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ABSTRACT

In this paper, we investigate the role of solar laser technology as a pivotal element in advancing sustainable and renewable energy. We begin by examining its wide-ranging applications across diverse fields, including remote communication, energy storage through magnesium production, and space exploration and communication. We address the current challenges faced by solar laser technology, which include the necessity for miniaturization, operation at natural sunlight intensity without the need for concentrated power, and efficient energy conversion. These improvements are essential to elevate their operational performance, beam quality, and cost-effectiveness. The promising prospects of space-based solar-pumped lasers and their potential role in magnesium generation for a sustainable energy future highlight some of the vast application opportunities that this novel technology could offer.

I. DEMANDS FOR SUSTAINABLE ENERGY RESOURCES

Inefficient energy harvesting has become a central concern in the discourse on climate change due to its compounding effects on greenhouse gas emissions and Earth's energy balance. At the microscopic level, inefficiencies in energy conversion processes, be it in industrial machines, power plants, or even renewable energy technologies, invariably result in the loss of a portion of the harvested energy as waste heat. When not harnessed, this heat can directly contribute to localized warming, and when scaled globally, it can impact climatic patterns. From a thermodynamic perspective, inefficient systems necessitate the consumption of more primary energy resources to achieve the desired output. For instance, first-generation coal-fired power plants, operating at suboptimal efficiencies, emit a substantially higher quantity of CO_2 per unit of electricity generated when compared to their modern, more efficient counterparts or alternative energy sources such as wind or solar.[1,2] This surplus CO_2 has a direct and enhanced greenhouse effect, trapping more of Earth's outgoing infrared radiation, leading to rise in global temperature.[3]

The inefficiencies in energy harvesting are not solely confined to the extraction and conversion processes. Transmission losses in outdated power grids, suboptimal designs of solar panels that fail to absorb the full spectrum of sunlight, or wind turbines positioned in less-than-ideal locales further add to the systemic inefficiencies. When aggregated on a global scale, these cascading inefficiencies not only exacerbate the challenges of meeting the growing energy demand but also contribute significantly to climate change by increasing our carbon footprint. Addressing these inefficiencies in harvesting and conversion is imperative for a sustainable future. Enhanced research in materials science, thermodynamics, and engineering can pave the way for breakthroughs that can mitigate the impacts of climate change by making energy systems more efficient. Over time, numerous insightful articles have emphasized the global imperative to shift toward renewable energy sources.[4–6] As global populations rise and the demand for energy surges, projections indicate an escalating energy requirement. This discourse encompasses the urgent search for alternatives to fossil fuels due to the dwindling reserves of hydrocarbon-based sources, leading to heightened geopolitical tensions and societal disruptions.[7,8] The imperatives of pollution management and the challenges posed by climate change further underscore the necessity for cleaner energy solutions. One prominent answer lies in harnessing solar energy, which offers an abundant, eco-friendly, and virtually inexhaustible power reservoir.

The sun is projected to last for another 4–5 billion years. Our planet receives more energy from the sun in one hour than all humankind's energy consumption in a year. This positions solar energy as arguably the most substantial and harnessable renewable energy resource available to us, making it a recommended long-term energy alternative solution. Nonetheless, its contribution to our energy needs remains surprisingly minimal.[10] Sunlight is both non-directional and semi-coherent. The Earth's atmosphere reflects about 30% of this energy into the cosmos. Moreover, the diurnal cycle ensures that each night plunges us into total darkness, reminding us of our reliance on this celestial body. In regions such as Europe, this dependence becomes even more pronounced during winter.[9,11] This variability, coupled with seasonal changes, introduces challenges in harnessing solar power, as these fluctuations can impact the efficiency of solar energy generation (Fig. 1).

Solar-pumped lasers, an innovative intersection between renewable energy and laser technology, have emerged as a noteworthy development over the past decades. They are specifically designed to tap into the vast reservoir of energy that the sun offers, transforming it directly into coherent laser light. This unique capacity to use solar power to produce laser emissions brings a potentially sustainable solution for high-power laser applications and marks a significant step toward green laser technology. Solar-pumped lasers operate by using sunlight to energize the laser's gain medium. This sun-powered process could result in an efficient way to generate laser emissions, bypassing the need for traditional electrical or chemical energy sources.

