Concepts for wireless energy transmission via laser

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The present paper intends to link several disciplines in an attempt to describe an application of optical systems slightly out of their mainstream applications. Back in the middle age, optics, then the "science of light" has been fundamental in understanding our universe and changing our perspective of our place in it. Optics in form of laser communication and the use quantum encryption are entering the field of space telecommunication and might well reveal to be the single most enabling technology for the introduction of secure and high bandwidth communication. In the present paper a different application of optical links is discussed, using laser links not only as a communications channel but also as a means to transfer energy without wires. Different concepts and applications of wireless power transmission via laser are discussed, including terrestrial and space-based applications.

1. INTRODUCTION

While the science of light and vision has always fascinated and influenced humans, the beginning of modern optics might be traced back to the famous "Book of Optics" by Ibn al-Haytham*, which for the first time describes the theory of vision and light as a ray theory, unifying geometrical optics with philosophical physics. His book already described experiments with lenses, mirrors, refraction, and reflection. Modern scientific optics, with the invention of the telescope in the 17^{th} century by Dutch and Italian astronomers and mathematicians revolutionised our way of viewing the universe and the place of Earth and thus ultimately our own place within it.

Optics is already one of the most cross disciplinary disciplines, spanning from physics, chemistry, mathematics, electrical engineering up to architecture, psychology and medicine. This paper intends to describe the application of optics and light in an area where it is traditionally only marginally present: energy transmission.

2. WIRELESS ENERGY TRANSMISSION

The first attempts to transmit energy wirelessly with the purpose of doing so are attributed to N. Tesla† at his laboratory in Long Island, New York just 30 years after J. Maxwell‡ had predicted in 1873 the transport of energy trough vacuum via electromagnetic waves, validated in principle 15 years later by H. Hertz§. [1]

Following the invention of the magnetron and the klystron in the 1920 and 1930, the developments during the second world war made microwave beams available to a wider scientific community. The first successful engineering approach to use microwaves for effective energy transmission was done by W. Brown¶ in the 1960s, by powering among other devices a tethered helicopter. [2]

The first power stations in Earth orbit, taking advantage of the absence of day-night cycles to harvest the energy of the sun were described by the early space pioneers K. Tsiokovski** and H. Oberth††. Peter Glaser is recognised as the first to combine the visions of these early space pioneers with the practical advances in transmitting energy without wires by W. Brown in his 1968 publication in Science, which contained the first engineering description of a solar power satellite (SPS). [3] It established a vision of a sustainable, practically non-depletable and abundant source of energy to meet world energy demands and triggered the imagination of researchers around the globe.

Since this pioneering article, several small and larger scale studies and experiments have been performed around the world in order to mature the concept of solar power satellites further. For a description of how the concept had evolved since the 1968 publication, it is referred to [4]. While these studies and experiments were generally intensified during times of high carbon fuel prices and received lower attention during times of low oil and gas prices, the idea was never considered mature enough to be put on a larger industrial scale, but the general concept of abundant, virtually CO_2 emission free power generated in orbit and transmitted to where needed on

* Ibn al-Haytham, 965-1040; also known under the names of *Alhacen* or *Alhazen*
† Nikola Tesla, 1856-1943
‡ James Maxwell, 1831-1879
§ Heinrich Hertz, 1857-1894

¶ William Brown, 1916-1999
** Konstantin Tsiolkovski, 1957-1935
†† Hermann Oberth, 1894-1989

Earth has most of the time been considered as too attractive to not pursue further. The most comprehensive study was done during 1979, when the US DoE and NASA made a joint technical analysis (frequently quoted as “SPS reference study”) on the options of SPS. [5]

Furthermore, all studied so far essentially concluded that there were no principal technical “showstoppers” to the concept. On the other hand, with each redesign cycle based on new technology, the total mass in orbit, cost and complexity of the entire system decreased substantially, indicating a remaining potential for further improvements. [5] [6] [7] [8]

The most daring concepts was probably proposed by Criswell et al. in 1990: The proposed lunar power stations would be very large installations on the moon, generating energy from solar irradiation on the moon to transmit it to Earth, passing via relay stations and reflectors in Earth orbit. [9] [10]

Following the theoretical works in the 1950s and the first presentation of a functioning laser in 1960, the use of lasers as a means to transmit energy became apparent. [11] [12] At the same time, the first photovoltaic cells were mounted on spacecraft to complement the energy provided by batteries to extend the spacecraft operational life.

The much higher maturity level of microwave devices and the resulting order of magnitude higher overall efficiency has however prevented the concepts of wireless energy transmission by laser to enter into the mainstream SPS concepts for most of the last 30 years. Recent exceptions include the papers of Brandhorst, Steinsiek, Cougnet, Fork, and Luce. [13] [14] [15] [16]

The present paper argues that advances in laser technology and operational as well as engineering advantages of concepts based on laser power transmission provide ground for further interest in this concept and a stronger involvement of the scientific laser community.

This paper concentrates on technologies for long-distance wireless power transmission technologies. Short and medium range wireless power transmission (e.g. via induction or evanescent wave coupling) are not considered. [17]

3. WIRELESS ENERGY TRANSMISSION TECHNOLOGIES

In general, effective wireless energy transmission concepts need to comply with a range of fundamental constraints:

- possibility to transfer the energy though an atmosphere[‡‡]; transparency of the atmosphere to the used wavelength;
- possibility for directional emission;
- possibility to convert the energy from the form of its source (solar, electric, heat) to a transmittable form (e.g. microwave, laser, accoustic);
- possibility to convert the transmittable energy form back into a useful form of energy (e.g. electricity, hydrogen).

