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The second fusion of laser and aerospace—an inspiration for high energy lasers

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Since the first laser was invented, the pursuit of high-energy lasers (HELs) has always been enthusiastic. The first revolution of HELs was pushed by the fusion of laser and aerospace in the 1960s, with the chemical rocket engines giving fresh impetus to the birth of gas flow and chemical lasers, which finally turned megawatt lasers from dream into reality. Nowadays, the development of HELs has entered the age of electricity as well as the rocket engines. The properties of current electric rocket engines are highly consistent with HELs' goals, including electrical driving, effective heat dissipation, little medium consumption and extremely light weight and size, which inspired a second fusion of laser and aerospace and motivated the exploration for potential HELs. As an exploratory attempt, a new configuration of diode pumped metastable rare gas laser was demonstrated, with the gain generator resembling an electric rocket-engine for improved power scaling ability.

Keywords: high energy laser; HEL; gas dynamic laser; alkali laser; electric thruster; metastable rare gas

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Introduction

The conceptual building block of lasers originated from A. Einstein's theory of stimulated emission in 1916. In 1951, C. H. Townes proposed stimulated emission at microwave frequencies and realized the first microwave maser in 1954[1]. Then scientists thought on transferring the stimulated emission from microwave to optical frequency, with the terminologies 'Optical Maser'[2] or 'Laser'[3] invented. The first laser was demonstrated by T. Maiman in 1960[4], which ushered in an era of laser development. After that, the demand for military lasers was stimulated, and the R&D of high-energy lasers (HELs) started. Different types of lasers emerged, joining the race towards high power output.

By reviewing the 60-years history of HELs[5–9], it is clear to see that breakthroughs were always achieved by revolutions of energy injection and heat dissipation methods. And this progress was pushed by a deep fusion of HELs with other disciplines. Among these interdisciplinary areas, the aerospace technology was undoubtedly the most powerful impetus. In the mid-1960s, the first fusion of HEL and aerospace came. The chemical rocket-engine technology promoted the birth of gas flow and chemical lasers, which finally realized megawatt output in the 1980s, turning the long-held science fiction into reality. Driven by the development of diode lasers, the HELs experienced a second revolution at the turn of the millennium, towards developing robust electric lasers with improved efficiency, enhanced capability, and

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reduced size and weight. It's worth noting that, as HELs went from chemistry to electricity, so did the aerospace technology. Nowadays, the in-space adjustment of satellites or deep space exploration are all propelled by the electric rocket-engines (also known as 'electric propulsion' or 'electric thruster' in aerospace terms). The properties of these electric rocket-engines are highly consistent with the goals of current HELs, including electrical driving, efficient heat dissipation, little medium consumption and extremely light weight and size. Hence, it is rational to envision a second fusion of laser and aerospace, which may drive a revolutionary development of HELs, just as what has happened in history.

The first fusion - chemical rocket-engines promoted the birth of gas dynamic lasers

One year after T. Maiman's ruby laser, the neodymium-doped crystal laser was born, and then the neodymium-glass laser[10,11]. At that time, encouraged by the attainable large bulk of glass, the flash-pumped solid-state laser was the first choice for HELs. But it soon proved unrealistic due to inefficient energy injection and catastrophic thermal effects by mid-1960s. In 1963, K. Patel invented the discharge excited CO_2 laser, and quickly amplified the power to continuous 200 W output, which was a shocking result at that time[12]. However, due to the non-quantized electron energy in the gas discharge process, it was difficult to achieve selective pumping, which fundamentally limited the laser efficiency. Also, the heat dissipation capacity of longitudinal flow was far from meeting the requirements. The 1.5 kW CO_2 laser of Hughes required a 10 m oscillator followed by a 54 m amplifier. Although Raytheon has achieved 8.8 kW and efficiency of 13%, it required a discharge tube of 600 feet[9], which was unrealistic for further scaling.

CO_2 gas dynamics laser - the first generation rocket-engine laser

The bottleneck of HELs at the time was resolved by the fusion of laser and aerospace technologies. In the mid-1960s, N. Basov et al. suggested to use differential relaxation between energy levels during rapid adiabatic expansion of molecules to achieve population inversion[13]. A. Kantrowitz, a rocket scientist, together with E. T. Gerry et al. at Avco Everett Research Laboratory, proposed to expand the high temperature gas through supersonic nozzles, which resembled a chemical rocket-engine to produce population inversion without external pumping. In 1966, E. T. Gerry et al. built the first combustion-driven CO_2 gas dynamics laser (GDL)[14]. Figure 1 shows a transition from a rocket engine to a gas dynamics laser. In a rocket engine, the hot gas in the combustion chamber is exhausted through a Laval nozzle, which chokes and a supersonic jet is formed converting most of the thermal energy into kinetic energy. Comparably, in a gas dynamics laser, an array of similar nozzles is used to generate a supersonic lateral flow, which combines the advantage of large gain volume and fast heat dissipation. The laser works in a self-sustaining mode because the energy was obtained from the fuel combustion rather than additional injection. Together with the large-aperture unstable cavity[15], these technologies jointly paved the way for laser power amplification. Because the laser worked very much like a rocket engine, it was also called the "rocket-engine laser". By 1970, Avco had scaled the CO_2 GDL to 135 kW, which soon gave birth to the famous Airborne Laser Laboratory (ALL) program[9].

