SOLAR PUMPED LASERS TO DIRECTLY CONVERT SUNLIGHT TO LASER RADIATION

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Notice of Interest in response to NASA RFI:

GAME CHANGING DEVELOPMENT PROGRAM, INDUSTRY-DEVELOPED POWER BEAMING TECHNOLOGY - REQUEST FOR INFORMATION - NNH15ZOA001L
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Solar Pumped Lasers: Description of Suggested Technology

There are many applications in space which can be facilitated by space based power beaming. In all of these, lasers have a major advantage over microwave systems in that they can be made much smaller and more compact. Of all the different types of lasers available, solar pumped lasers give much higher system efficiency and much less waste heat, as well as improved reliability and simplicity.

We will focus primarily on space based solar power [SBSP] as an application below, but the technology is not limited to that usage. High power and high efficient solar pumped lasers have a large potential for other applications, e.g. nano-materials production, materials processing, magnesium cycle of hydrogen production, free space laser communications, energy transmission and desalination.

It has been proposed to use microwaves to beam down power to Earth from space based solar power stations in Geosynchronous Orbit. However the Rayleigh diffraction limited optics requires enormous antennas, typically a few kilometers in diameter, and huge power levels, of 5GW to 10GW. A much lower cost of entry investment (100x lower) is afforded by use of optical or infrared lasers with much shorter wavelength, hence much smaller system size, e.g. 10MW, with one meter size collimator mirror diameter. Since there is no "grid power" in space, most spacecraft today use solar power sources, mostly photovoltaic solar cells. Powering lasers requires high levels of power. PV solar cells are usually less than 25% efficient. This multiplied by a typical 20% “wall plug” efficiency of lasers results in overall a mere 5% efficiency (95% waste heat!). This strongly motivates interest in solar pumping of lasers to greatly increase overall efficiency; theoretical efficiency of about 38% is possible. Other potential benefits of solar pumped lasers would be reduced weight and reduced number of components affording higher reliability (reduced number of failure modes) versus an electrically pumped laser powered from PV cells.

Space based solar power beaming would be most cheaply and efficiently performed using lasers with solar pumping, versus PV electrical pumping.

Yagi and Saikia et al [9, 10, 11, 12] have reported High-efficiency lasing by using an advanced ceramic, Cr:Nd:YAG ceramic laser medium, and an artificial solar-light pumping source. This material lases at 1024 microns wavelength. This has opened up ample opportunities for creation of highly effective solar pumped lasers with wide range of powers, on the basis of different solar concentrators or Fresnel lenses, which in turn can promote occurrence of new environment-friendly laser technologies.

We propose the development of a pilot line of solar laser based research, development and use of high-effective solar pumped lasers taking advantages of the highly-sensitized Cr:Nd:YAG ceramic laser mediums and the thin-disk laser technologies, technologies and by increasing the absorption efficiency of Nd:YAG using external frequency conversion of large amount of unabsorbed solar photons instead of Cr^{3+} codoping. To reach this challenging target, project partners will develop new high-efficient lasers, will research in parallel the most suitable architectures of solar lasers and cost-effective solar laser technologies, and will demonstrate space power beaming technology with solar powered lasers.

Solar lasers have been researched for 50 years with major emphasis on free space wireless optical communication and power transmission applications. Realization is now within reach with advanced ceramic laser materials. The innovation is the development of solar pumped lasers besides combining advantages of the highly-sensitized Cr:Nd:YAG ceramics and the thin-disk laser technologies by increasing the absorption in Nd:YAG via external frequency conversion of large amount of unabsorbed solar photons and returning them back to the Nd:YAG with minimal losses. The best candidates for such frequency conversion, namely frequency down-shifting would be Cr3+ doped GSGG, YSGG, LICAF, LISAF, Ti3+doped Sapphire and so on rather than Cr3+YAG whose emission spectrum overlaps relatively poorly with Nd:YAG absorption bands at room temperature.

If the efficiency of the laser pumped by solar light is 20%, in order to provide 200kW laser power there will be a need for 1MW of solar power which can be harvested from ~1250m2 at solar radiation intensity at the Earth surface ~800W/m2. In principle this can be realized with the lasers on large scale solar concentrators like the Uzbek big solar furnace (BSF), but from the practical point of view and also in order to meet the requirements such as low cost of equipment and quick return, it is preferable to build the laser-power station consisting of fiber bundle coupled lasers on small-scale parabolic concentrators. For instance a single laser module can be implemented on parabolic concentrator with a diameter of 1-2m. In the case of 2m concentrator the solar power collected will be of about 2.5kW from which 500W laser power can be obtained at efficiency of 20%. So, in order to reach the power of 200kW there would be a need for 400 such laser modules.