While this paper concentrates on laser energy transmission, it is useful to compare its performances and parameters with microwave energy transmission, the most widely studied wireless energy transmission technology. In principle, laser energy transmission systems are very similar to energy transmission via microwave technology: the power source (solar, electricity) is converted into an emitter or an emitter array that generates the directional electromagnetic radiation, which is subsequently absorbed in a receiver, which transforms the energy back into a more useful, transportable form, e.g. electricity, heat, hydrogen.

The key difference, the wavelengths used, implies the major other differences between the laser and microwave-based concepts: While most wireless power transmission rely on microwave frequencies of either 2.45 or 5.8 GHz (0.12-0.05 m; both in the industrial, scientific and medical (ISM) frequency band), laser energy transmission takes advantage of the atmospheric transparency window in the visible or near infrared frequency spectrum. (Fig. 1)

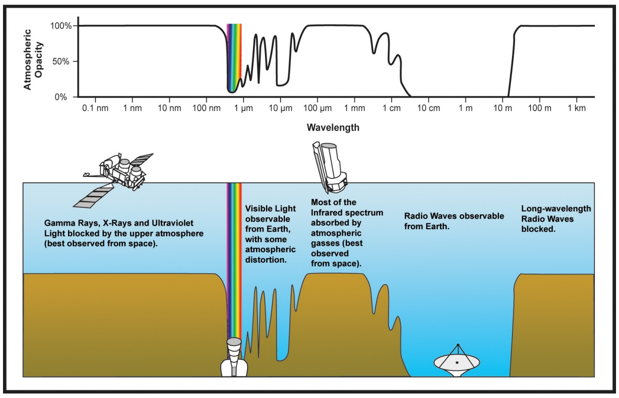

FIG. 1: Transmission and absorption in Earth atmosphere. (source: NASA)

[‡‡] For simplicity, only terrestrial applications are considered for the purpose of this paper. The principle remains of course the same of wireless energy transmission between to objects in space and from deep space to planetary surfaces.

The five orders of magnitude frequency difference determine the sizing of the emitters and receiving devices as well as the energy density of the transmission beam according to standard optics principles. Similar to the higher data rate achievable with optical data links (Fig. 2), laser energy transmission allows much higher energy densities, a narrower focus of the beam and smaller emission and receiver diameters.

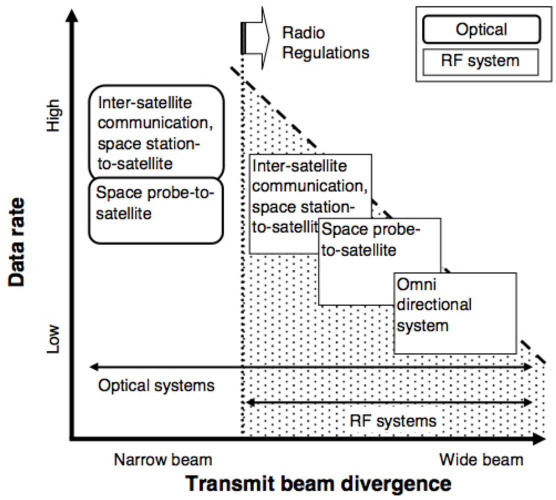

FIG. 2: Classification of satellite communication systems by beam divergence and data rate. (source: [18])

3.1. Wireless power transmission experiments

The principles of wireless power transmission as considered for SPS and other applications has already been demonstrated for both technologies: RF and laser systems.

3.1.1. Microwave-based experiments

Microwave-based experiments have demonstrated so far the possibility to supply power to e.g. helicopters, baloon-based platforms, experimental airplanes, experimental cars, rovers and cell phones. The first experiment was conducted by W. Brown in 1964, when also the first "rectenna"[§§] and invented and used.

The longest distances between emitting and receiving points achieved so far is in the order to hundred kilometers. The largest amount of energy transmitted so far was during an experiment by the US Jet Propulsion Laboratory in 1975, when 30 kW were transmitted from a 26 m diameter parabolic dish to a 1.54 km distant rectenna with 85% efficiency. [19]

The first energy transmission in space between two objects was achieved by N. Kaya et al. in 1983. [20] The first airplane powered by a ground based microwave emitter was launched in Canada in 1987 with the aim to test a wireless power transmission technology to be used for powering high altitude, quasi-stationary platforms. [21] Similar experiments were performed in Japan in 1993 and 1995, powering from the ground a small airplane and a balloon respectively. [22] [23] The electronic beam steering by phase control of a microwave beam from space to Earth using a pilot signal has been demonstrated in a sounding rocket experiment in 2006 by Kaya et al. . [24]

In a completely different power range and for completely different applications, also the power supply to RFID chips are to be considered an application of wireless power transmission by microwaves. Furthermore, these generally use the same ISM frequency band.

3.1.2. Laser-based experiments

While over the years, several laser-based wireless power transmission experiments and applications have been suggested and described, only relatively few actual experiments have been carried out compared to the number and diversity of microwave-based experiments described in the previous section.