Better rocket-engine lasers through chemistry

Although the long wavelength (~10.6 μm) and poor atmospheric transmission limited the long-range application of CO_2 lasers, the incredible rocket-engine scheme

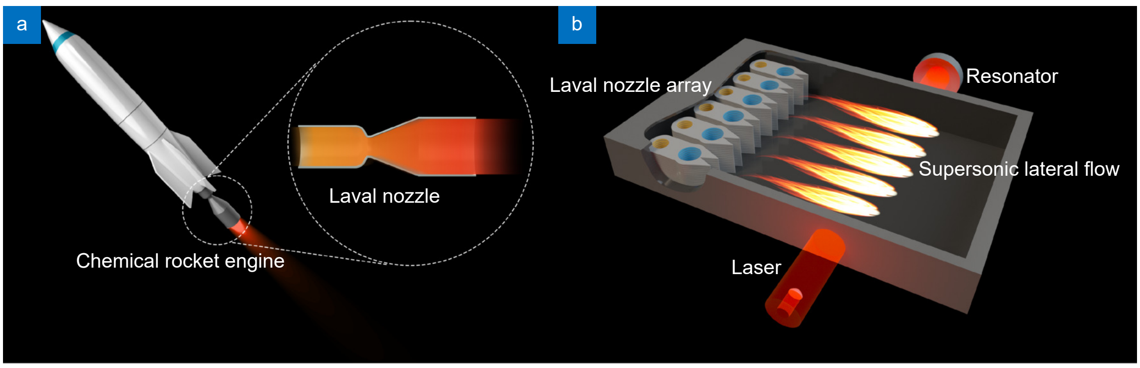

Fig. 1 | Transition from chemical rocket-engine to gas flow and chemical lasers.

paved the way for the latecomers - the shorter wavelength and more efficient chemical lasers. In 1969, D. J. Spencer et al. used the rocket-engine configuration to generate 630 W continuous HF laser. In the initial design, the arc-heated N_2 was used for dissociation of SF_6 to generate F atoms, and then H_2 was injected into the supersonic fluorine flow to create vibrationally excited HF that was made to lase in a cavity[16,17]. In the following year, the energy injection was changed from arc-driving to combustion-driving by R. A. Meinzer et al., which enabled the laser operating in a self-sustaining mode[18]. Since then, the combustion-driven chemical lasers became rocket-engine lasers of real sense.

The energy of chemical lasers directly comes from the release of molecular bond energy in chemical reactions, which has the highest energy storage density in nature except for nuclear energy. The specific power of HF/DF chemical lasers was more than 100 J/g, which was much higher than CO_2 lasers. Following the initial demonstration, the TRW Inc. quickly scaled the DF chemical laser to an amazing power level. In the early 1970s, the Baseline Demonstration Laser (BDL) realized 100 kW, and then the Navy ARPA Chemical Laser (NACL) reached 400 kW. In 1980, the 2.2 MW Mid-Infrared Advanced Chemical Laser (MIRACL) was completed, and the power level of which still maintained the world record[8]. Meanwhile, the 1.315 μm chemical oxygen iodine laser (COIL) also solved the key technical problems in power scaling. Even in today's view, this was still an astonishing development rate. Since then, the ground-based, space-based, and airborne chemical lasers all went into engineering. Until 2010, the COIL mounted on a Boeing 747 (ABL, Airborne Laser) shot down a missile in flight[19].

Pushed by the fusion of laser and aerospace, the chemical lasers finally turned the megawatt HELs from a dream into reality. Although these big rocket-engine lasers could produce impressive raw power, they were massive and complex devices containing hazardous chemicals. The chemicals' consumption was large, e.g., ~10 kg/s for a megawatt DF laser, which needed to be refueled with complex logistics. The total size and weight were extremely large, e.g., the Airborne Laser had to be squeezed into a Boeing 747 jumbo jet, which was as heavy as ~55 kW/kg[20]. These barriers seriously restricted the practical applications of chemical lasers, and the need for compact electric lasers was born.

HELs from chemistry to electricity

Maturation of diode lasers for practical use

Before the mid-1960s, the solid-state lasers (SSLs) based on crystal and glass produced more power than gas lasers, and were the first choice towards HELs. But the serious drawback was that they turned only a small fraction of the flash-pumped energy into laser light, and accumulated excess heat inside the medium. The failure to scale flash-pumped SSLs and the successful demonstration of GDLs had ever pushed SSLs out of the HELs' vision in the 1960s.

