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PERSPECTIVE

nature photonics

Prospects and physical mechanisms for photonic space propulsion

Igor Levchenko[1,2], Kateryna Bazaka[2], Stephane Mazouffre[3], and Shuyan Xu[1]

An abundant source of energy in space, electromagnetic radiation can provide spacecraft with a gentle yet persistent thrust for interplanetary and interstellar missions. Early success of micro-laser and solar propulsion platforms confirm their potential for near-Earth and deep space exploration, although practical realization of reliable photonic devices is not trivial. Motivated by an interest in space exploration, this brief report outlines the recent achievements in this young field. We highlight several light-enabled mechanisms of thrust generation via photon-matter interactions such as photonic pressure and ablation, optical gradient forces, light-induced electron emission and others, with potential technological impact in the contexts of space propulsion. Finally, we outline some of the key challenges and possible solutions for practical applications of these mechanisms, and propose a classification and guiding principles for future development of the field of photonic propulsion.

PROPOSED by Arthur Kantrowitz in 1972, the idea of photonic propulsion is now developing rapidly[1], with 2009 seeing the first micro-laser propulsion system on-board the KKS-1 microsatellite launched into orbit as a hosted payload of greenhouse gas monitoring satellite Ibuki. The thruster installed on KKS-1 used laser as an auxiliary system, with the main thrust for attitude control and fine modification of the orbit of this small, 3 kg satellite generated by a chemical engine. However, the next version of this satellite will employ a dual mode laser system capable of producing thrust by laser ablation[2]. It appears that application of lasers in space propulsion has begun. Not surprisingly, it started with small satellites that recently emerged as significant players on the back of major progress in miniaturization of electronics, robotics, and penetration of nanomaterials[3] into space technology. These advances have led to the emergence of more affordable and versatile spacecraft solutions, considerably expanding the available designs and functions of spacecraft, and enabling the uptake of these technologies by commercial sectors[4,5]. The satellite technology is now progressing to the stage where it can be effectively and economically used for intelligent, sustainable utilization of Earth's limited resources for the benefit of current and future generations of humans[6,7].

Upcoming large-scale projects require inexpensive next-generation spacecraft that could efficiently travel and operate in space. For instance, Iridium NEXT communication project will rely on a second-generation global network of about hundred telecommunications satellites that either have already been launched or expected to launch in 2018[8]. Even more massive, the OneWeb satellite constellation will bring together several hundred satellites at low Earth orbit to deliver a global Internet broadband service to individual consumers as early as 2019.[9] Deep space and interplanetary programs have experienced similar trends. New exciting missions include the NASA's New Horizons program[10], e.g. the Jupiter–Pluto probe[11], OSIRIS-REx mission to orbit 101955 Bennu asteroid,[12] Stardust mission that delivered the interstellar dust sample to Earth[13], Asteroid Redirect Mission to capture and redirect a near-Earth asteroid to a stable orbit around the Moon[14], NeXT (New exploration X-ray Telescope) mission[15], and highly-ambitious robotic exploration of Mars[16] and even aspirations for Mars colonization[17].

For many such missions, there is an evident lack of efficient, reliable, long-acting propulsion systems[18] to support extended operation and distant travels. To address these challenges, over the last several decades attention has turned to novel systems, such as those based on light-driven propulsion, which are now being rapidly developed. Indeed, while KKS-1 satellite is considered the first demonstration of a laser-driven thrust system in space, the use of light for thrust and control forces dates back to Mariner 4 mission launched to Mars in 1964, which used solar pressure vanes of 0.65 m^2 each. Later, the Mariner 10 launched to Mercury in 1974 and Hayabusa asteroid probe deployed in 2003 used electric power generating solar panels as light vanes for attitude control. Recent examples include the already assembled but yet to be tested Sunjammer spacecraft that features an impressive 1,200 m^2 solar sail[19], and successfully tested LightSail 1 mission fitted with a foldable solar sail of 32 square meters[20].

The profound effect of electromagnetic radiation on spacecraft performance came to prominence when Pioneer 10, a famous interplanetary probe, began to show an anomalous slowdown. Having puzzled researchers for 20 years, the Pioneer anomaly was eventually explained in terms of anisotropic heating of the spacecraft by onboard radioisotope thermoelectric generator, resulting in the emittance of photon flux towards the direction of flight. Seemingly negligible, this flux nevertheless caused noticeable change of the spacecraft velocity[21,22]. Not surprisingly, external light radiation was explicitly taken into account for the long exposure Kepler space telescope missions, such as the Second Light campaign successfully completed in May 2018[23].

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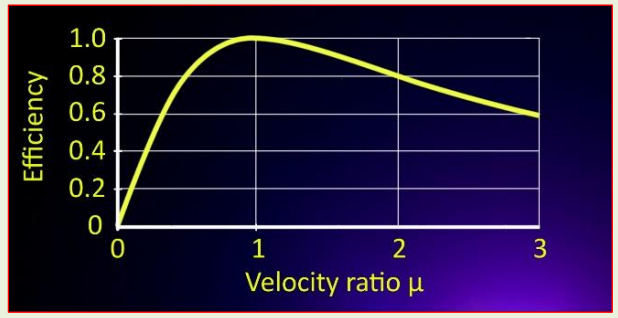
Box 1 | Key principles of propulsion.

From Newton's third law of motion, the only method to create thrust in space is to expel some mass from the spacecraft to be accelerated, according to $F = \dot{m}V_{ex}$, where V_{ex} is the mass expell velocity relative to spacecraft, and $\dot{m}$ is the mass consumton rate, $kg \times s^{-1}$. Remaining within a classical physics paradigm, we disregard systems that violate the law of momentum conservation, such as so-called *electromagnetic propulsion* that uses electromagnetic forces in a closed cavity[31].