Classified experiments involving laser power transmission technology demonstration have been reported to have taken place in the 1980s during the US Strategic Defence Initiative. These seem to have been conducted building on a heritage from the Apollo programme that used ground-based lasers with reflectors on the Moon to measure the Earth-Moon distance. Once of the observatories involved has been the Air Force Maui Optical Station (AMOS) located ontop of mount Haleaki in Hawaii, US. The SDI concepts would use ground based eximer lasers with adaptive optics and a roughly 5 m mirror in GEO and another mirror in a polar orbit at roughly 1000 km altitude. [25] [26] [27]

In 2002 and 2003, Steinsiek and Schäfer demon-

[§§] A rectenna is a power conversion device from converting microwave to DC. The first rectenna developed by W. Brown was composed of 28 half-wave dipoles terminated in a bridge rectifier using point-contact semiconductor diodes. Later, the point contact semiconductor diodes were replaced by silicon Schottky-barrier diodes which raised the microwave-to-DC conversion efficiency from initially roughly 40% to 84%. [2] [19]

strated ground to ground wireless power transmission via laser to a small, otherwise fully independent rover vehicle equipped with photovoltaic cells as a first step towards the use of this technology for powering airships and further in the future lunar surface rovers. [28] The experiment was based on a green, frequency-doubled Nd:YAG laser at only a few Watts. It included the initiation and supply of the rover including a micro-camera as payload as well as the pointing and tracking of the moving rover over a distance up to 280 m by applying active control loops. (Fig. 3)

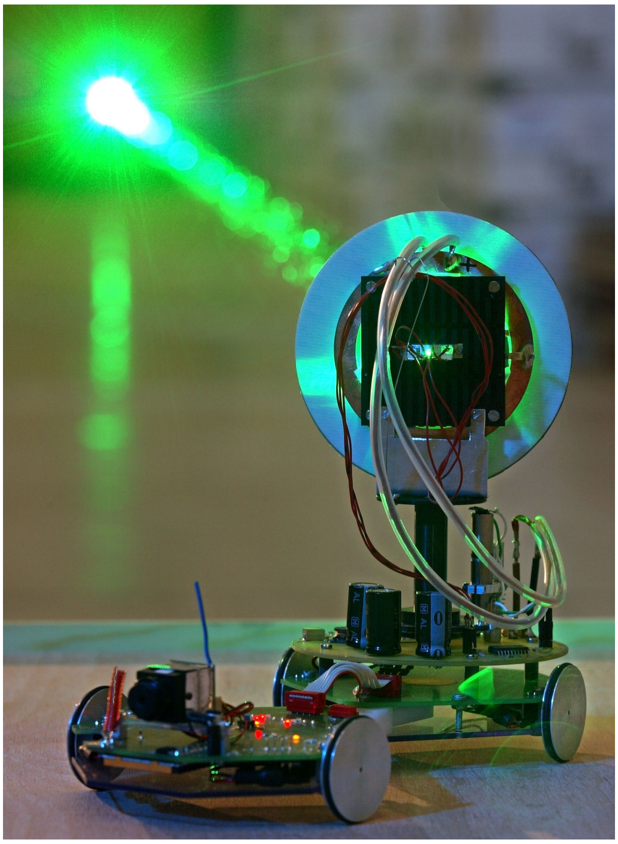

FIG. 3: EADS developed, fully laser powered autonomous rover. (source: EADS)

Recently, similar experiments, however focussing less on the beam control and beam steering aspects but rather on the total transmitted power levels have been carried out in the frame of a context related to space elevators, organised and co-funded by NASA. Ground-based lasers have been used to power small PV-covered "climbers" attached to a tether with the objective to achieve maximum climbing speeds. [29] [30]

One of the advantages of microwave power transmission over the use of laser has been the possibility to avoid moving parts in space by using an electronic beam steering system based on the control of the phase of a matrix of emitters. Recently, Schäfer and Kaya have however demonstrated that a similar system is in principle also possible for laser based systems by presenting a new concept for a retrodirective tracking system. [31]

In the proposed concept, the power transmitter utilises a receiver's pilot signal to obtain information about its direction by conjugating the signal's phase inside a nonlinear medium. The emitted power therefore transmitted back to the direction of the receiver by the phase-conjugated signal beam. In this way, power can be concentrated by an array of phase conjugators, which offer the possibility to provide a large aperture in order to increase the intensity at the receiver's photovoltaic panels. The control of the phase and the direction of the readout beams provides control over the interference pattern, its position, and its size, offering new possibilities for the design of space-based power stations. [31]

3.2. Laser power transmission

Lasers generate phase-coherent electromagnetic radiation at optical and infrared frequencies from external energy sources by preferentially pumping excited states of a "lasant" to create an inversion in the normal distribution of energy states. Photons of specific frequency emitted by stimulated emission enter and are amplified as standing waves in a resonant optical cavity. The most efficient DC-to-laser converters are solid-state laser diodes commercially employed in fiber optic and free-space laser communication. Alternatively, direct solar-pumping laser generation has a major advantage over conventional solid state or gas lasers, which rely on the use of electrical energy to generate laser oscillation since the generation of electricity in space implies automatically a system level efficiency loss of roughly 60%. To generate a laser beam by direct solar pumping, solar energy needs to be concentrated before being injected into the laser medium. The required concentration ratio is dependent on the size of the laser medium, the energy absorption ratio and the thermal shock parameter (weakness of the material to internal stress caused by a thermal gradient).

3.2.1. Laser selection

In principle, all lasers can be used for transmitting power. Using the general conditions as described in section 3 specifically applied for the selection of lasers, these imply in addition constraints related to the

- efficiency of the laser generation process, and the

- efficiency of the absorption and laser-to-electric conversion processes.

Specifically for direct solar pumped lasers, there are several types of materials suitable as laser medium: From the standpoint of resistance to thermal stress, sapphire seems the optimal material for the laser medium. Since large sapphire crystals are very difficult to produce, most concepts rely on YAG (yttrium aluminum garnet) laser crystals. Concerning the required energy densities, solar energy compression ratios of a few hundred times are required for YAG lasers.

Applications in space or from space to Earth add additional constraints regarding:

- laser generation system mass;
- laser generation temperature requirements (preference for very high temperature operations in order to allow for a low radiative heat rejection system mass and small size);
- absence of "consumables" and other potential waste products;
- high laser beam quality to avoid the use of lenses and achieve small receiving surfaces;
- control of the phase (arrays of matrices of different laser, possibly used in order to form virtual, large apertures).