In this perspective, we first highlight the potentially transformative applications of solar lasers, as shown in Fig. 2. We discuss their promising role in (i) revolutionizing sustainable energy cycles, such as the magnesium economy,[12] (ii) boosting the efficiency of solar energy conversion,[13] and (iii) their offer for wireless energy transmission in hard-to-reach zones in space-based solar power systems and interplanetary communication.[7,14–16] Having established their potential, we scrutinize the performance metrics and hurdles encountered by state-of-the-art solar lasers over the past decade. We further investigate innovative strategies aimed at overcoming these obstacles, which could pave the way for solar lasers to achieve their full potential. We refer the readers interested in the foundation and evolutionary journey of solar laser technology to the following detailed review articles and books.[17–20]

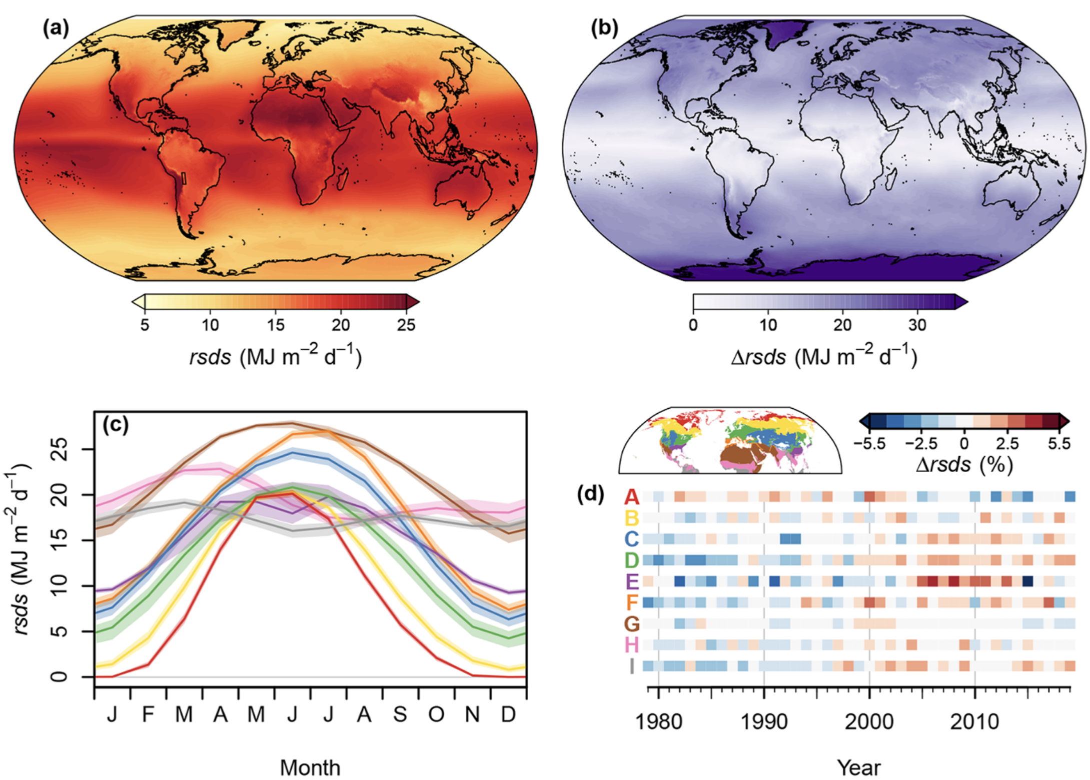

FIG. 1. (a) Global map of the climatological mean of surface downwelling shortwave radiation (rsds) from 1981 to 2010. (b) Global map of the range (max–min) of monthly rsds means for the period 1981–2010. (c) Seasonal cycle of rsds in the biomes of the Northern Hemisphere for the period 1981–2010. The polygons indicate the range from the 40th to 60th percentiles, and the lines indicate the medians. (d) Temporal change in annual mean rsds by biome. Deviations in the percentage of the long-term (1979–2019) annual mean are shown. The red (A) represents the polar and subpolar zone; yellow (B) represents the boreal zone; blue (C) represents dry mid-latitudes; green (D) represents temperate mid-latitudes; purple (E) represents subtropics with year-round rain; orange (F) represents subtropics with winter rain; brown (G) represents dry tropics and subtropics; pink (H) represents tropics with summer rain; and gray (I) represents tropics with year-roundrain.[9] Reproduced with permission from Brun, Earth Syst. Sci. Data 14, 5573–5603 (2022); licensed under a Creative Commons Attribution (CC BY) license.