Presently, space propulsion is enabled by three major types of systems. The *chemical* propulsion systems feature very high thrust-to-mass ratio η reaching 2000 $N \times kg^{-1}$, yet have the lowest exhaust velocity V_{ex} = 5000 $m \times s^{-1}$ for the best available fuels. The *electric* propulsion systems accelerate ions by electric field and demonstrate much higher exhaust velocity reaching10^5 $m \times s^{-1}$ (with no physical limitations to prevent further enhancement of V_{ex}), but at significantly lower thrust levels[25,32]. Finally, *light-driven* propulsion platforms that use the momentum of photons feature the highest exhaust velocity V_{ex} = 3×10^8 $m \times s^{-1}$ (light velocity) and hence, they are the most efficient in the terms of mass efficiency. However, a very low energy efficiency of such thrusters implies their use as secondary systems, mainly for attitude control[33], or in more complex platforms that produce thrust through the interaction of light with matter (i.e., via laser ablation). The energy efficiency of any propulsion system is expressed in terms of energy spent to velocity gained by the payload:

$$\gamma = \frac{2\mu}{1+\mu^2},$$



where velocity ratio $\mu = V/V_e$, V is the velocity gained by the payload (spacecraft), and V_e is the mass exhaust velocity. The graph shows that an increase in exhaust velocity *indeed minimizes the spacecraft mass to be spent for acceleration* but requires much more energy, since all power is spent on spacecraft acceleration when the exhaust velocity equals to spacecraft velocity ($\mu = 1$, an ideal efficiency). When $\mu >> 1$, the most part of energy is spent on *acceleration of the propellant but not the spacecraft*, while heating and ionization consume the bulk of energy at $\mu < 1$. Thus, the energy efficiency of the light source is close to zero, and hence, a massive amount of energy is required to produce notable thrusts (even at the highest possible mass efficiency). Energy is a limited commodity on current spacecraft, so it should be taken into consideration for any thruster design. More details on the key principles of propulsion and energy efficiency could be found in publications and textbooks[34].

The feasibility of any interplanetary journey is critically linked to the efficiency of the associated propulsion system, which directly determines the flight range and travel time[24,25]. The fundamental laws of nature point to electric propulsion[25,26] and optical systems[27,28] as primary candidates for long-operating thrusters[29], with optical systems having the advantage of a very high specific impulse equal to the speed of light. **Box 1** outlines some basic physics of propulsion, including important dependence of thruster energy efficiency on exhaust velocity, emphasizing low efficiency of simple light-driven systems. However, more sophisticated solutions and physical mechanisms provide the necessary foundation for future photonic spacecraft, where light provides a highly-efficient means of transportation within the Solar system and, potentially, for interstellar travels. In this brief report, we critically examine the opportunities and salient features of presently-identified physical mechanisms that govern propulsion and position/orientation control of spacecraft by light in space[30].

Types of photonic propulsion platforms

At a general level, all **photonic propulsion systems** can be divided into the two major categories, namely:

(i) Propellant-less systems, which produce thrust by emittance or reflection of light (i.e., photons with a zero rest mass), and

(i) Propellant-based systems that create thrust by light-driven ejection of a flux of particles of non-zero rest mass (atoms, ions, etc.).

For propellant-less systems (i), the primary mechanism of trust generation is the momentum exchange between photons and elements of spacecraft, while in the second case – the momentum exchange between spacecraft and a flux of propellant ejected using light (ii). Second important parameter to consider is the location of the source of energy. Both categories could use either internal (on-board, i.e. nuclear reaction-based) or external (i.e., laser installed on another spacecraft, or on the surface of Moon or Earth) power sources to generate light energy and produce thrust.

Besides, all propulsion systems could be subdivided based on their functional role, namely *primary systems* that are used to change spacecraft velocity (to change the orbit, interplanetary transit trajectory, etc.), and *secondary* systems whose designation is primarily to control the spacecraft attitude and maintain orientation during missions requiring precise aiming, such as space-based long exposure astronomical observations. In general, primary thrust platform usually feature higher thrust levels, while the secondary ones are often required to produce very low thrust pulses for ultra-precise positioning.

Moreover, due to quite diverse requirements for the technical realization of propulsion systems, it would be meaningful to consider separately the natural (Sun) and artificial (most typically, laser beams) light sources.

Hereinafter we will first briefly characterize several tested configurations of space photonic thrust platforms, only to illustrate specifics of practical application of light-produced forces. Then, we will examine the physical mechanisms of thrust production by light.

Box 2 | Photonic propulsion.

Having an invariant mass of zero, when travelling at the speed of light $c = 3\times10^8$ m×s^{-1} in space, a flux of photons can nonetheless display the property of mass, and transfer the momentum p to a solid surface upon interaction, i.e. during emittance, absorbance or reflectance. The momentum of a photon can be expressed as[35]:

$$p = {}^{h}/_{\lambda}, \quad (2)$$

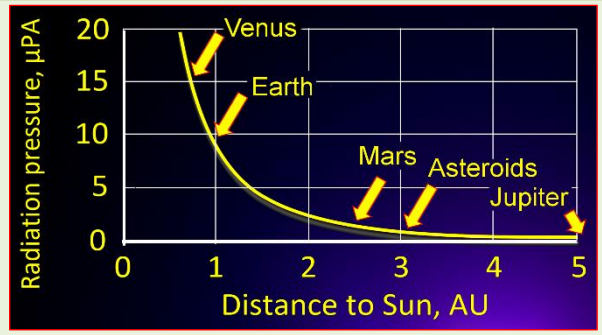
where h is the Planck's constant (6.63×10^{-34} m^2 kg/s, and λ is wavelength. Considering the relationship between the energy and momentum as $E = p\times c$, a light beam produced by a source, such as a laser, can thus generate a thrust of