Nanotechnology has made it possible to achieve high transparency, large-size, homogeneous solid state laser materials. The ceramic fabrication technology was a fundamental breakthrough for the development of high-power laser applications. In particular, the wide opportunity has emerged for creation of the powerful and highly efficient solar pumped lasers. Recently, it was reported high-efficiency lasing (theoretically 38% efficient) by using an advanced ceramic, Cr:Nd:YAG ceramic laser medium, and a metal halide lamp as an artificial solar-light pumping source. However, the laser output was only 300mW level.

Combining advantages of the highly-sensitized Cr:Nd:YAG ceramic laser mediums (other than above mentioned active element of a rod-form with a low concentration of Cr3+ ions) and the thin-disk laser technologies [or alternative designs comprising of Nd:YAG and above enumerated external frequency converting materials instead of Cr3+ codoping] could allow to reach high efficiency, close to the result obtained with artificial solar light at the laboratory conditions. This will be a major technology breakthrough.

The Chief Scientist of this project will be Dr. Shermakhamat Payziyev. He designed and fabricated the stand of the solar laser on the base of the Big Solar Furnace (BSF) at the Institute for Materials science of the Scientific and Production Association “Physics-Sun” (Uzbekistan). Using crystalline Nd3+:YAG rods his team demonstrated the possibility of utilization of 1 MW BSF for pumping purposes. Laser radiation power of 80W has been obtained from single Nd3+:YAG rod with working sizes of 6x130 mm installed in the multi-element secondary concentrator.

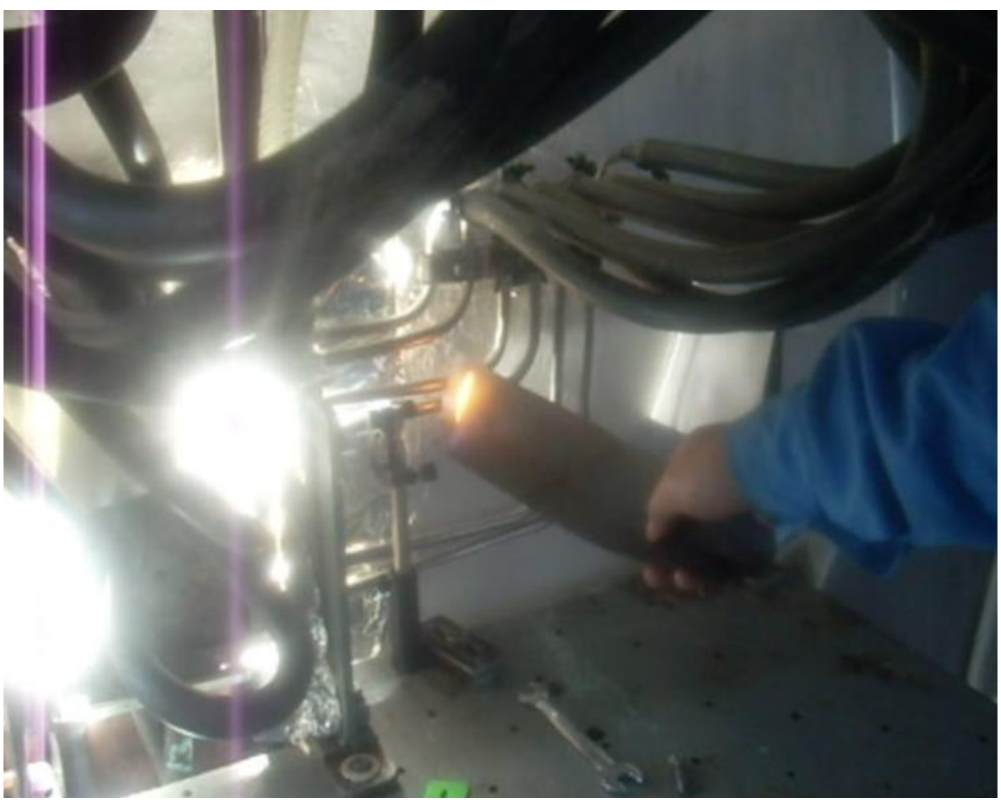
Another main result of these studies was the development of a computer model of the solar lasers which is based on ray-tracing and Monte-Carlo methods. The model makes calculations for lasers of a various configuration and active elements of the different form. Based upon experimental results and with use of the computer models there have been performed numerous calculations for different laser configurations. It was shown that the conversion efficiency of solar energy into the laser can be up to 25% of the solar flux energy collected at the focal area of BSF.