Fortunately, with the development of GDLs, a far-reaching technology has quietly matured, that was the practical use of high-power diode lasers. Although first discovered as early as 1962[21], the initial p-n homojunction device was far from application at that time. In the decades that followed, a convergence of technologies continued to be developed, including crystal growth technologies, quantum well structure, materials passivation technologies, and heatsinking technologies etc.[22] Until 1990s, the high power diode laser developed to reach a milestone, with a 1 cm bar exceeded 100 W continuous wave output at room temperature[23]. In the following thirty years, the performance of diode lasers kept improving while the price kept dropping. Compared to the flash lamps, diode lasers converted much more electrical energy into light, and their wavelengths could match the absorption bands of solid-state mediums, significantly improving the efficiency and reducing the waste heat. Meanwhile, the poor maneuverability and complicated logistics proved a fatal flaw for GDLs. The focus of HELs gradually turned into electrically driven SSLs around the 2000s, which were favored for their high efficiency, compactness, infinite magazine and more flexible field capability.

Diode pumped solid-state lasers (DPSSLs) – 100 kW-level electric HELs

In addition to the difference of energy injection, GDL and DPSSL dissipate heat in fundamentally different ways. For GDL, the heat is removed by the rapid gas flow, something called the 'garbage disposal' principle. While for DPSSL, the heat has to be carried away from the fixed medium by conduction cooling. In the early stages, the neodymium (Nd^{3+}) doped rod lasers were the main choice. But the low surface-to-volume ratio of the rod shape seriously limited the heat conduction capacity, resulting in a series of thermal effects that seriously deteriorated the beam quality or even led to material fracture. To solve these problems, DPSSLs were developed towards both reducing the heat generation and improving the heat conduction. For the former purpose, as the brightness of diode lasers enhanced, the ytterbium (Yb^{3+}) could be effectively pumped, which gradually replaced the Nd^{3+} due to its simpler energy-level structure, much higher quantum efficiency and lower heat generation. Since the first room-temperature operation of Yb^{3+} doped SSL by T. Y. Fan et al. in 1991[24], most of the current high-power DPSSLs used ytterbium ions. For the latter purpose, the structure of the solid-state medium developed in two directions. One direction moved to the 'big and slender' geometry, typically the slab and disk lasers, which was favored for efficient heat dissipation through large contact area and short thermal conduction path. Northrop Grumman has enabled power scaling of a slab solid-state laser beyond 15 kW from a single aperture, and then combined 7 channels to realize the first 100 kW-level DPSSL in 2009[25]. For better cooling capacity, General Atomics used a large number of distributed gain mediums that were immersed in a refractive-index matched cooling liquid, which was reported to reach 150 kW in 2015[26]. The other direction turned to the 'thin and long' geometry, that was, the fiber lasers. As first proposed by E. Sitzer in 1988[27], the double-clad fiber lasers benefit from tightly confined geometry to generate highly efficient laser output and excellent heat dissipation due to an exceptionally large surface-to-volume ratio. In 2009, IPG successfully achieved a 10 kW single mode output[28]. Power scaling demonstrations were realized by beam combination, e.g. the 44 kW coherent combining system[29], the 150 kW spectral beam combining system[30], and more recently, the 500 kW multimode fiber laser system.

It's worth noting that, although many attempts have been made to improve the power and beam quality, the power from a single aperture DPSSL still stayed at tens of kilowatts for nearly a decade. The fundamental reason was the intrinsic limited heat dissipation capacity of the solid materials. Almost all the power scaling demonstrations relied on beam combination, but still far below the GDLs. In addition, beam combination technologies still face challenges as the power and combined channel increase. Thus, at the current state, DPSSLs mainly aim at tactical applications on a level of tens to hundreds of kilowatts, and the road towards megawatts still remains a challenge.

The second fusion - electric rocket-engines inspired new ideas for HELs

Renaissance of gas lasers by diode pumping

To break through the power limit of DPSSLs, a new laser concept - the diode pumped alkali lasers (DPALs) was proposed by W. F. Krupke in 2001[31,32]. The concept used the diode laser to pump a gas medium - the saturated vapor of alkali metal, which has an exceptionally high quantum efficiency (>98%) and extremely large atomic cross sections, approximately 10^7 larger than ytterbium. Any of the three alkali elements could be used as the gain medium, with pump wavelengths lying among the high-power diode emission bands (766 nm, 780 nm and 852 nm for K, Rb and Cs, respectively). The DPALs are attractive for their unique gas-solid fusion characteristics, that is, a perfect combination of diode pumping, high plug efficiency and gas flow heat dissipation. In other words, the DPAL could be seen as a very efficient DPSSL, but with a highly effective convectional cooling ability. These properties physically lay the foundation for DPALs towards a single-aperture megawatt HEL with light weight and size[33,34]. In the first decade after invention, the main work focused on principle verification and device research. Due to high chemical reactivity and narrow absorption band of alkalis, the engineering implementation of DPALs was challenging, with a series of critical technologies to be addressed, including the narrowband diode pumps, flowing alkali gain generator and corrosion-resistant optical elements etc. With significant engineering progresses since 2010, the power increased rapidly. In 2016, a Rb DPAL at Lawrence Livermore National Laboratory reached 34 kW[35], and subsequent work was under way for further scaling.