$$F = {}^{W}/_{c}, \quad (3)$$

where W is the power required to produce the light beam. The typical thrust energy price of 3.3 μN×kW^{-1}is found from (3).
The pressure that the incident flux of photons imparts on a flat surface of a sail can be expressed as:

$$P = (1 + k)\frac{E}{c}cos^2\alpha, \quad (3)$$

where P is the pressure, Pa; k is the reflectance of the material onto



which the flux is applied ($k = 0\ldots1$), E is the radiation power density, ×m^{-2}, and α is the angle of the surface in relation to the incident light. Considering the radiation power density of the Sun to be E_E = 1361 W/m^2 (at the Earth's orbit), it is possible to attain the solar pressure of P_E = 9.08 μPa. The attainable solar pressure falls down to 3.9 μPa at the Mars' orbit according to the r^{-2} law (where r is the distance from the Sun), and thus mere 0.3 μPa is available at the Jupiter's orbit, thus suggesting a physical limit for solar sail space exploration (see figure above).

Table 1 lists several representative examples of systems that belong to the aforementioned categories. They differ in terms of configurations and physical mechanisms of thrust generation. It should be emphasized that virtually all aforementioned types of photonic propulsion systems are now under active exploration, with some representative examples illustrated also in **Figure S1** (Supplementary Information, SI**)**. The specific physical mechanisms of thrust generation via light-matter interaction require critical examination.

It should be noted that while some of these propulsive forces are relatively large and thus could be used for production of significant levels of thrust and as such, for space travel, others are relatively low. Yet, they could potentially be useful for spacecraft manoeuvring and accurate position control, since their vector could be adjusted over a wide range.

Light Generators. A type of photonic thrusters where generators emit the light for thrust is the simplest system from a physical point of view. Indeed, any light source such as a laser produces thrust and thus could be considered a thruster. However (see **Box 1** for the physical mechanisms associated with this type of thrusters), the level of thrust produced and the energetic efficiency (energy price) of such thrusters is very low, specifically at 3.3 μN×kW^{-1}. To compare, a typical modern electric propulsion thruster produces a thrust at a cost of 30 mN×kW^{-1}, thus being 10^4 times more efficient. Nevertheless, the use of a light source as a thruster has several advantages. Firstly, it does not require propellant, i.e. it does not use onboard mass for creating thrust. Although it should be noted here that for systems that rely on onboard light generators, they will require a reliable onboard supply of power to generate photons. Moreover, with the capacity to produce extremely low thrust levels, this system could be very attractive for ultra-precise attitude control in space. Finally, the thrust of the onboard-installed light source could be significantly multiplied by the reflection of light between two spacecraft.

Thrust systems that use light pressure and solar sails. The gentle pressure of solar light particles onto a surface, e.g. a solar sail, can provide a persistent source of motion, which, when captured correctly, may generate a sufficient net acceleration of the sail and the attached spacecraft in the chosen direction of travel.[36] Thus-generated thrust is approximately two times higher when the surface of the solar sail is highly-reflective rather than absorbing. The absorption and reflection of the Sun's radiation, and resulting radiation pressure, play a significant role in the behaviour of objects within the Solar system, e.g. in the formation and orientation of comet tails[37]. Box 1 briefly summarizes the key physical relations that describe radiation pressure propulsion. A concept of a commonly used foldable solar sail is shown in **Figure 1a**. To date, several projects and missions have taken advantage of solar sail propulsion, including IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun, the first true solar sail spacecraft fully propelled by sunlight)[38], CubeSail (a 3U-class Cubesat project developed by Surrey Space Centre, UK)[39], NanoSail-D[40], and others[41]. Although a simple and a relatively low efficiency approach, solar sail propulsion nevertheless provides a practical and reliable solution for near-Earth exploration.

Photonic propulsion by single and multiple reflections. In contrast to Sun light, the use of lasers, i.e. highly coherent light beams, allows to control the light beam propagation. As a consequence, a much more efficient production of thrust can be achieved either by focusing the light onto sails or by trapping powerful beams in a cavity formed by a mirror standing on the spacecraft and a mirror placed on a celestial body like Earth, the Moon, a planet or even an asteroid. The laser can also be external, i.e. located outside the spacecraft. Indeed, while a single reflection of a photon beam has the ability to produce a weak specific thrust of 3 μN×kW^{-1} due to a very inefficient energy exchange between incident photons and spacecraft, there are *no physical limitations* on recycling photon energy. A design consisting of an immovable mirror installed near the laser beam

Table 1 | Examples of various configurations of the photonic thrust platforms

	Type	Configuration and description	Example
Propellant-less photonic thrusters	Systems with external light sources	Solar sails: Systems utilising solar light to produce thrust applied to surfaces	CubeSail[39,43], NanoSail-D[44], IKAROS[45] missions
		Systems utilising single reflectance of light from external lasers.	Breakthrough Starshot accelerated by powerful Earth-based (or orbit-based) lasers[46]
		System that significantly multiply the thrust by reflections and trapping photons between mirrors on separated space platforms	Proof-of-concept demonstration stage[47,48]
	Systems with internal (on-board) light sources	Light produces thrust directly by transferring the photon momentum during emittance	May be suitable for ultra-precise manoeuvring and attitude control
		Light produces thrust by multiple reflection between the two mirrors installed on the two spacecraft	May be suitable for ultra-precise manoeuvring and mutual attitude control
Propellant-based photonic thrusters	Systems with external and on-board light sources	External laser beam produces thrust via ablation	Lightcraft project– first flight demonstrator[49,50]
		Hybrid system – External laser beam produces thrust by ablation in arc discharge thruster	Lab demonstrator – hybrid laser-plasma thruster[51]
		Powerful pulsed laser creating thrust by igniting plasma	Air-breathing pulse-laser powered orbital launcher – a concept proposed[52]
		Laser ablation plasma with additional electromagnetic acceleration	Lab demonstrators[53] and two-mode thruster for the next version of KKS-1 satellite[2]

generator has been proposed to re-reflect the laser beam several times back to the spacecraft. This process may be repeated hundreds of times, significantly multiplying the resultant specific thrust to a much greater value, e.g. 5.10 mN×kW^{-1} for 770 times mirrored back and forth, which is comparable with that produced by highly efficient electric propulsion systems. Yet, in contrast to electric propulsion thrusters, photonic laser propulsion does not require spacecraft-installed power sources and propellant supply[42], and thus may be lighter and more cost-effective to launch.