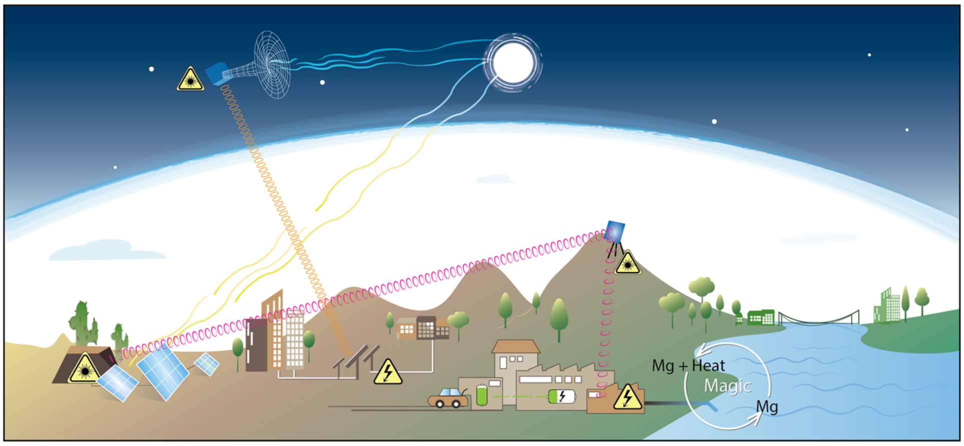

FIG. 2. Graphical abstract representing the selected application of solar lasers for sustainable energy generation and optical communication. Availability of efficient solar pumped lasers allows for sustainable driving of chemical cycles such as magnesium injection cycle (MAGIC),[12] enhancing the efficiency of the solar panels,[13] enabling optical communication in exclusion and remote zones or interplanetary communication,[15,16] and realization of solar-based space power at optical frequencies.[7,14]

II. POTENTIAL TRANSFORMATIVE APPLICATIONS

A. Magnesium economy

Solar lasers have a great potential to drive fossil-fuel-free energy cycles for electricity generation or chemical energy storage.[21–24] Magnesium has a great potential for green energy cycles as it is the eighth most abundant material element on Earth with an estimated weight of 1.8×10^{15} tonnes in the ocean and an energy density ten times higher than hydrogen.[12] However, extracting 1 kg of magnesium requires 10 kg of coal, making the process energy-intensive, expensive, and dependent on fossil fuels. Solar radiation as a renewable energy source can be converted directly or indirectly into other forms of energy, such as heat and electricity, and could play a role in creating new fossil-fuel-free engine cycles. As shown in 2008, solar lasers could be used to drive high-temperature chemical reactions, such as the magnesium injection cycle (MAGIC), and make it possible to convert the magnesium oxide in seawater into magnesium.[25–29] In MAGIC, the mixture of magnesium and water is ignited at 500 °C. During this reaction, the generated hydrogen gas reacts with oxygen gas to generate water and magnesium oxide and releases immense energy. The residual of the magnesium oxide can then be irradiated by 1 kW of laser power with a 1 mm focus size, ideally from a solar laser, for magnesium refinement and closing the sustainability cycle. The only by-product of this reaction is hydrogen, which can also be cleanly burned to produce even more heat or siphoned off for use in fuel cells. The MAGIC cycle makes the solar-powered magnesium economy a competition of a hydrogen economy.[10] Such technology benefits directly from the availability of high-power solar lasers with high conversion efficiency.

B. Power by light

In numerous places and scenarios, such as exclusion zones,[30] mines, aircraft, and satellites, direct harnessing of electrical energy to run electronic devices is either impractical or ill-advised.[31–37] Optical power transfer, or PBL (power-by-light), is a savvy alternative in these unique scenarios. Historically, the inception of wireless energy transmission can be traced back to Nikola Tesla's pioneering endeavors in the early 20th century.[38] A typical PBL system comprises a light source, a transmission medium, and a light receiver. The transmission medium can be categorized into two primary options: those utilizing optical fiber links and those transmitting optical power wirelessly through open space or the atmosphere. The light source changes the electrical power from a safer region into optical energy. This energy is then conveyed via the transmission medium to the light receiver, which then reconverts the optical energy into electricity, thereby energizing the electronics within exclusion or remote zones.

For many applications, laser power beaming stands out for its numerous advantages over alternatives such as solar panels or nuclear reactors. The low conversion efficiency of solar panels and the low energy density of solar light demand for large areas of solar panels. This equates to an excessive amount of materials and infrastructure. Moreover, the large-area solar collectors would block sunlight from hitting the ground, causing potential ecological impacts and changing the local thermal balance, making the large-scale collection of solar energy on the surface of the Earth problematic. The efficiency of solar panels is optimized for a narrowband light. As an example, it has been demonstrated recently that the efficiency of the photovoltaic power converter can be increased to 68.9% for converting the coherent laser light at 858 nm to electricity.[13] The efficiency of the single-junction photovoltaic cells is dictated by the Shockley–Queisser limit.[39] Commercially available photovoltaic cells typically consist of first-generation crystalline or polycrystalline silicon cells.[40,41] Employing multijunction thin-film cells cut the material expenses,[42] and the second-generation photovoltaic cells offer high efficiencies up to 47.6%.[43] However, a significant drawback is the rarity and toxicity of many of these components. New materials, including organic compounds and perovskites, have been explored but suffer lower efficiency and stability.[44]