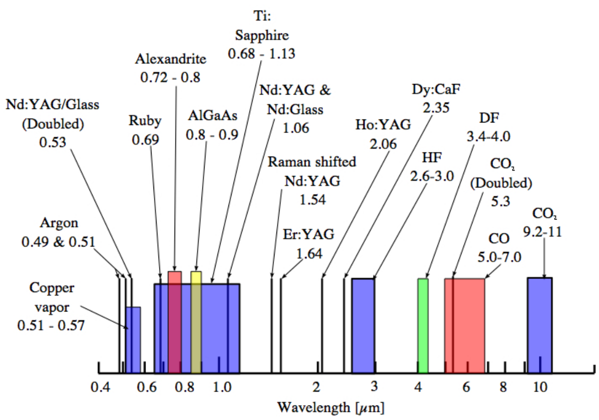

FIG. 4: Spectral output of several types of lasers. (source: [32])

Scholars on terrestrial solar pumped lasers generally differentiate between two types of "solar pumped lasers": direct and indirect solar pumped versions. In this classification, the "solar pumped" description relates to the sun as origin of the power source, with indirect solar pumped lasers first converting it via e.g. PV panels into electricity which is then used for population inversion inside the gain medium. Direct solar pumped lasers use the solar irradiation directly as energy source injected into the laser gain medium.

Under this classification, practically all space based lasers would fall under the category of "solar pumped lasers". Therefore, literature related to space applications usually makes the distinction between standard lasers (in the terrestrial laser power community called indirect solar pumped lasers) and solar pumped lasers (called direct solar pumped lasers in the standard literature on lasers).

3.2.2. Standard indirectly pumped lasers

An analysis of the suitability of different laser types has shown that for the visible frequency range, solid state lasers are in general considered as the most suitable candidates for (space) solar power applications, including diode lasers and diode-pumped thin disk lasers. [33] Especially the later ones have achieved very high power levels of up to kW and overcoming some of the limitations of high power diode lasers, like thermal lensing by reducing the thermal gradients in the material. [34]

In general, these lasers rely e.g. on a laser diode or on materials like Nd:YAG. Currently, the laser diode is the most efficient laser, with an up to 80% plug-in efficiency and an emitted wavelength in the range of 795-850 nm. The most important development effort seems to be made for diodes emitting in the range of 950 nm (pumping of 1.55 μm fiber laser). For larger scale space applications for wireless power transmission, large area emitting system with thousands of individual diodes could be realised. In this case, the main limitation is the thermal control of such diode panels to maintain optical coherence.

Most of the solid state lasers are based on crystal technology (Nd:YAG, Nd:Y_2O_3, Ruby, etc). These lasers are optically pumped in the visible range. The Nd:YAG laser (1.064 μm) is the most widely used; it can be efficiently pumped by laser diodes or solar radiation, emitting visible radiation at 0.532 μm. The overall system efficiency for the laser diode pumped concept is reported at about 15%. [33]

3.2.3. Direct solar pumped lasers

Direct pumping uses sunlight as the source of the pumping light in order to generate the laser beam. In order to achieve the required power densities for the inversion process, sunlight at 1 $a.u.$ needs to be concentrated from its natural 1387 W/m^2 to concentration values between 200 and a few thousands depending on the lasing medium. In order to avoid very large collecting and concentrating surfaces (reflectors or lenses), direct solar pumped lasers add additional constraints to the selection process described above:

- low energy densities for the population inversion in order to allow for practically achievable solar energy concentration ratios;
- high temperature lasing rods able to be combined in series;
- highly efficient hear removal systems.

The laser rods can be made of a variety of materials; many recent studies have focused on using semiconductor materials. The power output of direct solar pumped lasers depends fundamentally on the overlapping between the standard solar emission spectrum and the laser absorption one. The speculated slope efficiency of this type of pumping is up to 2-3% [35]. The components of this system are a solar collector, laser medium and on the receiving end either photovoltaic panels or a heat-based conversion system for the conversion of the laser beam back to electricity. Alternatively, as for standard lasers, lasers in the infrared wavelength region might be used to via further concentrations to directly generate hydrogen via the molecular dissociation process.

One of the most critical technical challenges is the design of an efficient heat removal system from the laser medium. Even with the reported very high conversion efficiencies only part of the injected solar energy will appear as laser output. [36] The remaining energy will generate heat. This energy increases the internal energy of the laser medium but does not appear as laser output. It is therefore important to design the system so that those parts of the solar spectrum that do not contribute to the laser output are filtered and don't reach the laser medium in the first place. One options could be polymer films with a wavelength-dependent reflectance ratio.

Direct solar pumped lasers present some considerable advantages for space applications, making this technology in principle more attractive for use in space than on Earth:

- Since in space, the energy for laser pumping needs to come from solar radiation[¶¶] the efficiency of the photovoltaic solar to electric conversion system needs to be included in a laser technology system analysis. Space PV system efficiencies in the order of 30 to possibly 40% are assumed to be achievable within the next 5 years. Therefore 15% efficient direct solar pumped lasers would compete with laser systems with a 50% laser generation efficiency, not accounting for other aspects.
- The elimination of the intermediate conversion process from solar into electricity in space, which eliminates the need for most of the electronics. Eliminating the electricity intermediate step also solves one of the potentially limiting factors of "traditional" solar power satellite concepts, namely problems due to high voltages (e.g. arching,).

A fiber laser with optimised sun collector could be an interesting alternative, but only a very small number of theoretical studies have been carried out to date and it is difficult to currently quantify the application of this technique for direct solar pumped lasers.