With external powerful lasers, even single-reflective configurations could be quite efficient when the laser beam is focused onto a spacecraft-installed sail (a mirror). Being strongly focused, a laser creates significant light pressure, well exceeding (by several orders of magnitude) the values specific to sunlight. Interestingly, this approach is now being considered as the only currently available technique for accelerating artificial objects to sub-light velocities. Recently proposed and actively explored, the Breakthrough Starshot project[46] aims at reaching our neighbouring star system, Alpha Centauri, in just over 20 years by using ground-based lasers capable of accelerating small space probes to the velocity of 100 million miles an hour (47,000 km/s, i.e. 16% of light velocity). No other technical system has so far been identified as capable of reaching this milestone advance.

Laser powered propulsion systems. This is another family of thrust systems where the light (laser) beam is used to transfer the energy from Earth (or another outpost) to a spacecraft. However, rather than relying on photon reflectance for direct thrust production, here the photon beam is used to directly interact with a solid target mounted on the spacecraft, thereby creating a beam of matter, the emission of which produces thrust. Thus in this case, photon-matter interactions of various types are the primary mechanism for thrust generation, and there is no requirement for power supply or thruster on the space vehicle itself, just a solid target that can be seen as propellant. An alternative configuration relies on the direct transfer of energy subsequently used to power an onboard thruster, e.g. by generating strong light-driven electric fields in layered nanostructures, see the Outlook section. These approaches alleviate the need for onboard power supply dedicated to propulsion.

Evidently, these systems could be highly versatile and promising, given a wide variety of mechanisms by which the photonic energy of a laser beam can be harvested and transformed into thermal, electric, or electromagnetic energy utilized for propellant acceleration and thrust production. Among others, systems based on light-induced ablation (experimentally proven Lightcraft project[50]), as well as other mechanisms discussed below could be used.

Physical mechanisms of thrust generation by light

The above outlined configurations utilize various mechanisms of light−matter interaction for thrust generation. Some of the aforementioned configurations differ by these mechanisms, while others use the same or quite similar principles (e.g., thrust produced by reflection of sunlight and external laser beam implies the same physical mechanism). The physics of thrust generation by reflection of either sunlight or external light is a major principle outlined in **Box 2**. Below we briefly examine several important mechanisms behind the direct conversion of light into thrust.

Mechanical forces due to light-induced ablation. As mentioned above, the photonic thrust system could be designed to use laser radiation from a ground or space-based power station, as well as on-board power unit for the light-driven acceleration of a solid or liquid propellant[49, 54]. Importantly, application of the light-ablating microtrusters in spacecraft are already under development[2]. Notable advantages of this approach include possible external generation of power, i.e. the main power source is not accelerated with the spacecraft and hence, could be large and/or dangerous for the crew, e.g. a nuclear reactor; and the use of efficient propellants which ensures a desired specific impulse.