Solar lasers could enhance the transformation of solar light into electrical energy in low-efficiency photovoltaic cells by (i) solar lasers that convert the solar irradiation directly to a coherent beam at the efficiency peak of the solar panels or (ii) taking advantage of lasers' intra-cavity power amplification to offset the converter's lower efficiency. This converter could be a low-efficiency transparent photovoltaic cell or a thermoelectric cell incorporated within a metallic laser-cavity mirror with a low intra-cavity loss. By integrating the laser action with a power-converting cell acting as an absorber, power-conversion efficiencies comparable to commercial silicon photovoltaic cells can be achieved.[45,46]

It has to be considered that due to safety concerns regarding maximum exposure to the cornea and skin, lasers operating within the 1510–1750 nm and 2100–2325 nm spectral ranges are especially sought after.[47] Yet, the hurdle in these wavelengths is the subpar efficiency of the available photovoltaic converters. These demand advancements in the operational wavelength and efficiency of solar lasers and photovoltaic converters. Solar lasers have great potential to be used in wireless power transmission systems to transmit energy over long distances and convert solar radiation to a monochromatic light suitable for efficiently harvesting energy. While lasers may not transmit as effectively through Earth's atmosphere compared to microwaves, they provide a considerably higher energy density and are suited for use with more compact transmitters and receivers. This makes them a viable and sustainable option for interplanetary communication, as well as a potent method for long-distance energy transmission and communication. Furthermore, solar lasers could contribute to these endeavors by providing a sustainable solution.[16,48–50]

C. Space-based solar power

In recent years, the idea of space-based solar power (SBSP) has received considerable attention again. Here, to mitigate the effect of atmospheric attenuation and seasonal and atmospheric changes, solar radiation is collected and converted in space. Electromagnetic waves link the space system to terrestrial systems containing a receiver, convertor, and utilization. The idea of harvesting energy in space and transporting it to the ground was suggested at the dawn of the space age.[51] The initial proposals were based on converting sun-generated electricity into microwaves, which would be power-beamed to the ground. Microwaves have the advantage of significantly better efficiencies, sound transmission through the atmosphere, even during periods of heavy cloud cover, and low equipment cost. However, they require very large receiving antennae on the ground, with a diameter of up to 10 km.[52] In the 1970s, scientists at the Lawrence Livermore National Laboratory suggested using laser light instead of microwaves, which, in turn, reduced the overall size requirements for the receiver by a thousandfold to 30 m. Moreover, the weight of the laser satellite would be 10% of that of a microwave system, reducing the overall cost.[10,52] The laser is then beamed to the power generation station on Earth, which contains molten salt as the medium to capture and store the received energy. Then, it is incorporated into a generator system utilizing steam turbines and electrical generators.

Estimates hold that SBSP could generate 40 times as much energy as generated by Earth-based solar power. A comprehensive system analysis identifying vital system components has indicated a potential economic advantage of solar-pumped lasers over solar photovoltaic power, provided the lasers can attain efficiencies exceeding 1%.[53] Harvesting solar energy in space and power-beaming the collected energy to a receiver station on Earth is a very attractive way to help solve mankind's current energy and environmental problems. Space-based solar power is clean, sustainable, and always available, independent of the time of day and the weather. Its transportation to anywhere in the world is much easier than fossil energy. Moreover, solar lasers in space can be used to precisely measure distances of millions of kilometers, detect trace gases in the atmosphere of Earth from a satellite, or transmit data between satellites at very high rates.

Based on a proposal by Holloway *et al.*, a diode laser system coupled to solar panels could deliver 1 MW of power with 20% wall-plug efficiency. Such architecture employs 3600 m^2 solar panels to convert solar light to electricity at 40% efficiency, delivering 5 MW of power. This power is then used to pump diode lasers with 50% conversion efficiency. For any given receiver station on Earth, the solar power beaming station can illuminate a specific receiver for ~9 min at the megawatt power level. After the 9 min, the solar power beaming station will not be able to see that particular receiver and should, therefore, switch to another receiver on Earth.[54] However, the lower conversion efficiencies of the laser-based system mean that considerably more energy is wasted in heat than with microwave systems, and this heat must be managed as part of the satellite operation.[55] Moreover, the space system must accurately point toward the Sun, while the transmitter and the receiver must maintain a precise and stable alignment. A desirable laser for space communications would derive all its power efficiently and directly from the sun.