3.2.4. Recent and ongoing research

Most of the very early solar power satellite systems were based on microwave power transmission. But since the very early phases, laser power transmission was considered as an alternative. [5] Studies included already in the late 1970s laser based SPS, their economic rationale, their integration into a hydrogen economy and their potential interactions between high power laser beams and the environment, including the investigation of potential mitigation techniques to minimize the environment effect by a judicious choice of laser operating parameters. [37] [38]

The use of laser based wireless power transmission was revisited in the early 1990s by Landis. [39] [40] Since several years, the Japanese space agency JAXA is pursuing a solid and targeted R&D programme towards the development of space based solar power stations, including as the two main technical options the microwave and laser based concepts. New designs and laser system options have been proposed.

The JAXA proposed laser based system is based on direct solar pumped lasers using a Nd:YAG crystal. A reference system has been designed, delivering in its full configuration 1 GW. The entire system would be built in a highly modular way, with individual modules of 100 $m \times 200$ m primary mirrors and an equally large radiator system as base unit delivering 10 MW each and stacked to a total length of 10 km in orbit. (Fig. 5 and Fig. 6) [41] [42]

In 2004, JAXA and the Osaka based Institute for Laser Technology have reported an experiment with direct solar pumped laser beam (using simulated solar light and a fiber laser medium made from a neodymium-chrome doped YAG (Nd-Cr:YAG) crystal and disc type bulk crystal) with conversion ef-

[¶¶] For the purpose of this paper, applications based on the use of nuclear reactors and pulsed "one-time" high power defence related laser applications in space are not considered.

ficiencies from the input power to the output laser power with 37%. [36]***

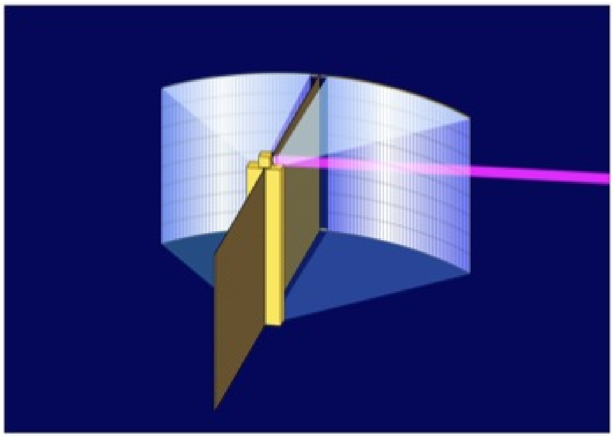

FIG. 5: JAXA L-SPS 100x200 m reference unit delivering 10 MW via direct solar pumped lasers. (source: JAXA)

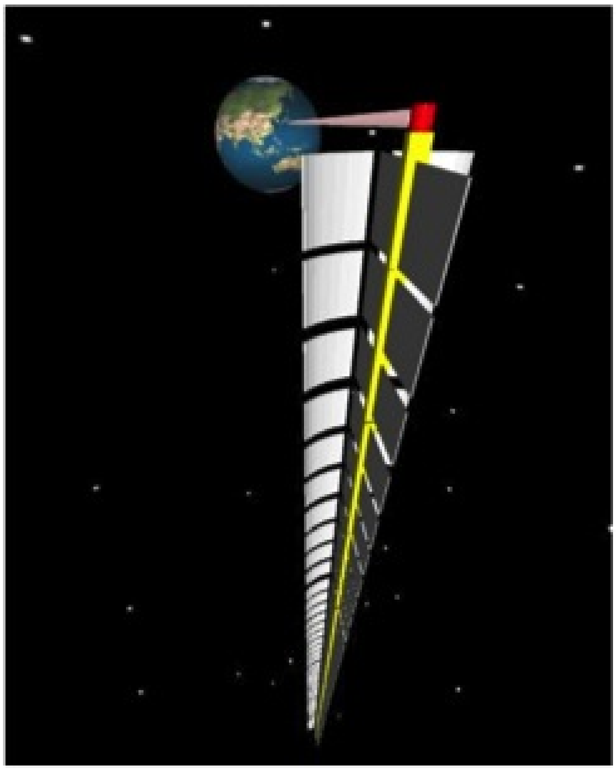

FIG. 6: JAXA L-SPS fully deployed reference system delivering 1 GW via direct solar pumped lasers. (source: JAXA)

*** Peer reviewed publications confirming the order of magnitude increase over previously reported highest efficiencies are to the best knowledge of the author still pending.

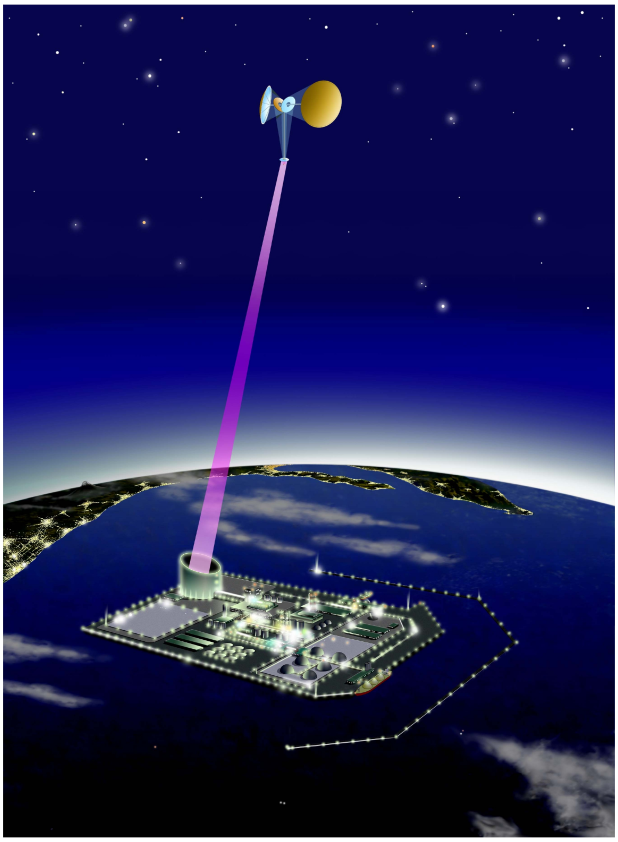

FIG. 7: JAXA L-SPS system diagram. (source: JAXA)

In Europe, the European Space Agency (ESA) has federated European research communities and industry in 2002 into the European SPS Network. A multi-phased programme plan provided the frame for several studies related to laser based SPS.