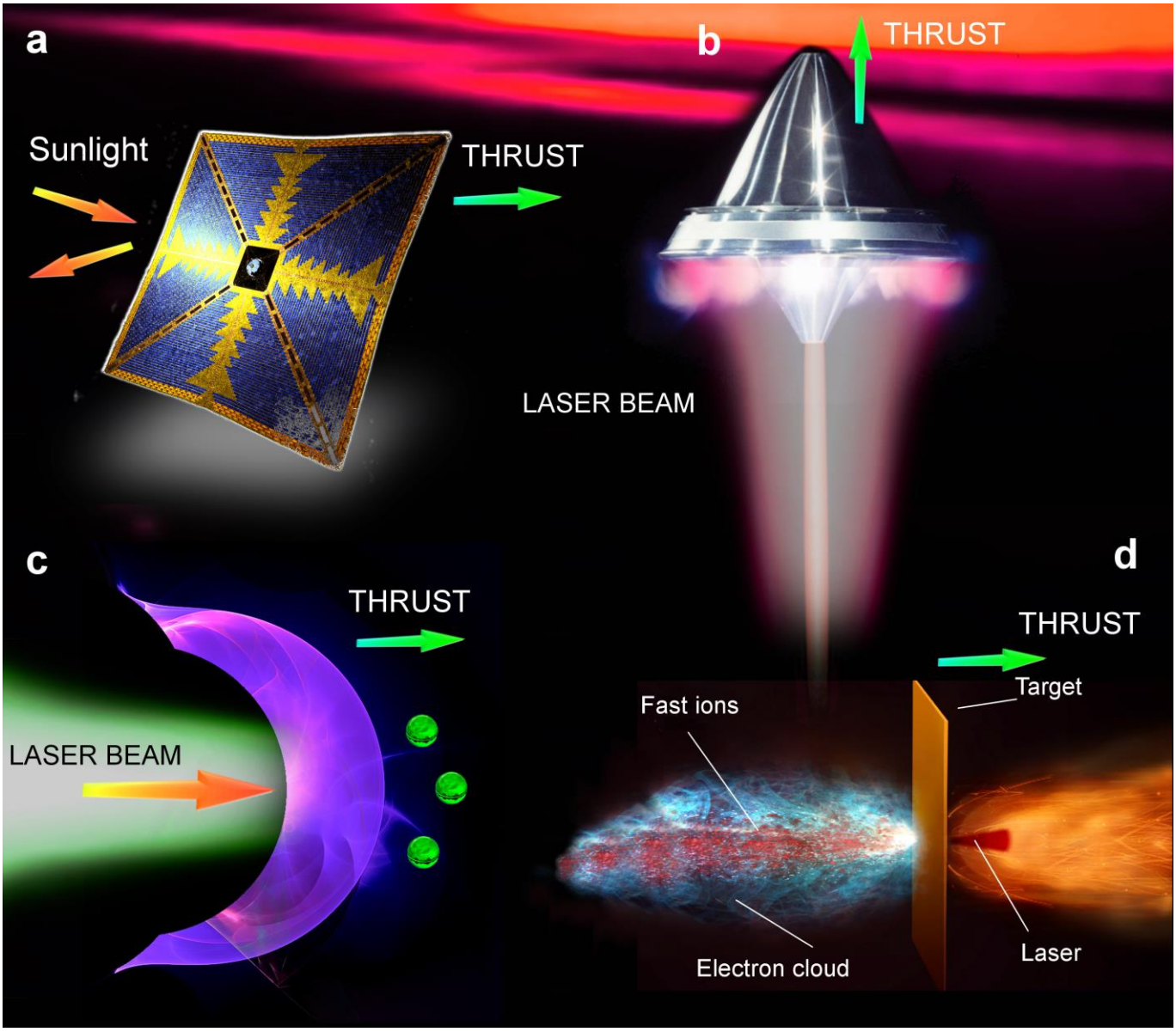


Figure 1 | Examples of photonic propulsion systems. (a) Solar sail for JAXA (Japan Aerospace Exploration Agency) return mission to Trojan asteroids. The spacecraft will be equipped with a solar sail and ion thruster, with energy being harvested by thin-film photovoltaic cells attached directly to the solar sail. Sail size is 2500 m^2, with 30,000 photovoltaic cells that ensure about 5 kW power at 5 Au distance to Sun, with extremely efficient energy conversion system of 1 $kW \times kg^{-1}$[55]. (b) Lightcraft, the first demonstration of photonic-powered object, capable of stable flying by the action of ground-based laser onto ablative solid propellant placed in the parabolic light-focusing cavity[49]. (c) Radiation pressure-assisted thrust generation using a thin target (RPA-SL). Energy gain at the level of 1 MeV is confirmed experimentally, and 100 MeV is predicted by theoretical assessments. Importantly, laser radiation interacts here with the dense laser-generated plasma. More details on the physical mechanism and specific details can be found in literature[56,57]. (d) Schematics of the mechanism of fast ion beam extraction from laser-irradiated solid target, which utilizes a focused laser beam to create a beam of MeV-energized proton/ion beams. Reprinted from [58].

A coherent low-diverging laser beam is well-suited for such a task under space conditions, where absorbance is extremely low. Yet, efficient energy transportation from the power station to the spacecraft by photons is not a trivial task. Unavoidable power losses could be compensated by increasing the emitted power, provided that the power requirement of the spacecraft are quite moderate compared to the power generation capabilities of the Earth-based or low-orbit residing stations. However, beam divergence which is determined by a relation:

$$\delta \sim \lambda / D, \tag{1}$$

where λ is the wavelength, and D is the beam diameter, could be significant. Therefore, the initial spacecraft acceleration using the laser beam should be sufficiently intense to avoid the need for light transfer over greater distances, where beam divergence will cause excessively high losses (or will require the use of very large antennas). For instance, with a wavelength of several hundred nm and a beam diameter of about 1 m, at a distance of 10^4 km

between the spacecraft and the power station the divergence reaches 10^{-7}, doubling the diameter of the beam.

While beam divergence is a critical issue for the interplanetary flights, it is far less significant for near-Earth missions, such as orbit keeping. It should be noted that the laser ablation propulsion is not a technology limited to microthrust levels intrinsic to orbit keeping tasks, and could be successfully applied to enable more powerful thrusters (even those designed for the launch phases). Nevertheless, laser ablation potentially can be quite efficient at the micro thrust levels[59,60].

The ablation-enabled photonic thrust devices could operate in transverse and coaxial modes, when the laser beam is delivered to propellant from the side[61] to illuminate the propellant through a transparent window, or the reactive jet is coaxial to the photon flux[62]. Apparently, transverse mode allows for much more flexibility in terms of thrust vector control. Specific impulse in both cases could be efficiently varied by changing the power density at propellant surface by controlling the duration of laser pulse and focal radius. The propellant exhaust velocity can vary from the numbers typical for chemical thrusters (about 5000 $m \times s^{-1}$) to very high levels reaching 50,000 $m \times s^{-1}$, since the exhaust velocity is $I_{SP} = \sqrt{2kT_i/m_i}$, where m_i is the ion mass, and T_i is ion temperature which can reach 10,000 K in laser focus. Moreover, when plasma is crated in the laser focus, the plasma-induced electric fields also contribute to the exhaust velocity. Importantly, the thrust-to-weight ratio for photonic space thrust systems utilizing the ground-based light and power sources is much higher compared with the electric propulsion platforms utilizing onboard power systems[63]. **Figure 1b** illustrates *Lightcraft*, the first demonstration of photonic-powered object, capable of stable flying by the action of ground-based laser. While generation of thrust in Lightcraft relies upon shock waves produced in air, laser-matter interaction plays a fundamental role in the delivery of energy to this system.