In the subsequent sections, we delve into the performance and challenges of state-of-the-art solid-state solar lasers as one of the most advanced types of solar lasers developed in the past decade. We then explore potential strategies for addressing these challenges, focusing on two main avenues: the development of novel gain media designed for low pumping thresholds compatible with the intensity of natural sunlight and the implementation of innovative pumping schemes, such as blackbody lasers, to harness solar energy more efficiently. These discussions aim to outline a roadmap for enhancing the efficacy and applicability of solar lasers, paving the way for their broader adoption in sustainable energy systems.

III. EMERGING INNOVATIONS IN SOLAR LASER TECHNOLOGY

A. Solid-state solar lasers

The first solar laser was demonstrated by Kiss *et al.* in 1963,[56] and the first solid-state solar laser was developed by Young in 1966.[57] In this system, the solar radiation was concentrated into a rod of Nd:YAG by a parabolic mirror, resulting in an output power of 0.8 W with a total efficiency of less than 1%. Various designs based on primary and secondary focusing geometries have been realized to enhance the solar light collection and increase the pump intensity on the gain medium. The primary focusing geometry is mainly made of a Fresnel lens or a parabolic mirror, combined with heliostat mirrors and conical pump cavities. The focused light is then coupled to the secondary focusing modality consisting of non-imaging optics, such

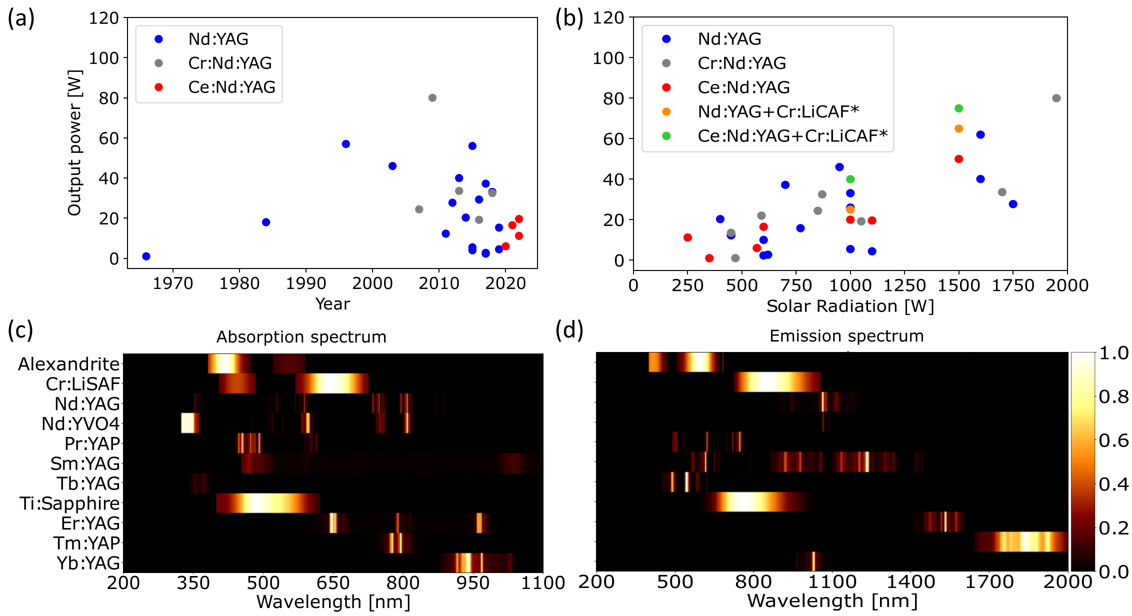

FIG. 3. Evolution of (a) output power and (b) optical-to-optical conversion efficiency in solar-pumped solid-state lasers since their inception.[19,58–85] (c) The absorption and[89–99] (d) emission spectra of common solid-state gain media.[93,97,100–108]

as compound parabolic concentrators (CPC) or ball lenses, for further focus and an increase in the solar pump intensity in the laser gain medium. Figures 3(a) and 3(b) show a comprehensive summary of the advancements in solar-pumped solid-state lasers from their inception, showcasing the progression in output power and the optical-to-optical conversion efficiency.[19,20,58–88]

To be a candidate for solar pumping, a laser material with a high ratio of fluorescent lifetime, low lasing threshold, operation at room temperature, and broadband absorption is desired. A comparison between the absorption and emission bandwidth of the common solid-state laser gain media is shown in Figs. 3(c) and 3(d). Neodymium-doped YAG (Nd:YAG), Ti:sapphire, Cr:LiSAF, and alexandrite have a broad absorption bandwidth. However, their partial overlap with the solar spectrum and their high upper state lifetime demand for high solar pump intensity. Therefore, in addition to optimizing collection efficiencies, multiple research groups have explored various methods to boost the conversion efficiencies of solar-pumped lasers by developing innovative gain materials.