Although the alkali atoms are nearly ideal for HELs due to their simple energy level structure and extremely large atomic cross-sections, they are difficult to handle. From a thermodynamic point of view, the alkali gain medium is in a saturated vapor phase with complex transport characteristics. From a chemical point of view, the alkali atoms are the most active element in nature, which have extremely strict cleanliness requirements for sealing, use and maintenance. The high chemical reactivity also increases the risk of window corrosion and photochemical reaction inside the medium. To tackle these inconveniences, new laser concepts were successively proposed, promoting the vigorous development of the high energy diode pumped gas lasers (DPGLs)[36]. The most representative was a laser concept that mostly resembled the DPALs, named the diode pumped metastable rare gas laser (DPRGL), which was first proposed by J. Han and M. C. Heaven in 2012[37]. Instead of the active alkali atoms, rare gas was chosen as the laser medium. Specifically speaking, the metastable rare gas atoms (Ar^*, Kr^* and Xe^* etc., the asterisk represents 'metastable state') were used, with nearly all the dynamic processes similar to DPALs. It is interesting to note that, the rare gas (especially xenon) is also the working medium in modern electric rocket-engines, and a large number of metastable atoms exist in the plume of such engines. Some connections emerge between laser and aerospace again.

Electric rocket-engines - the future of in-space propulsion

As mentioned above, HELs gradually went from chemistry to electricity from the 1990s. Similar trends appeared in rocket-engine technologies. The electric rocket-engines are commonly used in the modern in-space propulsion. In general, electric rocket-engines are any means of producing thrust in a spacecraft using electrical energy. It aims at achieving thrust through extremely high exhaust velocities while consuming very tiny amount of propellant. Unlike the chemical rocket-engines that generate huge thrust-to-weight ratio to lift the spacecraft off the ground, the electric rocket-engines are favored for extremely high specific impulse, low propellant consumption and long-time running, which are suitable for long-duration and long-distance in-space missions, such as stationing keeping of satellites or deep-space exploration. In history, the concept of electric propulsion was born at the beginning of the last century. Significant research programs were established in the 1960s both in the US and Russia, and became common in the 1980s[38]. Today, as technology maturity increased, the majority of in-space propulsion is provided by electric propulsion. To fulfil different missions, many types of electric thrusters have been developed, including electrothermal, electrostatic and electromagnetic thrusters. Among them, the most popular version is the electrostatic propulsion, including the Hall effect thruster[39] and the gridded ion thruster[40]. Both use electric potential differences to accelerate ions (typically xenon) to exhaust the propellant at extremely high velocities.

New thoughts towards HELs inspired by electric rocket-engines

Now we came to a key question, that is, how the electric rocket-engines relate with lasers? In fact, the properties of electric rocket-engines are highly consistent with the current HELs' pursuit - electrical driving, high efficiency, excellent heat dissipation, little medium consumption and extremely light weight and size. Looking back the history of the first fusion of HELs and aerospace, we intuitively recognized the possibility of a second fusion.

Initially, we focused on the medium in the plume of the electric thrusters, like metal or rare gas atoms, to see if certain species could support lasing by diode pumping. Fortunately, the concept of DPRGLs, which was mentioned above, inspired some possibilities. The motivation to develop DPRGLs is to explore a better laser system, which could inherit the scaling ability of DPALs, while overcoming the complexity due to highly reactive alkalis. In these lasers, the rare gas (Ar, Kr and Xe) is excited to the lowest metastable state ($1s_5$ in Paschen notation) by electron collision. Then these metastables support a three-level laser scheme, including diode pumping ($1s_5 \rightarrow 2p_9$), collisional relaxation ($2p_9 \rightarrow 2p_{10}$) and lasing ($2p_{10} \rightarrow 1p_5$). The laser operation mechanism, as well as the optical properties of metastable rare atoms are all similar to DPALs. In addition, a prominent advantage of DPRGL is the use of rare gases, which absolutely avoids the chemical reaction risk, enabling a convenient and robust system.