Radiation pressure-assisted thrust generation. One of practically important mechanisms of thrust generation is based on the utilization of radiation pressure acceleration (RPA). When very intense laser radiation interacts with dense laser-generated plasma, the radiation pressure may overcome the thermal pressure and accelerate the plasma as a piston. Typically, with laser power density of the order of 10^{22} W cm^{-2} and low-density targets, about 100 MeV can be reached according to the theoretical assessments, and 1MeV was confirmed experimentally[56]. When the target is thin enough, i.e. thinner than the light wavelength, the RPA-LS (radiation pressure acceleration-light sail) regime is realized, which is especially interesting for the light-enabled space propulsion. In this regime, very thin (and hence, very light) targets are used, and the threshold for pulse transmission is determined by the relativistic transparency mechanism. Experimental assessments have demonstrated promising results, along with certain constrains[57]; however, this system is now considered as one of the only realistic options for the future interstellar travels[64]. Schematics of the RPA-LS is illustrated in **Figure 1c**.

Thrust via laser-driven emission of highly energetic protons and ions. The systems that utilize a focused laser beam to create a MeV-energized proton/ion beams could potentially be a highly efficient light-enabled thrust system. It could be considered as a variant of ablation system, but it involves different physics. Importantly, an electron cloud is generated along with the fast ion/proton beam, thus a quasi-neutral plasma is ejected in this case, preventing the build-up of electric charge onboard and making the cathode-neutralizer unnecessary.

While the ablation-based systems utilize mostly the thermo-kinetic principles of matter acceleration, the MeV-energized proton/ion beams are produced by the light-generated electric field. Specifically, as described in the framework of the Target Normal Sheath Acceleration (TNSA) model, ions are accelerated by an intense electric field, which arises at the rear side of the laser-irradiated solid target as a result of highly energetic electrons being accelerated at the front surface, with the emission of ions being normal to the rear surface. After several cycles of exposure to the laser-generated electric field, a large number of plasma electrons gain sufficient energy to reach the relativistic velocity. Being lighter, the electrons are displaced forward faster than ions, leading to the formation of quasi-static charge-separation fields between the former and the remainder of the plasma. By tuning the laser pulse and engineering the target to possess specific properties, e.g. sub-micrometric scale nanostructure or level of impurities, it may be possible to achieve a sufficient degree of control over the TNSA process.[58,65]As a result, ion beams of extremely high energy can be produced. In the regime when electron cloud compensates the electric charge of the ejected ion beam, neutral plasma could be used for an efficient light-driven thrust generation in vacuum. **Figure 1d** outlines the fast ion beam generation by light.

An important difference between the two above described mechanisms is that in the case of radiation pressure acceleration, light interacts with a dense laser-generated plasma, with plasma being accelerated as a whole piston; whereas the second method (Figure 1d) relies on light interaction with a solid target, producing an energized beam of protons or ions.

Thrust via photon-induced electron emission. Many of the above described techniques ensure relatively weak forces at the levels of a solar pressure, i.e. about 10 $\mu N \times m^{-2}$when multiple reflection of photons is not used. However, direct light-induced electron-based macroscopic propulsion with a thrust of several orders of magnitude larger than the light pressure was recently reported[66]. It was demonstrated before that laser indeed could efficiently accelerate electrons[67], yet in this case a novel mechanism was proposed, whereby bulk graphene comprising crumpled sheets is moved by *photon-induced ejected electron emission*, which arises from a unique combination of the macro-scale morphology and band structure of graphene sheets and follows an Auger-like path. However, the build-up of electrical charge on the propelled object could be a serious problem, cutting off the thrust-generating electron current and building up the charge on spacecraft[68]. Moreover, serious concerns were raised on the possible thermal effects caused by the interaction of hot graphenes with the residual air in the test vessel (see the relevant discussion elsewhere[69,70]). The authors believe that at the moment, this promising principle requires further investigation before it can be considered as a viable method of space propulsion.