We propose to develop new high-efficient lasers, and to research in parallel the most suitable architectures of solar lasers and cost-effective solar laser technologies. Dr. Payziyev will relocate to Clarkson University in New York, USA where the initial research will be performed.

Figure-1: The Big Solar Furnace [BSF] in Uzbekistan

Figure-2 A piece of paper ignited by the solar pumped laser at BSF – a still frame from this internet video:

https://www.youtube.com/watch?v=ZAyflI8U53Y



The Nature of a NASA Partnership

1 NASA Contributions to Partnership

- Technical Expertise
  - NASA has considerable expertise with advanced space telescopes, such as Hubble and Spitzer. The technologies related to precision optical design and precision attitude control and pointing are directly relevant to designing space based laser systems. We would like data dump from those NASA experts and an ongoing dialogue as work proceeds.
  - NASA has experience with systems engineering involving lasers which would be valuable. For example, the Lunar Reconnaissance Orbiter carried a laser communications payload. Lasers are used under NASA contract to range the Apollo Lunar Retro-reflectors, we would like to learn the safety protocols for those operations.
  - NASA has studied and evaluated large solar reflectors and Fresnel lenses, this expertise would be highly relevant
  - NASA has relevant safety expertise with aerospace lasers which would be very valuable. We would like to collaborate to learn which standards would be applicable to a new laser development in aerospace applications
- Test Facilities
  - Materials Testing facilities: Advanced Materials test and fabrication facilities exist at the NASA Marshall Space Flight Center in Alabama. This could help overcome a major challenge which is to fabricate the thin disk ceramic YAG materials as the laser medium. If such materials cannot be commercially purchased it would be necessary to synthesize them. In this process, powder is converted into a fully dense and transparent polycrystalline ceramic material at approximately 65% of the melting point, see reference [14].
  - NASA Glenn Research Center has been extensively involved in spacecraft solar power systems. The test facilities, e.g. sun simulators, would be very useful for developing new solar pumped lasers.
  - Facilities for testing large precision optical system would be useful, such as those used for space telescopes, e.g. the Spitzer and James Webb space telescopes.
- Hardware
  - We would be interested to learn of any optical components which NASA could provide, e.g. mirrors, lenses, Fresnel lenses, of various sizes. For example, left over hardware from space telescope programs, e.g. the Spitzer and James Webb space telescopes, would be useful; including tooling, GSE, breadboard hardware, engineering models, flight spares, etc.
- Software
  - We would be interested to learn if NASA has developed any software for optical systems design, e.g. for lasers communications systems, space telescopes, or LIDAR

2 Feasibility of a partnership

We believe a partnership with NASA as described herein would be feasible. The main challenge will be obtaining a sufficient level of interest from the private financing community; considerable R&D is required which represents a higher risk than private investors normally tolerate. Key to this will be NASA providing clear and detailed roadmaps for applying the technology within the NASA budget environment. There are presently no commercial markets for power beaming, so it is difficult to see how such technology could be developed without visionary leadership from the government.

3 Intellectual property:

This is an open item. We will need to obtain financing from third parties, and it is difficult to predict their expectations for intellectual property. It is likely that they would expect complete ownership and all new data developed would be proprietary. Government use of the data would probably be limited, depending on the extent of NASA contribution agreed. Details will need to be negotiated as funding partners are brought on board

4 Potential industry contributions:

Leeward Space Foundation (LSF) is a non-profit and would act as a "Business Incubator" and facilitator. LSF would partner with one or more new for-profit corporation[s] to raise financing on the open market. LSF will provide expertise of our Chief Scientist Dr. Shermakhamat Payziyev who is a world leader in the field of solar pumped lasers. We also have the strong support of Professor Pier Marzocca at Clarkson University, New York, who will facilitate collaboration of that institution.

5 Technology Readiness Level:

The TRL of the ceramic disk solar pumped laser technology is currently at TRL-3, i.e. proof of concept has been demonstrated as described in references [11, 12] below. Active R&D on the technology is continuing in Japan, but we believe it has not yet reached TRL-4.