The pioneering demonstration by Han and Heaven from Emory University and a series of subsequent experiments successfully validated the concept[41−44]. Rawlings et al. from Physical Science Inc. first explored this new concept in a microwave-driven microplasma array and demonstrated the highest optical-to-optical conversion efficiency (~55%) relative to the absorbed power so far[41]. Mikheyev et al. from the Lebedev Physical Institute realized lasing in a dielectric barrier discharge[45]. Zuo et al. from Huazhong University of Science and Technology also studied lasing characteristics in the DPRGL using a repetitively pulsed discharge[43,46]. Although not as perfect as DPALs, a power scaling analysis by B. Eshel et al. from the Air Force Institute of Technology theoretically demonstrated the possibility of a 100 kW DPRGL with high efficiency. Their analysis also gave the required conditions, including pump intensity (~20 kW/cm^2), metastable density (~10^{14} cm^{-2}) and gain volume (~70 cm^{-3})[47]. The critical point was how to produce dense metastables in a large volume, which was the main focus of the current research. For this purpose, different gas discharge methods were studied, including the pulsed DC[42], radio-frequency[48] and microwave discharges[49]. Although significant progresses have been made, some limitations still exist. Current schemes generally conducted gas discharge in a confined region, such as a small gap between electrodes, and the discharge region was directly used for diode pumping. In these configurations, the gain volume was difficult to expand, limited by arc pulling, electrode damage, non-uniform atomic distribution etc. Moreover, intense pumping could change the state of discharge, and lead to parasitic oscillation between electrodes.

To break through these bottlenecks, the principle of electric rocket-engines inspired new ideas. It was worth noting that, the working medium of modern electric rocket-engines was also the rare gas (xenon), and the plume generally contained metastables in a large volume[50–52]. Despite the physical conditions differs, the architecture is inspiring. Like GDLs that resembled the chemical rocket-engine's structure, the plasma generator of DPRGLs could be designed like an electric rocket-engine to produce a plume rich in metastables, which is separated from the discharge region. In such a configuration, the above problems could be solved, and the power scaling ability of DPRGLs could be effectively improved.

Demonstration of Ar-based electric rocket-engine type DPRGL

To test the idea above, a preliminary demonstration of a Ar-based DPRGL in an electric rocket-engine type has been made in 2022[53]. The plume of a Ar/He plasma jet was successfully utilized to realize lasing under diode pumping (also called the 'plasma-jet type'). Despite the thought was initially motivated by the Hall thrusters, the device was much more like an arc thruster - an electro-thermal type.

The experimental setup is shown in Fig. 2. The discharge was driven by a 13.5 kHz AC power supply with a maximum voltage of ~1 kV. An atmospheric Ar/He gas mixture was fed to the tube and gas breakdown occurred between the inner electrode and the nozzle wall. The plume, which was the region of interest, had a width of 1 mm and a height of 6 mm and contained a high density of Ar metastables, with a peak value of ~10^{14} cm^{-3}. The pumping source was a narrowband diode laser centered at the $1s_5 \rightarrow 2p_9$ transition of Ar (811.53 nm). A transverse pumping scheme was applied with the directions of plasma plume, diode pump light and output laser vertical to each other. A flat-concave resonator was used with a 70% reflectivity of the output coupler.

Under continuous pump, a maximum of 466 mW laser output was observed for an absorbed power of 1.94 W, with a slope efficiency of 33%. The relatively low efficiency attributed to some obvious factors, including short gain length, broad pump linewidth and periodic changes of the metastables due to low discharge frequency. Further optimization was underway. To the best of our knowledge, this was the first time to realize lasing in a plasma-jet type DPRGL, which preliminary verified the possibility of a second fusion between HEL and aerospace.

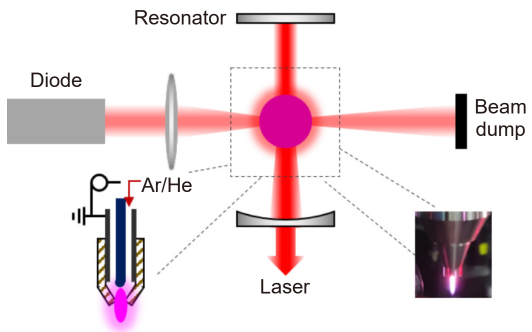

Fig. 2 | Experimental setup of an Ar-based DPRGL in a plasma jet. The insets demonstrate the structure and picture of the plasma jet used in this experiment. Figure reproduced with permission from ref.[53], © 2022 Optica Publishing Group.

Prospect of a second fusion between HELs and aerospace

For the plasma-jet type DPRGLs, the direct way for power scaling is to increase the gain volume using an array of plumes, which resembles the nozzle arrays in chemical lasers. Figure 3 represents an envision from an electric rocket-engine to a plasma-jet type HEL. Multi-jets that contain sufficient metastables at a proper pressure merge into a large volume. It should be noted that the propagation of the plasma jet from the discharge region to the pumping region was not only driven by the gas flow. The applied electric field also plays an important role in the propagation process. Thus, the propagation speed of the plasma was far beyond the flow speed and the requirement for the flow speed is not strict. In order to increase the volume and compensate for the loss of metastables due to collisional decay (~10 μs for Ar*), additional electric field energy could be delivered into the plume. High power diode lasers are used to provide intense and uniform pumping. The gain is efficiently extracted by an unstable resonator to form high power laser output with high beam quality.