As part of the first phase, together with EADS Astrium the use of laser power transmission for space to space applications were studied, including powering surface elements on the Moon and Mars, Earth-orbiting satellites and deep space missions. The lunar surface application has been identified as the most promising application.

The relatively conservative and compact design incorporated four parallel laser systems, connected to a 1.5 m diameter telescope capable of emitting 6 kW power. The lasers are based on solid state diode pumped technology. In order to allow the system in lunar orbit to provide power to small lunar surface elements, the system design required a pointing accuracy of only 86.2 nrad. Going into some details on the overall system aspects, a rover acquisition process had been defined, which would reply on a small laser beacon or corner cube implemented on the rover and receiver optics on the orbiting SPS. Each telescope would have to be actively controlled to achieve fine pointing accuracy. The rover(s) receiver surface is to be equipped with wavelength optimized solar PV cells. The spot size dimensions at rover level measure 14.4 m in diameter and would thus be substantially larger than the rover receiver area, but on the other hand assure sufficient power during moving of the rover and margins on the pointing accuracy. The total power the rover was estimated to receive from such a system was approximately 650 W. [15].

A satellite would be located in Earth-Moon Lagrange point L1-L2 at a distance of about 58,000 km. The system could provide a permanent illumination of any spot of roughly half the moon. The system would use four Nd-YAG lasers, each with a 10 kW rating and a 1 m diameter telescope. The SPS would include one power system, one deployable radiator (about 120 m^2) per laser module and a receiver system that measures 100 m^2 of PV cells.

Subsequent more recent work refined further the detailed options on the choice of the positioning of the laser based SPS in lunar orbits, confirming the large advantage of laser based systems over microwave-based systems for such lunar surface applications. [43]

As part of the same first phase of the European SPS Programme plan, two studies were performed assessing among other aspects the optimal way to integrate space based with terrestrial solar power plants, assessing the microwave as well as laser options. [44] [45] [13] [14]

To date, a number of laboratory-based experiments have taken place, which have shown the promise that this type of power transmission holds for the future. An optical fibre design has been proposed by G. Phillipps, in which an optical fibre to deliver the solar radiation to a lens or to a lens system constructed at the end of the crystal. [46] This lens or lens system will concentrate the radiation and will direct it onto the laser medium. In the case of Nd:Cr:GSGG, the output power is 3.2 W with a collecting area of 0.41 m^2 from the input power of 200 W. The slope efficiency of that system was found to be 1.6%.

An experiment to illustrate the difference between two laser types: Nd:YAG and Nd:Cr:GSGG was carried out by U. Brauch et al. [47] These laser types were selected because of there physical properties. This comparison indicated that solar pumped solid state lasers, especially the Nd:Cr:GSGG laser, are the best choice for space-power transmission.Their experiments with direct solar pumped Nd:Cr:GSGG and Nd:YAG lasers at 77 K and 300 K showed that cooling the laser crystals to temperatures much lower than 300 K reduces thermal problems, increases efficiency and improves beam quality. They have also shown that the overall system efficiency can be increased by splitting the solar spectrum into different parts for conversion to laser power and to electrical power. The estimated values were 17% for a laser/photovoltaic system and 27% for a laser/solar dynamic system.

A two stage collector test was completed by P. Gleckman, in which it was demonstrated that the laser types Nd:YAG and Nd:Cr:GSGG, when end pumped in a two-stage solar concentrator consisting of 40.6 cm diameter primary which forms a 0.98 cm diameter image, could produce 55 W of sunlight was squeezed into a spot 1.27 mm in diameter with a 55% efficiency. With this efficiency, two-stage end pumping of solid state laser rods had the potential for an improvement on the previous direct pumped solar laser. [48]

4. OTHER APPLICATIONS OF LASER-BASED WIRELESS POWER TRANSMISSION

4.1. Planetary and lunar surface applications

Apart from the above presented large scale solar power satellites for providing power to Earth or their orders of magnitude smaller versions for space-to-space energy transmission, relatively large-distance laser power transmission are also considered to avoid the complexity and mass of cables for planetary or lunar installations in combination with a surface power plant. Such a plant could either be solar powered (e.g. small solar powered stations installed on spots of permanent sunshine very close to lunar pole) or be a small lunar surface nuclear reactor. [49] [50]

4.2. Powering tether “climbers” for a space elevator

In the frame of the ongoing studies related to space elevators [29], the power supply for the tether construction and payload carrying “climbers” represents a substantial challenge. Wireless power transmission via lasers is currently the best option. In order to advance the related technology, NASA is organising and co-funding since several years competitions with the aim to supply sufficient power from the ground for “climbers” to reach a minimum speed. [30]

4.3. Wireless power driven propulsion

Laser or microwave-driven acceleration by photon reflection has been proposed for propelling spacecraft for science missions to the outer solar system and even to nearby stars. In principle, such wireless beam-driven probes have the advantage that energy is used for the acceleration of only the payload (and the receiving/reflecting structure usually called a “sail”) but not the propelling beam generator.