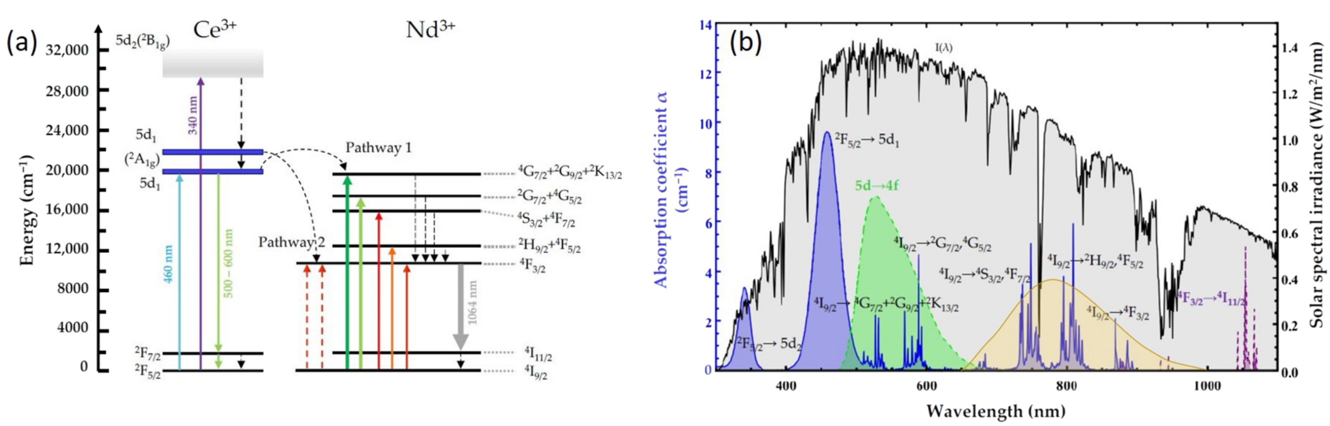

FIG. 4. (a) The energy levels of cerium and neodymium ions with cross-relaxation paths.[77] (b) Solar spectrum (gray), the absorption spectrum of Ce (0.1%):Nd (1.1%):YAG (blue), the emission spectra of cerium (green), and neodymium (purple) and emission spectra of Cr:LiCAF (yellow).[64,77] Reproduced with permission from Garcia *et al.*, Energies **15**, 5292 (2022); licensed under a Creative Commons Attribution (CC BY) license.

Cerium (Ce^{3+}) has a broadband absorption spectrum in the ultraviolet and visible range. When co-doping with the Nd:YAG crystal, it can significantly improve the efficiency of the laser. Cerium absorbs at 339 and 460 nm and has a broad fluorescence spectrum spanning from 500 to 600 nm. The emission spectrum overlaps with the excitation peaks of the neodymium ions, resulting in increased absorption and, therefore, optical-to-optical efficiency of the solar laser (Fig. 4).[18,25,59,61,65,72,77,80,109] Alternatively, it has been suggested that employing crystals such as Cr:LiCAF as an external frequency converter to downshift large amounts of unabsorbed solar photons could enhance the efficiency of solar Nd:YAG lasers and reduce the pump intensity lasing threshold.[64]

Although theoretical models suggest that broadband-pumped lasers could achieve a balanced efficiency limit of 31%,[110,111] experimental demonstrations of solar lasers have consistently shown efficiencies under 10%.[12,119–121] Several obstacles must be overcome to make solar pumping competitive with conventional pumping schemes. Solar radiation needs to be concentrated to very high intensities to achieve the laser threshold when pumping currently available laser materials. This concentration process requires precise pointing of the optics toward the Sun[112,113] and leads to significant heat accumulation in very small spaces within both the concentrator and the laser crystal. The substantial heat within the laser crystal necessitates the use of specialized cooling methods, compromises laser performance, and increases the risk of catastrophic failure due to the limitations of the materials used. In addition, a major drawback of solar pumping is the absence of energy storage capabilities. Un-like electrical energy, which can be readily stored in capacitors and batteries to overcome periods of solar radiation unavailability due to satellite orientation or solar occultation by a planet, solar-pumped systems lack this flexibility. Furthermore, achieving reductions in the size and weight of solar lasers to make them comparable to photovoltaic (PV) panels could unlock new possibilities for their application.

B. Low-threshold solar lasers

Solar-pumped lasers benefit from eliminating large concentrating lenses and precise solar tracking. Furthermore, it is crucial to capture diffused horizontal sunlight or harvest solar energy on overcast days, as diffused solar radiation constitutes, on average, 49% of the annual total solar irradiance.[114,115] Low-threshold lasers hold promise to address these challenges.