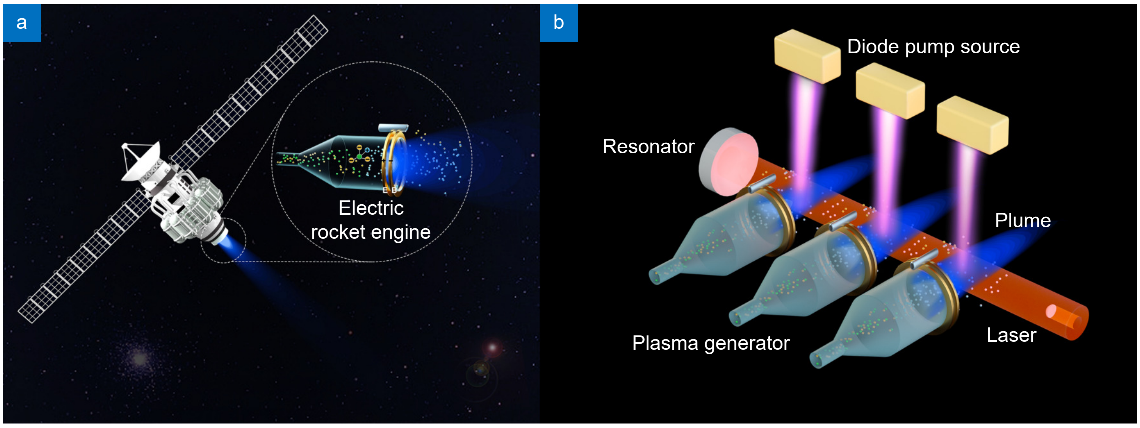

Fig. 3 | Envision from electric rocket-engine to future HELs.

At a constant pump intensity, the pump and laser powers scale linearly with the gain volume. The required gain volume for a 1 MW system was roughly estimated as ~300 cm^3, with typical parameters of ~20 kW/cm^2 pump intensity, 1×10^{14} cm^{-2} column density of metastables and 60% optical conversion efficiency. The heat is efficiently dissipated by gas flow, with a mass flow rate on an order of 10 g/s. The specific power, mass flow rate and gain volume for gas GDLs and diode pumped gas lasers are compared in Table 1, in which the values are only order of magnitude estimations. It should be noticed that, unlike gas flow and chemical lasers, the energy source for diode pumped lasers are externally injected rather than chemical energy, so the terminology 'Specific Power' for diode pumped lasers are not particularly proper, only listed here for an intuitive comparison. Compared with gas flow and chemical lasers, the diode pumped gas lasers are highly efficient and compact. Furthermore, the laser medium for both DPAL and DPRGL could be re-used, enabling a circulation system, which extends the application platforms.

It should be pointed out that the jet-type DPRGL is only an example which aims to explain how the technology of electric rocket-engines advances laser development. Other thoughts are expected by fusion of HELs and aerospace.

From the technical point of view, the critical technologies for future development of DPRGLs include two aspects: one is the metastable atomic generator that could generate a large volume and high density metastables with desired temperature, the other is the high-power linewidth-narrowed diode pumping source.

As an advanced diode pumped gas laser, the DPRGL is a potential candidate towards an electrically driven, single aperture scaled megawatt-level HEL system with extremely light weight and small size, which will be ideal for directed energy application on various mobile platforms. Such HEL systems are also suitable for space applications including active debris removal and power beaming. Besides, a mid-power DPRGL system can also be used for laser cutting, welding etc. in industry.

Conclusions

By reviewing the history of laser development, the first fusion of laser and aerospace led to the born of gas flow and chemical lasers, which was the only megawatt HEL till now. Current strategic applications call for electric megawatt lasers, which still remains a great challenge for DPSSLs. The gas-solid fusion laser system, represented by DPALs, provides a promising solution. Motivated by the latest aerospace development, a new laser configuration - the jet-type DPRGL is envisioned and preliminary demonstrated. The research for such lasers aims to explore a potential option towards a DPAL-like robust and compact megawatt laser system. We believe that the second fusion of laser and aerospace will inject new vitality into the future of HELs.

Table 1 | Comparison for 1 MW-level GDLs and diode pumped gas lasers.