5. CONCLUSIONS

The present paper intended to provide an overview over a relatively neglected are of research related to lasers: using lasers to transmit energy over large distances, and especially in and from space. Concepts and candidate technologies have been presented. Laser power transmission systems are still considered as less mature than microwave based systems. However, it is argued that due to recent advances in direct solar pumped lasers, the potential integration of space and terrestrial based solar power plants and potentially radical simplifications on the space system design, laser-based wireless power transmission concepts should be matured further in order to represent a credible alternative.

Both microwave and laser power transmission system are being considered, with laser systems offering larger improvement capacities and potentially much smaller systems. Among the most important challenges for the maturation of laser power transmission technologies to industrial applications in space are the following key ares:

Thermal Control: A key to large scale laser power transmission is the thermal system design. The concentration factors and lasing efficiencies require the efficient rejection of substantial amounts of heat.

Laser Rod Material: Research on the optimal laser rod material to balance the frequency, temperature, efficiency, modularity and stability requirements of space based direct solar pumped lasers.

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[1] Nicola Tesla. The transmission of electrical energy without wires. *Electrical World and Engineer*, March 1905. http://www.tfcbooks.com/tesla/1904-03-05.htm (acc. Dec. 08).

[2] William C. Brown. The history of power transmission by radio waves. *Microwave Theory and Techniques, IEEE Transactions*, 32(9):1230– 1242, September 1984.

[3] Peter Glaser. Power from the sun: Its future. *Science*, 162:856–861, 1968.

[4] Peter Glaser, F. Davidson, and K Csigi. *Solar Power Satellites*. John Wiley & Sons, 1998.

[5] US Department of Energy. Doe/nasa reference system report for satellite power system (sps). Technical Report DOE/ER-0023, US DoE, Oct. 1979.

[6] John Mankins, Harvey Feingold, Michael Strancati, Alan Friedlander, Mark Jacobs, Doug Cornstock, Carissa Christensen, Gregg Maryniak, and Scott Rix. Space solar power - a fresh look at the feasibility of generating solar power in space for use on Earth. Technical Report SIAC-97/1005, NASA, SAIC, Futron Corp., April 1997.

[7] Martin Hoffert, Ken Caldera, Gregory Benford, David Criswell, Howard Herzog, Atul Jain, Haroon Kheshgi, Klaus Lackner, John Lewis, Douglas Lightfoot, Wallace Manheimer, John Mankins, Michael Mauel, John Perkins, Michael Schlesinger, Tyler Volk, and Tom Wigley. Advanced technology path to global climate stability: Energy fo a greenhouse planet. *Science*, 298:981ff, Nov. 2002.

[8] Wolfgang Seboldt, Michael Klimke, M. Leipold, and N. Hanowski. European sail tower SPS concept. *Acta Astronautica*, 48(5-12):785–792, 2001.

[9] D. R. Criswell and Waldron R. D. Results of analyses of a lunar-based power system to supply earth with 20,000 gw of electric power. In *Procedings of SPS 91 Power from Space: the Second International Symposium*, pages 186–193, Paris, France, April 1991.

[10] David R. Criswell. Solar power via the moon. *The Industrial Physicist*, pages 12–15, April/May 2002.

[11] R. Gordon Gould. The laser, light amplification by stimulated emission of radiation. In P.A. Franken and R.H. Sands, editors, *The Ann Arbor Conference on Optical Pumping*, page 128. University of Michigan, June 1959.

[12] T.H. Maiman. Stimulated optical radiation in ruby. *Nature*, 187:493–494, 1960.

[13] Chris Hendriks, Norbert Geuder, Peter Viehbahn, Frank Steinsiek, and Johann Spiess. Earth and space-based power generation systems. Technical report, ESA final report - EcoFys, DLR, EADS ST, 2004.

[14] Volker Quaschning, Norbert Geuder, Peter Viehbahn, Frank Steinsiek, and Chris Hendriks. Comparison of solar terrestrial and space power generation for Europe. In ESA, editor, *SPS'04 Conference - Solar Power from Space*, Granada, Spain, 30 June - 2 July 2004. ESA.

[15] Claude Cougnet, Emmanuel Sein, Alain Celeste, and Leopold Summerer. Solar power satellites for space exploration. *Journal of the British Interplanetary Society*, 59(8):290–296, 2006.

[16] Henry W. Brandhorst and David R. Forester. Effects of the atmosphere on laser transmission to GaAs solar cells. In *54th International Astronautical Congress*, number IAC-03-R.3.08. IAF, Oct. 2003.

[17] David Castelvecchi. Wireless energy may power electronics. *MIT Tech Talk*, 51(9), November 2006. http://web.mit.edu/newsoffice/2006/techtalk51-9.pdf (acc. Dec. 08).

[18] Morio Toyoshima. Trends in satellite communications and the role of optical free-space communications. Technical report, Vienna University of Technology, NICT, 2004.

[19] William C. Brown. The history of wireless power transmission. *Solar Energy*, 56:3–21, 1996.

[20] Nobuyuki Kaya, H. Matsumoto, S. Miyatake, I. Kimura, M. Nagamoto, and T. Obayashi. Nonlinear interaction of strong microwave beam with the

ionosphere – minix rocket experiment. *Space Power*, 6:181–186, 1986.

[21] J. J. Schlesak, A Alden, and T. Ohno. A microwave powered high altitude platform. In *Proceedings IEEE MTT-S Int. Symp.*, pages 283–286, 1988.

[22] H. Matsumoto. Milax airplane experiment and model airplane. In *Proceedings 12th ISAS Space Energy Symposium*, Tokyo, 1993. ISAS.