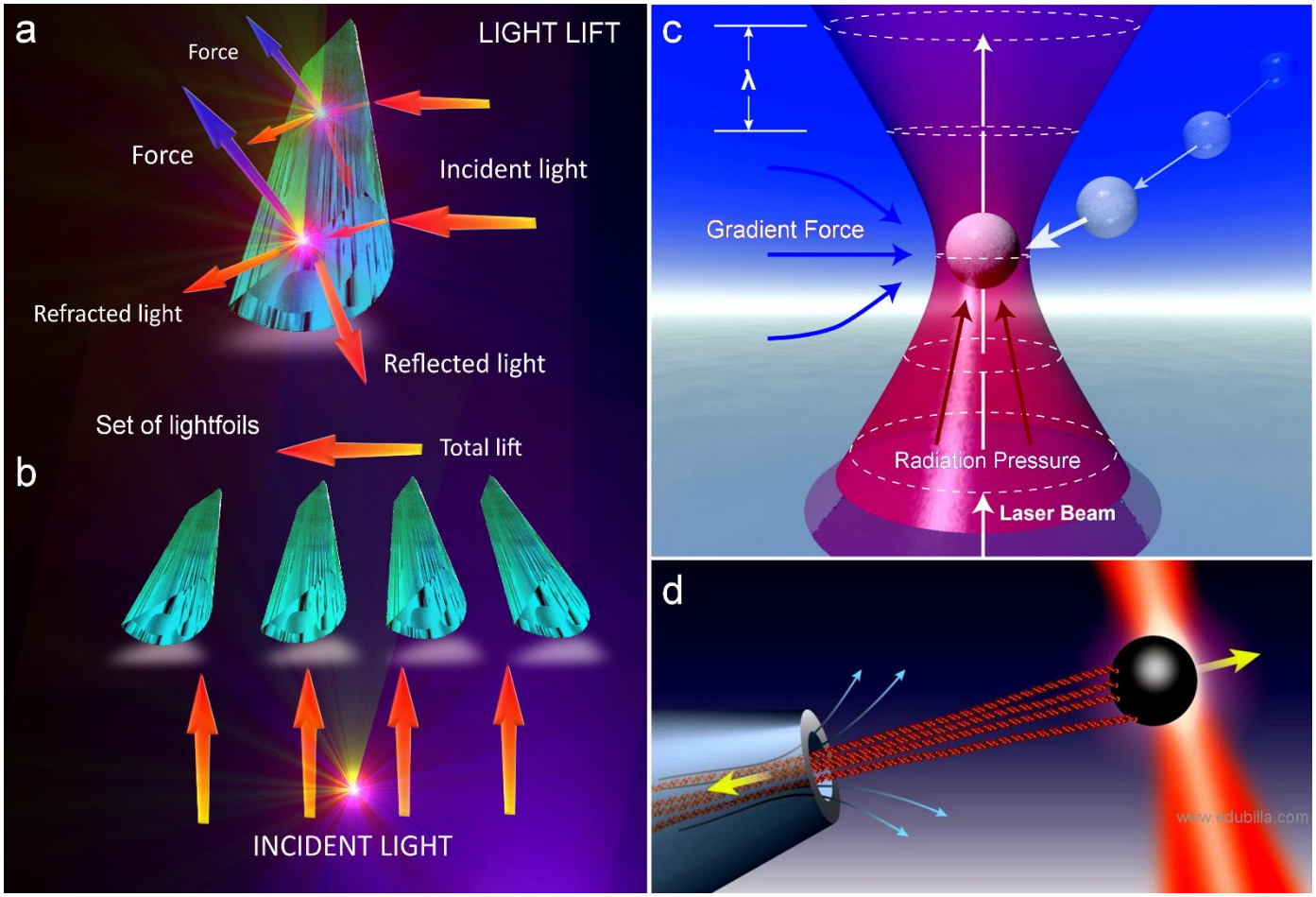


Figure 2 | Photon-induced forces for thrust vector control. (a) The principles of optical lift. A rod with the shape of a longitudinal half-cylinder (left) experiences a moment of force and is set in motion (right), lifting from the bottom of the chamber with a force, which is transverse to the incident light[72]. (b) Schematic of the optical lift array suitable for controlling a solar sail thrust vector or manipulating small objects. Light illuminates the array from the bottom and produces a side force vector of the optical lift. A typical rod diameter is 5 µm, with the length determined by the available technique (about 10 to 100 µm). (c) A spherical transparent particle being subject to gradient forces. Reprinted from[73]. Microparticle is trapped near the light beam focus, and hence, could be accelerated by moving the laser focus. (d)Microparticle trapped in the light beam could exert a side force.

Photon-induced forces for thrust vector control

Along with the thrust generation for spacecraft acceleration, the control of spacecraft orientation and attitude is the second important problem which in general requires thrust, and hence, energy and propellant. Importantly, control of spacecraft orientation requires significant and often fast change of thrust vector to ensure rotational moment, and this could be problematic in photonic propulsion. Indeed, while orientation with the help of solar or laser-reflecting sails could be reached by changing the orientation of sails relative to spacecraft centre of mass (note that re-orientation of huge solar sail made of ultra-thin material may pose a serious problem), other techniques are also possible. Here we will briefly consider two additional options, namely the *optical lift effect* and mechanical forces due to *optical gradient*.

Optical Lift. Particularly suited for spacecraft orientation is optical lift[72], a phenomenon that occurs when an incident uniform photon beam imparts a transverse lift force onto the surface of a *refractive* object of an asymmetric airfoil-type shape, a process in its essence very similar to the Bernoulli principle of hydrodynamic lift (**Figure 2a, b**). Despite its relatively simplicity and wide potential scope of applications, photonic-assisted force generation that focuses on shaping the object, rather than the light is a relatively new direction for the field of photonic propulsion[71].In relation to the space thrust aspects, the optical lift has a great promise for the creation of *additional* (to the direct light pressure) thrust and *efficient control of the sail-powered spacecraft* and solar sail orientation. In the proposed concept, precisely shaped and aligned microrods are exposed to sunlight, at which point it would act as a solar sail, propelling forward, as well as *experience a transverse lift force*. Several carefully positioned arrays would be sufficient to achieve necessary control of the spacecraft orientation in space (Figure 4b). Furthermore, the microrod arrays integrated with reflective sails could be used to increase forward thrust [71].

The forces of an optical lift phenomena could be calculated using the known Kutta–Joukowski theorem, where the aerodynamic lift force in the x-direction can be expressed in terms of the pressure p at every point on a surface as $F_x = \oint p\hat{n} \cdot$

$\hat{x}da$, where $\hat{n}$ and da denote the unit vector perpendicular to the surface and an area element on the surface, respectively. In optics, the factor $p\hat{n} \cdot da$ represents the local force at a dielectric interface, which is always orthogonal to the surface. Theoretical predictions estimate that for a dielectric semi-cylindrical rod, up to 20% of the momentum from the irradiating light beam can be transformed into a stable lift force[74]. When integrated with the solar sails, the optical lift systems could both enhance the thrust and enable positioning of the spacecraft is space[75].

Mechanical forces due to optical gradient. The utilisation of optical gradient forces is one more important physical mechanism that ensures acceleration of micro- and nano-particles, and hence, production of highly controllable force[76,77]. Actually, when a highly-focused laser beam is shone on a spherical particle, it is subject to scattering and gradient forces. The latter can be quantified by integrating the Maxwell stress tensor over an artificial boundary region that included the particle $\vec{F}_{EM} = \oint \overline{\overline{T}}_M \vec{n} dS$, where $\vec{F}_{EM}$ is the electromagnetic force, $\overline{\overline{T}}_M$ is the Maxwell stress tensor and $\vec{n}$is the outgoing vector normal to the surface. The particle is polarised by the electric field, where the magnitude of thus-induced dipole is dependent on the polarizability, α, of the particle. Specifically, it is determined by the volume of the particle and the difference between its refractive index, n_p, and that of the surrounding medium, n_m. Further discussion on the physical mechanisms of light trapping could be found in[78,79], see **Figure 2c, d**).