6 Business Model

Currently there is no commercial industry of power beaming, so there are no established business models in this field. Start date and end date of our activities cannot be predicted at this time, it depends on the receipt of funds as described below.

We would like to explore the following approaches:

6.1 – Letter of Interest to purchase Devices:

We understand that the reference NASA RFI NNH15ZOA001L does not provide any NASA funding. We propose to obtain private funding, e.g. Angel Investors and/or Venture Capitalists, to productize the solar pumped laser technology to a TRL level which would be of application in the NASA Power Beaming roadmap. Some seed money could be raised by "crowdfunding". In order to facilitate fundraising, it would help greatly if NASA would provide us with a "Letter of Interest" or "Letter of Intent" explaining the NASA roadmap for power beaming, and the extent to which solar pumped laser technology would be relevant. If possible we would like a level of detail with operating parameters and requirements, e.g. type and number of units which would be purchased over what time frame, beamed power levels desired, size of receiver, distance to receiver and operating location and application.

Status of Crowdfunding laws: As of 31 Jan 2015, the 2012 Federal JOBS Act is not yet effective, awaiting SEC rulemaking for equity crowdfunding. However, as of today fourteen states have intrastate crowdfunding exemptions in place, and several other states are in various stages of considering the idea [Florida and N. Carolina have rejected the approach]. Here is a list of states with programs in effect, along with their maximum allowed fundraising cap and maximum allowed non-accredited investor cap.

Alabama ($1M, $5,000)
Colorado ($1M)
Georgia ($1M, $10,000)
Idaho ($1M, $5,000)
Indiana ($2M, $5,000)
Kansas ($1M, $1,000)
Maine ($1M, $5,000)
Maryland ($100k, $100)
Michigan ($1M, $10,000)
Oregon ($250K, $2,500)
Tennessee ($1M, $10,000)
Texas ($1M, $5,000)
Washington ($1M, $2,000)
Wisconsin ($1M, $10,000)

Seed money of $250K to $1 M should be adequate to build a working prototype and generate data sufficient to establish a credible business plan for obtaining more substantial funding from corporate investors for full scale productization and space flight test.

6.2- Power Purchase Agreement (PPA)

In financing of terrestrial electrical utility power plants, it is customary for a public [or private] power distribution utility to enter into a "Power Purchase Agreement"[PPA] with a power "generating utility". On the basis of the PPA, the "generating utility" can obtain financing through debt or equity from large banks or venture capital funds. These "Wall Street" type financing institutions are very familiar with PPAs and readily loan or invest funds on the basis of a properly worded and executed PPA, especially with established customers. Our main concern is that the value of the NASA market potential is probably smaller than the size of PPAs they typically fund.

Once the technology of solar pumped lasers is demonstrated at the appropriate TRL, then we propose that a power generating company be set up to generate beamed power and deliver it to NASA spacecraft and facilities. NASA would purchase this power in a similar way to power currently purchased from terrestrial power utility companies. We propose to enter into discussion with NASA to determine suitable opportunities for beaming power to NASA spacecraft and facilities, and devise a roadmap to negotiate a mutually satisfactory PPA for each target application. NASA would in effect act as an "Anchor Tenant". LSF is a non-profit foundation, we anticipate acting as a Business Incubator and facilitator, spinning off one or more new for-profit companies to partner with NASA for establishing and executing a PPA.

Appendix-1: Background Context: SPACE BASED SOLAR POWER

The concept of solar power satellites (SPS) was first published by Glaser in 1968 [1]. SBSP involves a large solar power array (either Photvoltaic (PV) or thermo-dynamic (TD)), in Earth orbit (typically GEO) attached to a wireless power transmission system (WPT), which beams power to rectifying antennas (Rectennas) on the surface of the Earth.

A solar array in space (especially in GEO) has numerous advantages or an equivalent array on the surface of the Earth. Unlike terrestrial solar and wind power plants, SSP is available 24 hours a day, 365 days a year, in endless quantities. SSP is not affected by cloud cover, night, storms, dust and wind.

Furthermore, energy via WPT from space can be delivered to any point on the Earth's surface at no additional cost. In fact, a single spacecraft could serve multiple rectennas and the beam be switched between rectennas as local market conditions vary. Terrestrial solar system can only provide power to a nearby local market, as the cost of building new power lines to transmit solar energy to remote consumers is often prohibitive. Very often, areas with high sunlight have relatively few energy consumers, and the centers of major power consumption are often located in areas which are unfavorable for locating solar power installations.