	Specific power (J/g)	Mass flow rate (g/s)	Gain volume (cm^3)
Gas flow and chemical lasers	10^1–10^2	10^4–10^5	10^5–10^6
Diode pumped gas laser (DPAL and DPRGL)	10^7	10^1	10^2

References

1. Gordon JP, Zeiger HJ, Townes CH. Molecular microwave oscillator and new hyperfine structure in the microwave spectrum of NH_3. *Phys Rev* **95**, 282–284 (1954).
2. Taylor N. *Laser: The Inventor, the Nobel Laureate, and the 30-year Patent War* (Simon & Schuster, 2000).
3. Schawlow AL, Townes CH. Infrared and optical masers. *Phys Rev* **112**, 1940–1949 (1958).
4. Maiman TH. Stimulated optical radiation in ruby. *Nature* **187**, 493–494 (1960).
5. Zarubin PV. Academician Basov, high-power lasers and the antimissile defence problem. *Quantum Electron* **32**, 1048–1064 (2002).
6. Hecht J. A short history of laser development. *Appl Opt* **49**, F99–F122 (2010).
7. Carroll D. Overview of high energy lasers: past, present, and future? In *42nd AIAA Plasmadynamics and Lasers Conference* (AIAA, 2011);https://doi.org/10.2514/6.2011-3102.
8. Cook JR. High-energy laser weapons since the early 1960s. *Opt Eng* **52**, 021007 (2012).
9. Hecht J. *Lasers, Death Rays, and the Long, Strange Quest for the Ultimate Weapon*. (Prometheus Books, 2019).
10. Snitzer E. Optical maser action of Nd^{+3} in a barium crown glass. *Phys Rev Lett* **7**, 444–446 (1961).
11. Geusic J, Marcos HM, Van Uitert LG. Laser oscillations in Nd‐doped yttrium aluminum, yttrium gallium and gadolinium garnets. *Appl Phys Lett* **4**, 182–184 (1964).
12. Patel CKN. Continuous-wave laser action on vibrational-rotational transitions of CO_2. *Phys Rev* **136**, A1187–A1193 (1964).
13. Basov NG, Oraevskii AN, Shcheglov VA. Production of a population inversion in molecules of a working gas mixed with a thermally excited auxiliary gas. *Sov Phys Tech Phys* **15**, 126 (1970).
14. Gerry ET. Gasdynamic lasers. *IEEE Spectr* **7**, 51–58 (1970).
15. Siegman AE. Unstable optical resonators. *Appl Opt* **13**, 353–367 (1974).
16. Spencer DJ, Jacobs TA, Mirels H, Gross RWF. Continuous‐wave chemical laser. *Int J Chem Kinet* **1**, 493–494 (1969).
17. Spencer DJ, Mirels H, Jacobs TA. Initial performance of a CW chemical laser. *Opto-electronics* **2**, 155–160 (1970).
18. Meinzer RA. A continuous‐wave combustion laser. *Int J Chem Kinet* **2**, 335 (1970).
19. Horizons. Airborne laser shoots down missile in mid-flight. https://www.csmonitor.com/Technology/Horizons/2010/0212/Airborne-laser-shoots-down-missile-in-mid-flight.
20. Chronology of MDA's plans for laser boost-phase defense (August 26, 2016). https://mostlymissiledefense.com/2016/08/26/chronology-of-mdas-plans-for-laser-boost-phase-defense-august-26-2016/.
21. Keyes RJ, Quist TM. Recombination radiation emitted by gallium arsenide. *Proc IRE* **50**, 1822–1823 (1962).
22. Welch DF. A brief history of high-power semiconductor lasers. *IEEE J Sel Top Quantum Electron* **6**, 1470–1477 (2000).
23. Sakamoto M, Endriz JG, Scifres DR. 120 W CW output power from monolithic AlGaAs (800 nm) laser diode array mounted on diamond heatsink. *Electron Lett* **28**, 197–199 (1992).
24. Lacovara P, Choi HK, Wang CA, Aggarwal RL, Fan TY. Room-temperature diode-pumped Yb: YAG laser. *Opt Lett* **16**, 1089–1091 (1991).
25. McNaught SJ, Asman CP, Injeyan H, Jankevics A, Johnson AMF et al. 100-kW coherently combined Nd: YAG MOPA laser array. In *Proceedings of the Frontiers in Optics 2009* FThD2 (Optical Society of America, 2009); https://doi.org/10.1364/FIO.2009.FThD2.
26. Wilmington MA. Textron defense systems awarded funding for the DARPA HELLADS program. https://investor.textron.com/news/news-releases/press-release-details/2008/Textron-Defense-Systems-Awarded-Funding-for-the-DARPA-HELLADS-Program/default.aspx
27. Snitzer E, Po H, Hakimi F, Tumminelli R, McCollum B. Double clad, offset core Nd fiber laser. In *Optical Fiber Sensors* PD5 (Optical Society of America, 1988); https://doi.org/10.1364/OFS.1988.PD5.
28. O'Connor M, Gapontsev V, Fomin V, Abramov M, Ferin A. Power scaling of SM fiber lasers toward 10kW. In *Conference on Lasers and Electro-Optics* CThA3 (Optical Society of America, 2009); https://doi.org/10.1364/CLEO.2009.CThA3.
29. Missile defense agency for president's budget submission FY 2015: RDT&E Program.
30. Tang XJ, Wang G, Liu J, Geng L, Jiang DS. Development of high brightness solid-state laser technology. *Strateg Study Chin Acad Eng* **22**, 49–55 (2020).
31. Krupke WF. Diode pumped alkali laser. *US Patent Application* , 99272 (2001).
32. Krupke WF, Beach RJ, Kanz VK, Payne SA. Resonance transition 795-nm rubidium laser. *Opt Lett* **28**, 2336–2338 (2003).
33. Krupke WF, Beach RJ, Kanz VK, Payne SA, Early JT. New class of cw high-power diode-pumped alkali lasers (DPALs)(plenary paper). *Proc SPIE* **5448**, 7–17 (2004).
34. Krupke W. Diode-pumped alkali lasers aim for single-aperture power scaling. *SPIE Newsroom*, (2008). https://spie.org/news/1356-diode-pumped-alkali-lasers-aim-for-single-aperture-power-scaling?SSO=1
35. Wisoff PJ. Diode pumped alkaline laser system: a high powered, low SWaP directed energy option for ballistic missile defense high-level summary-April 2017. Report No. Lawrence Livermore National Lab. (LLNL), Livermore, CA (United States), 2017. https://doi.org/10.2172/1357366
36. Liu ZJ, Wang HY, Xu XJ. High energy diode pumped gas laser. *Chin J Lasers* **48**, 0401001 (2021).
37. Han JD, Heaven MC. Gain and lasing of optically pumped metastable rare gas atoms. *Opt Lett* **37**, 2157–2159 (2012).
38. Choueiri EY. A critical history of electric propulsion: the first 50 years (1906–1956). *J Propuls Power* **20**, 193–203 (2004).
39. Bapat A, Salunkhe PB, Patil AV. Hall-effect thrusters for deep-space missions: a review. *IEEE Trans Plasma Sci* **50**, 189–202 (2022).
40. Brophy J. Advanced ion propulsion systems for affordable deep-space missions. *Acta Astronaut* **52**, 309–316 (2003).
41. Rawlins WT, Galbally-Kinney KL, Davis SJ, Hoskinson AR, Hopwood JA et al. Optically pumped microplasma rare gas laser. *Opt Express* **23**, 4804–4813 (2015).
42. Han J, Heaven MC, Moran PJ, Pitz GA, Guild EM et al. Demonstration of a CW diode-pumped Ar metastable laser operating at 4 W. *Opt Lett* **42**, 4627–4630 (2017).
43. Zhang Z, Lei P, Song Z, Sun P, Zuo D et al. Optically pumped argon metastable laser with repetitively pulsed discharge in a closed chamber. *J Appl Phys* **129**, 143103 (2021).
44. Wang R, Yang ZN, Li K, Wang HY, Xu XJ. Experiment and