[23] Nobuyuki Kaya, S. Ida, Y. Fujino, and M. Fujita. Transmitting antenna system for airship demonstration (ETHER). *Space Energy and Transportation*, 1(4):237–245, 1996.

[24] Nobuyuki Kaya, Masashi Iwashita, Kouhei Tanaka, Shinishi Nakasuka, and Leopold Summerer. Rocket experiment on microwave power transmission with Furoshiki deployment. In *IAC 2006*, number IAC-06-C3.3.03, Valencia, Spain, 2006.

[25] J. O. et al. Dickey. Lunar laser ranging: A continuing legacy of the apollo program. *Science*, 265(5171):482–490, 1994.

[26] D. L. Begley. Relay mirror experiment. In *Proceedings SPIE*, volume 2699, pages 192–197, April 1996.

[27] H. A. Bethe, R. Garwin, K. Gottfried, and H. W. Kendall. Space-based ballistic missile defense. *Scientific American*, 251(4), Oct. 1984.

[28] Frank Steinsiek, W. P. Foth, K. H. Weber, Christian Schäfer, and H. J. Foth. Wireless power transmission experiment as an early contribution to planetary exploration missions. In *IAC 2003*. IAF, Oct. 2003.

[29] The space elevator - from concept to reality, December 2008. `http://www.spaceelevator.com` (accessed December 2008).

[30] Spaceward Foundation. Power beaming (climber) competition. `http://www.spaceward.org/elevator2010-pb` (accessed December 08).

[31] Christian Schäfer, Osamu Matoba, and Nobuyuki Kaya. Optical retrodirective tracking system approach using an array of phase conjugators for communication and power transmission. *Applied Optics*, 46(21):4633, July 2007.

[32] Wikipedia. Laser — wikipedia, the free encyclopedia, 2008. [Online; accessed 15-December-2008].

[33] Claude Cougnet, Emmanuel Sein, Alain Celeste, and Leopold Summerer. Solar power satellites for space exploration and applications. In ESA, editor, *SPS'04 Conference - Solar Power from Space*, volume SP 567, Granada, Spain, June 30 - July 2 2004. ESA.

[34] C. Stewen, M. Larionov, and A. Giesen. Yb:YAG thin disk laser with 1 kW output power. *OSA Trends in Optics and Photonics, Advanced Solid-State Lasers*, pages 35–41, 2000.

[35] M. Weksler and J. Shwartz. Solar-pumped solid-state lasers. *IEEE Journal of Quantum Electronics*, 24(6), 1988.

[36] Masahiro Mori. Medium efficiently converts solar rays into laser beams. *The Japan Times*, September, 9 2004.

[37] R. E. Beverly, III. Satellite Power System (SPS) laser studies. Volume 2: Meteorological effects on laser beam propagation and direct solar pumped lasers for the SPS. *NASA STI/Recon Technical Report N*, 81:12560–+, November 1980.

[38] R.G. Williscroft. Laser sps and the hydrogen economy. Technical report, National Space Society, 1980.

[39] G. A. Landis. Moonbase night power by laser illumination. *Journal of Propulsion and Power*, 8, 1992.

[40] G. A. Landis. Applications for space power by laser transmission. In *Proceedings SPIE*, volume 2121, pages 252–255, 1994.

[41] Masahiro Mori, H. Kagawa, and Y. Saito. Current status of a study on hydrogen production with space solar power systems (SSPS). In L. Summerer, editor, *SPS'04 Conference - Solar Power from Space*, Granada, Spain, June 30 - July 2 2004. ESA.

[42] Hiroaki Suzuki, Tatsuhito Fujita, and Masahiro Mori. Technology demonstration and elemental technology development of space solar power systems. In *Proceedings of the IAC*, number IAC-06-C3.2.4. IAF, 2006.

[43] Laura Torres-Soto and Leopold Summerer. Power to survive the lunar night: and SPS application? In *Proceedings of the 59th IAC*, number IAC-08-C.3.1.2, Glasgow, 2008. IAF.

[44] Volker Blandow, Patrick Schmidt, Werner Weindorf, Martin Zerta, and Werner Zittel. Earth and space-based power generation systems - a comparison study. final report 17682/03/NL/EC, ESA final report - LBST, 2004.

[45] Martin Zerta, Volker Blandow, Patrick Collins, Joelle Guillet, Thomas Nordmann, Patrick Schmidt, Werner Weindorf, and Werner Zittel. Earth and space-based power generation systems - a comparison study. In *SPS'04 Conference - Solar Power from Space*, Granada, Spain, June 2004. ESA, ESA.

[46] G. Phillipps. Sonnengepumpter, gütegeschalteter nd-laser. Technical report, Report of the Institute of Optics, Technical University of Berlin, December 1993.

[47] H.G. Brauch, J. Muckenschnabel, H. O'power, and W. Wittwer. Solar-pumped solid state lasers for space to space power transmission. *Space Power, Resources, Manufacturing and Development*, 10(3-4):285–294, 1991.

[48] P. Gleckman. Achievement of ultrahigh solar concentration with potential for efficient laser pumping. *Applied Optics*, 27(21):4385–4391, November 1988.

[49] Silvia De Grandis, Elvina Finzi, Carlo Lombardi, Diego Mandelli, Enrico Padovani, Matteo Passoni, Marco Ricotti, Lorenzo Santini, and Leopold Summerer. A feasibility study of an integral PWR for space applications. In *ICAPP'04*, Pittsburgh, USA, June 2004.

[50] Elvina Finzi, Carlo Lombardi, and Leopold Summerer. A lunar IPWR: A pre-feasibility study. In *IAC 2006*, volume IAC-06-D2.8.8, Valencia, Spain, Oct. 2006. IAF.