Radiative energy transfer could successfully decouple the conventional trade-off between solar absorption efficiency and the mode volume of the optical gain material through cascade energy transfer in a luminescent solar concentrator, therefore, lowering the lasing threshold.[116–122] In this technique, the luminescent colloidal nanocrystals are paired with traditional optical gain media, such as Nd^{3+} and Tm^{3+}, in a planar waveguide geometry. The absorbed solar light re-emits in the layer of luminescent colloidal semiconductor nanocrystals. A fraction of the emitted photoluminescence is then trapped in a sub-millimeter gain medium attached to the luminescent solar concentrator.[117,123] Based on this technique, an actively cooled solar laser with an optical-to-optical conversion efficiency of 0.023% and a collection efficiency of 0.21 W/m has been demonstrated.[114]

Several proposals have been made to engineer novel gain media for efficient, low-threshold lasing under natural sunlight. Mattiotti *et al.* proposed a new gain media inspired by the architecture of natural photosynthetic complexes, as one of the most remarkable aspects of many natural molecular aggregates is their ability to efficiently process extremely weak sources of energy or signals for biological purposes.[126–132] In their proposed hybrid structure, photosynthetic complexes in purple bacteria (*Rhodobacter sphaeroides*) surround a suitably engineered molecular dimer composed of two strongly coupled chromophores. The photosynthetic complex efficiently collects and concentrates solar energy to the core dimer structure, allowing for population inversion and lasing under natural sunlight [Fig. 5(a)].[124]

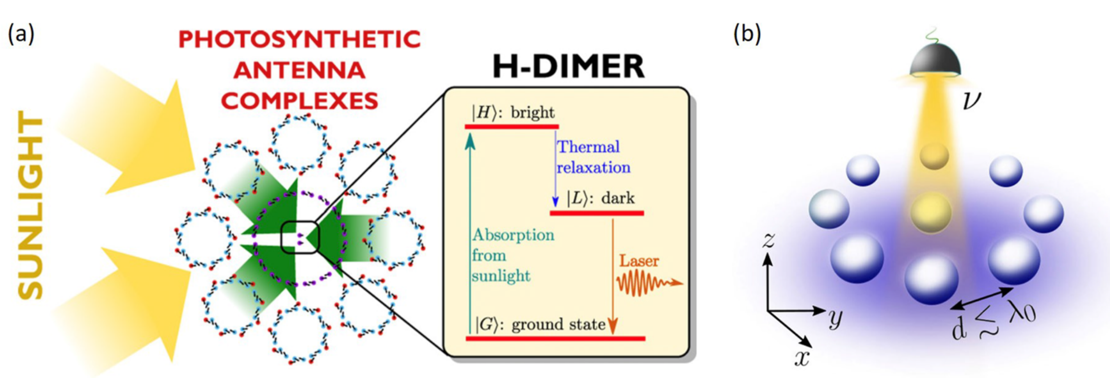

FIG. 5. (a) Photosynthetic antenna complex collects energy from sunlight, which is converted to electronic excitation and efficiently funneled to an H-dimer placed in the middle. Here, the excitation is absorbed to a bright, high-energy state, and it relaxes quickly to a dark, low-energy state. This mechanism prevents re-emission and allows population inversion between the dark and ground states and, therefore, lasing.[124] Reproduced with permission from Mattiotti *et al.*, New J. Phys. **23**, 103015 (2021); licensed under a Creative Commons Attribution (CC BY) license. (b) Coherent light emission from a partially pumped atomic array. A ring of atoms with an additional atom in its center incoherently pumped.[125] Reprinted Fig. 1(a) with permission from Holzinger *et al.*, Phys. Rev. Lett. **124**, 253603 (2020). Copyright (2024) by the American Physical Society.

In a recent study, Holzinger *et al.* proposed the implementation of a minimalistic sub-wavelength-sized laser with no pumping threshold. The proposed geometry contains a collection of atomic quantum emitters as the gain medium and resonator. A continuously pumped single atom surrounded by a nano-ring of identical atoms, as shown in Fig. 5(b), could emit spatially and temporally coherent light in a sub-wavelength laser cavity.[125,133]

C. Blackbody-pumped solar lasers

To address the challenges associated with solar energy collection, one innovative strategy that has been investigated involves blackbody-pumped solar lasers.[134–137] This approach uses solar radiation to heat a source, emitting thermal radiation based on the blackbody radiation law. When a large-area blackbody is used, it produces substantial thermal radiation that energizes a gain medium. The pumping efficiency of the laser improves in tandem with the temperature of the blackbody, thus boosting the laser's overall performance. An additional benefit of blackbody-pumped solar lasers is their intrinsic thermal storage capability. This feature enables the laser to continue operating without additional heat input until it reaches a critical temperature that matches its operational threshold. Such a characteristic could potentially allow a laser system to function even during the Earth's orbit on its dark side. Moreover, the total energy in the solar spectrum can be used to pump the gain medium.