modeling of the pulsed lasing in a diode-pumped argon metastable laser. *J Appl Phys* **131**, 023104 (2022).
45. Mikheyev PA, Han JD, Heaven MC. Lasing in optically pumped Ar: He mixture excited in a dielectric barrier discharge. *Proc SPIE* **11042**, 1104206 (2019).
46. Lei P, Zhang ZF, Wang XB, Zuo DL. Demonstration of transversely pumped Ar* laser with continuous-wave diode stack and repetitively pulsed discharge. *Opt Commun* **513**, 128116 (2022).
47. Eshel B, Perram GP. Five-level argon–helium discharge model for characterization of a diode-pumped rare-gas laser. *J Opt Soc Am B* **35**, 164–173 (2018).
48. Moran PJ, Lockwood NP, Lange MA, Hostutler DA, Guild EM et al. Plasma and laser kinetics and field emission from carbon nanotube fibers for an advanced noble gas laser (ANGL). *Proc SPIE* **9729**, 97290C (2016).
49. Kim H, Hopwood J. Scalable microplasma array for argon metastable lasing medium. *J Appl Phys* **126**, 163301 (2019).
50. Yang J, Yokota S, Kaneko R, Komurasaki K. Diagnosing on plasma plume from xenon Hall thruster with collisional-radiative model. *Phys Plasmas* **17**, 103504 (2010).
51. Berenguer C, Katsonis K. Plasma reactors and plasma thrusters modeling by Ar complete global models. *Int J Aerosp Eng* **2012**, 740869 (2012).
52. Yamamoto N, Tomita K, Sugita K, Kurita T, Nakashima H et al. Measurement of xenon plasma properties in an ion thruster using laser Thomson scattering technique. *Rev Sci Instrum* **83**, 073106 (2012).
53. Wang R, Yang ZN, Liu QS, Han K, Wang HY et al. Demonstration of a diode-pumped plasma jet-type rare gas laser. *Opt Lett* **47**, 3279–3282 (2022).

Competing interests

The authors declare no competing financial interests.