Presumably, powerful traps could be used not only for handling micro- and nano-objects[80,81], but also for accelerating them with a very high efficiency – an ultimate task for any reactive thruster. In the simplest case the trap-based space thruster system could be imagined as a source of nano-objects (aerosol particles or plasma-nucleated nanoparticles, e.g. fullerenes) which are being captured by the properly focused external laser beam, and then accelerated by, e.g., changing the beam focus causing displacement of captured nanoparticle.

Challenges and outlook

The aforementioned physical mechanisms and techniques have the capacity to realize two closely related propulsion tasks, namely:

- ✓ *Creation of photon-induced forces (thrust) to propel spacecraft for mass- and energy-efficient space travels,* and
- ✓ *Control of photon-generated forces with respect to their magnitude and direction to gently and accurately change spacecraft position and orientation*

Several promising mechanisms and techniques were examined, including light pressure due to momentum exchange with photons, mechanical forces due to light-induced ablation of the irradiated matter, mechanical forces due to optical gradient forces (optical lifts and traps), laser-driven emission of highly energetic protons, radiation pressure-assisted thrust, and forces due to light-induced electron emission by an Auger-like path. The key mechanisms of the force-producing photon-matter interaction have been described, focusing on those capable of enabling efficient utilization and conversion of light available in space, and exploration of the Solar System.

Significant progress has been achieved during the last decade in the understanding of above mentioned physical mechanisms that stand behind the light-matter interaction and conversion of photon beams to mechanical forces. Efficient, propellant-free light-enabled thrusters are closer to being practically realized, yet more proactive efforts are still required for the photonic space rocket to realize its full potential in advanced and emerging spacecraft applications.

Along with the apparent advantages of light-utilizing space thrust systems, such as high propellant utilization efficiency due to very high exhaust velocity reaching 3×10^8 m/s for solar sails and systems using multiple reflections of external lasers, some specific shortcomings are also intrinsic to these particular systems. While the systems with external light sources apparently feature lower mass, the beam divergence is the key problem for such platforms. On the other hand, the systems based on sunlight suffer from low power density at large distances from the Sun. Hence, large light-collecting systems (e.g. sails, solar panels) should be used.

Devices that ensure extremely high exhaust velocities, e.g. those producing thrust via laser-driven emission of highly energetic protons, are preferred for their highest propellant utilization efficiency. The mass of the onboard power source could nonetheless compromise this advantage.

One more critical challenge to overcome is related to the development of appropriate materials, which would maximize thrust by efficiently converting the energy of light into motion, and simultaneously, would be able to withstand bombardment by high energy photons and ions. Examples include solar sail materials that require reflectance close to 1, which can be achieved through sophisticatedly designed multi-layered materials. For example, few-layered graphene-based radiation-resilient films of about 5 nm thickness could be used for the radiation pressure acceleration-light sail.[82] Furthermore, outer space is a highly aggressive environment where the material would be subject to significant ion bombardment, micro-meteorite collisions, extreme radiation and temperatures, all of which can negatively impact the lifetime, properties and performance of the material.

Given the significance of the precision with which light should interact with the material to achieve maximum thrust efficiency, the development of suitable mechanical systems capable of reliably deploying and positioning the sail in outer space is critical. In fact, this requirement holds true for mirrors, solar arrays and propellant reservoirs for ablation-based techniques. Suboptimal positioning can be particularly limiting for systems with external energy sources such as ablation-based thrusters and external laser-powered electric propulsion system, which offer considerable efficiency and light weight but require very accurate orientation of the spacecraft to the external lasers.

The development of light propulsion-related materials should be complemented by efficient laser technologies, including high power, high frequency, and continuous wave systems. While miniaturization may not be a challenge for laser units located on Earth, a satellite or a Moon base, this could be

a considerable hurdle for lasers aboard the spacecraft. At present, laser sail systems working with moderate power lasers are certainly the most realistic approach.

Other photonic propulsion systems are also under active investigation, showing significant promise despite being at very early stages of development. Recently proposed plasmonic force space propulsion is a new approach of special interest and importance, as it takes advantage of yet another light-driven effect for thrust production. Indeed, for the first time the plasmonic nanostructures were used to accelerate and expel propellant in the form of nanoparticles directly by optical forces. Specifically, the resonance effects in layered multistage arrays of nanostructures are used to produce *gradient optical forces*, which accelerate the nanoparticles in the nanostructure. While still at the concept level of development, this technology is nevertheless highly promising for low thrust optical applications.[83]

Similar material-driven advancements have recently been demonstrated in several encouraging experiments. Stacked, multi-layered photonic microstructures demonstrate the ability to guide and confine electromagnetic modes and eventually ensure the efficient acceleration of charged particles by the laser beam. Although still a fair way from practical realization in space-based thrust systems, the technology holds significant promise and demands further exploration.[84]

The ultrashort pulse laser-driven particle acceleration on plasmonic metasurfaces is one more promising technology proposed for the direct particle acceleration by light. Plasmonic nanoantennas enhance and localize the electric field and thus result in the acceleration gradient of the value sufficient for particle acceleration. With a femtosecond laser at 800 nm and ultrashort pulses of about 16 fs, the acceleration gradient of about 11.6 $GV \times m^{-1}$ could be created.[85]

These examples evidence that the complex, hierarchical photonic, plasmonic, and metamaterial nanostructures can offer novel mechanisms for controlling interactions of light with matter, resulting in direct acceleration of particles by photons and light-induced electric fields. Future extensive research and developments will certainly open new opportunity in this promising photonic propulsion research direction. Furthermore, laser plasma accelerators require substantial work for device miniaturization and efficiency increase.

To overcome the numerous hardships and challenges on the path of photonic spacecraft development, consolidated research efforts in many fields including photonics, light-matter interaction, plasma physics, material science and space propulsion are required.

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