multiple modes.

At the "B" mark in the graph, the fluctuation in the circulating power reflects the switch from the single to double transverse modes. The simulation handles the multiple-transverse mode oscillation as the random but coherent combination of these electromagnetic fields. Therefore, the instantaneous intensity profile shows the randomly fluctuating pattern. In reality, we observe the averaged intensity profile over a long period compared to this oscillation frequency. And the averaged transverse mode pattern shows a circularly symmetrical pattern, as expected.

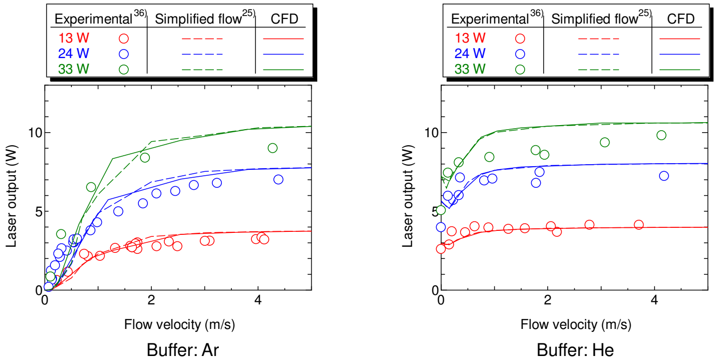

Fig. 8 Comparison of the calculated laser output power with experimental results.

The predictability of the simulation is verified by the comparison with the experimental results. We calculated the laser output power of our 12 W apparatus by varying the gas flow velocity and with different buffer gas species. By varying the thermodynamic properties of the gas and compares the output power, the validity of the fluid-dynamics part of the simulation is verified. Figure 8 shows the laser output power as a function of the gas velocity. The circular plots show the experimental results, and the lines show the numerical simulation. The good agreement showed the validity of our simulation code.

4.3 Cavity dumping operation

We demonstrated a repetitive pulsed operation of DPAL by cavity dumping for the first time. Repetitive pulse operation is often beneficial for high-power lasers when interactions with the material are considered. The reason why we did not employ Q-switching is that alkali metals have fairly short spontaneous emission lifetimes.

Figure 9 shows the main results of our cavity dumped DPAL. We employed a static-type DPAL whose output power was 6.6 W when operated in the CW mode. The graph shows the output power (red) and circulating power (blue)

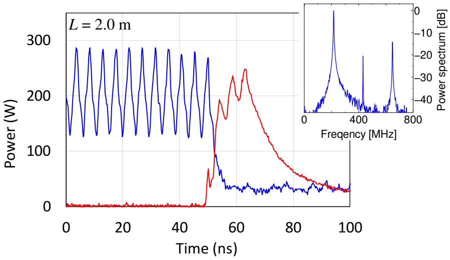

Fig. 9 Schematic diagram of the numerical simulation code

as a function of time. A pulsed output of 250 W, which is 38 times the CW power, has been demonstrated.

It is seen that the internal cavity power shows a saw-like structure. It is because the resonator is operated in double longitudinal modes. We found that at certain operational conditions, DPAL could be operated steadily in double longitudinal modes. As a result, the peak intensity of the circulating power is doubled because of the interference of these modes, and we gained higher peak power than with the single longitudinal mode operation.

5 Possible applications

Obviously, the properties of DPAL, such as the scalability to megawatts together with the high beam quality and high efficiency suits defense applications. Other than military applications, these properties of DPAL are suited to industrial applications, too. Recently, so-called "remote processing" has been introduced in laser cutting and welding. In remote processing, they use very long focal length optics, such as one meter, and the laser beam is steered by Galvano mirrors. With such processing methods, the speed of processing is not limited by the mechanical movement of the robot arm.

To realize remote laser processing, the laser needs not only high power but also high beam quality because the focused intensity of the laser is inversely proportional to the focal length and proportional to the squared beam quality (times-diffraction-limited). If there is a 100-kW laser with diffraction-limited beam quality, a new kind of application will emerge.

We have envisioned a more futuristic application of DPAL. There is a great deal of space debris orbiting the earth, and they are threatening space development. They are moving at approximately 8 km/s, so removing debris from the orbit is a challenge. Shooting debris from the earth as shown in Fig. 10 has been proposed decades ago, but not realized because there is no suitable laser that is capable of 1 MW output with diffraction-limited beam quality. DPAL is a strong candidate for such an application. The reason why we developed a cavity-dumping in DPAL is that repetitive pulse operation is beneficial to evaporate the surface of the debris.

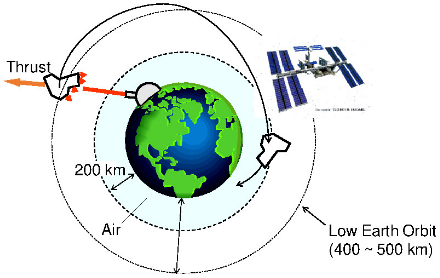

Fig. 10 Conceptual image of the space debris removal by a ground-based laser

6 Conclusion

A diode-pumped alkali laser (DPAL) is an optically pumped, highly efficient, extremely high-power gas laser. It has been scaled up to 30 kW since the first demonstration in 2003. The fundamental superiority of DPAL over the solid-state counterpart is discussed. Tokai University conducts basic researches with a 10-W class device and a numerical simulation code. Although the properties of DPAL are well suited to a directed energy weapon, the possible applications of DPAL are diverse. We envision utilizing DPAL for space debris removal.

References

[1] Dawson, J. W. *et al.* Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power. *Optics Express* **16** (17), 13240 (2008) .

[2] Zhdanov, B., Ehrenreich, T. & Knize, R. Highly efficient optically pumped cesium vapor laser. *Optics Communications* **260** (2), 696–698 (2006) .

[3] Schawlow, A. L. & Townes, C. H. Infrared and optical masers. *Physical Review* (6), 1940?1949 (1958) .

[4] Krupke, W. F., Beach, R. J., Kanz, V. K. & Payne, S. A. Resonance transition 795-nm rubidium laser. *Optics Letters* **28** (23), 2336 (2003) .

[5] Endo, M., Nagaoka, R., Nagaoka, H., Nagai, T. & Wani, F. Glebov, A. L. & Leisher, P. O. (eds) *Scalable pump beam arrangement for diode pumped alkali lasers.* (eds Glebov, A. L. & Leisher, P. O.) *Components and Packaging for Laser Systems IV* (SPIE, 2018).

[6] Endo, M., Nagaoka, R., Nagaoka, H., Nagai, T. & Wani, F. Modeling of diode-pumped cesium vapor laser by combination of computational fluid dynamics and wave-optics. *Japanese Journal of Applied Physics* **59**, 022002 (2020) .