Two factors limit the upper temperature of the blackbody: (i) thermal limitation of material and (ii) radiation losses out of the blackbody cavity through the solar light entrance hole. Such constraints have limited blackbody pumping systems to 2000 K, well below the thermodynamic limit of the sun at 5800 K.[138] Producing high-temperature blackbodies do not pose a significant technological hurdle, given their application in solar furnaces.[139,140] The primary challenge within these systems lies in achieving efficient coupling between the blackbody and the gain medium. Much research has been conducted on blackbody lasers based on gas gain media, where the thermally excited vibrational state of gas molecules is used for pumping the gas by collisional transfer of the vibrational energy. The energy transfer can occur via translational heating or vibrational heating. In translational heating, the blackbody heats the molecules of a transfer gas, creating a Boltzmann distribution of vibrational states, where the molecular translational, vibrational, and rotational temperatures come into equilibrium with the blackbody temperature. In the vibrational heating concept, the transfer gas molecules absorb a portion of the blackbody spectral radiation in a narrow absorption band and become vibrationally excited. The laser efficiency is limited to less than 1% when the vibrational energy transfer is used due to the inefficiency of the Boltzmann distribution in creating vibrational states. Moreover, the active cooling of the transfer gas is required. Translational heating can achieve higher efficiencies, but the difficulties rely on the efficient coupling of the transfer gas and the blackbody. The concept of blackbody pumping has been more advanced toward employing solid-state gain media, such as Nd:YAG, and high efficiencies up to 35% are anticipated.[141,142]

IV. PERSPECTIVE

As a high-intensity, renewable energy source, a solar laser with a simple design, no active electronics or moving parts, low threshold operation, and beyond 10% optical to optical efficiency holds the potential to significantly contribute to sustainable energy solutions and optical communications for space exploration.[16,17,48–50,143–145] Scaling down solar lasers to dimensions akin to those of photovoltaic panels could revolutionize their applications, for example, enabling wireless power delivery to electric vehicles and unmanned aerial vehicles.[146–151] This innovation is already under way, with the introduction of new crystalline silicon photovoltaic cells designed for power transmission from solar lasers. These cells are tailored for extremely high-intensity, monochromatic light at a wavelength of 1064 nm and function optimally at specific incident angles.[152–154] While micro-solar lasers offer to enhance the stability and resilience of the solar lasers to wind stress, thanks to their compact size and the efficient heat management facilitated by free or natural air convection,[155,156] there remains ample scope for further research. Enhancing the performance of solid-state solar lasers, particularly through the adoption of disk geometry,[157–159] presents a promising avenue. Such geometries can facilitate more efficient cooling and quicker heat removal, potentially improving beam quality and efficiency.[160,161] Furthermore, innovations in novel gain media for low-threshold lasing support the simplification and miniaturization of solar lasers. This allows them to function effectively at the sunlight's natural intensity threshold, opening new avenues for their application and performance.

The uninterrupted access to solar energy in space positions the concept of directly beaming it to Earth as highly compelling, ensuring superior energy conversion efficiency over time relative to conventional terrestrial solar panels. However, the realization of space-based solar-pumped lasers and magnesium-generating technologies as dependable energy sources is still in the distant future. Nevertheless, should these innovative approaches reach their full potential, they promise to provide a sustainable and clean energy supply. Beyond contributing to the magnesium economy, the advancement of efficient solar lasers could also enhance solar hydrogen production. This is particularly relevant for photocatalytic water splitting, which shows higher efficiency in the ultraviolet spectral range.[162,163] A leap in the efficiency, lasing threshold, and compactness of solar lasers could unlock a plethora of application opportunities. These range from powering devices in remote locations, bolstering the nascent low-Earth orbit economy, enhancing electric mobility, and facilitating operations underwater to enabling material processing, conducting atmospheric research, and advancing space propulsion technologies. Such innovations promise to transform a wide array of sectors through innovative solar energy utilization.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Michael Küblböck: Data curation (equal); Investigation (supporting); Writing – review & editing (supporting). **Jonathan Will**:

Data curation (equal); Writing – review & editing (supporting). **Hanieh Fattahi**: Conceptualization (lead); Data curation (equal); Formal analysis (equal); Funding acquisition (lead); Investiga-tion (lead); Methodology (lead); Project administration (lead); Resources (lead); Supervision (lead); Validation (equal); Visual-ization (equal); Writing – original draft (lead); Writing – review & editing (equal).

DATA AVAILABILITY

All datasets underlying the paper will be available to readers upon their request.

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