Unlike terrestrial solar, SBSP can provide continuous, predictable, reliable baseload power, avoiding the need for expensive energy storage system.

A1.1 LASERS VERSUS MICROWAVES

There is debate about the ideal frequency of radiation to use to beam down power via WPT. There is a range of microwave frequencies, and laser wavelengths which have been considered. One of the major challenges of a WPT and SBSP system is the diffraction limited optics, which cause the minimum system size to be very large compared with typical terrestrial power stations. This motivates use of higher frequencies (shorter wavelengths). However, as frequency is increased, the transparency of the Earth's atmosphere generally reduces (with some notable variations), and losses of power increase.

It is likely that early demonstrators will use lasers since the size of the system is orders of magnitude smaller and hence much lower capital cost of entry than for microwave.

The original NASA/Department of Energy (DOE) joint study of 1979-80 selected 2.5 GHz (12. 5 cm S-band) as the microwave frequency. This results in a minimum spacecraft size of 10 GW. At 5.8 GHz the size could be reduced to about 5 GW.

These numbers result from the Rayleigh diffraction equation which dictates the minimum beam spread angle as a function of the frequency and distance of separation between the transmitter and rectenna, according to this equation: where λ is the wavelength of the light, the sine of the corresponding angular resolution θ (or beam spread angle) is

$$\sin\theta = 1.22\ \lambda/D$$

where D is the diameter of the entrance pupil of the imaging lens (e.g., of a telescope's main mirror, or microwave transmit antenna in this case).

The size of the rectenna is dictated by a rule of thumb that the rectenna diameter should be approximately ten times the diameter (100 times the area) of the spacecraft transmitter antenna. This is because the space hardware cost is generally two orders of magnitude more expensive than ground hardware. Hence combining the 10 times rule with the diffraction criterion, results in the following sizes:

Table-1 Antenna and Rectenna Sizes for GEO

Frequency	Transmit Antenna Diameter	Rectenna Diameter	Rectenna Area	Power at 1 KW / sq-m	Power at 0.1 KW / sq-m
2.5 GHz	1.02 km	10.2 km	82 sq-km	82 GW	8.2 GW
5.8 GHz	0.67 km	6.7 km	35 sq-km	35 GW	3.5 GW
38 GHz	262 metres	2.6 km	5.4 sq-km	5.4 GW	540 MW

The power received by the rectenna is calculated by assuming a received intensity by the rectenna area. 1 KW/square-metre (1GW per square km) is less than the intensity of sunlight.

The 38 GHz is an interesting value. According to Zünd et al. [2], quote: ―"There is a minimum of atmospheric signal attenuation in the range of 2.45-5.8GHz, and also 35-38GHz. specifically we might expect losses of 2-6%, and 8-11% respectively. We will use a transmission frequency of 38GHz since this allows us to transmit the most energy into the smallest space, even when accounting for transmission losses."

Also:

"―our calculations added a considerable amount of mass for larger transmitter diameters, leading us to select a higher frequency of transmission (38GHz). This choice allowed us to afford a smaller antenna / rectenna combination, however substantially increased energy transmission density. The diffuse energy density offered with a 2.45GHz system required a massive increase in rectenna size, and offered no benefits in terms of cost."

38 GHz is in the Ka-band which is presently used by some communications satellites and lunar probes. The main disadvantage of this frequency is that it is very susceptible to ―rain fade. That is, when liquid precipitation is falling, even at moderately light intensity, the Ka-band signal is completely scattered and become ineffective. . This will result in some system outages, depending on the amount of rainfall prevailing at the rectenna location. This would favor arid desert locations versus tropical locations. Also a system of multiple geographically distributed rectennas could be installed, and the probability that all of them would be under rainfall (at any given moment) would be extremely low, and the SPS would have at least one rain-free rectenna available to beam to at any time.

Early demonstrations of SBSP might happen first with lasers, because the very short wavelength allows for diffraction limited optics a couple of orders of magnitude smaller than for microwave systems. The lasers which can penetrate the longest distance through air are in the region of 2 to 3 microns, this wavelength range is used by heat seeking missiles, for example.

A major benefit of SBSP is that the rectennas can be located anywhere in the world where there is sufficient uninhabited area. This again favors higher wavelengths, since the rectennas will be smaller and easier to site. High frequency rectennas could become ubiquitous. This flexibility in siting is a significant advantage compared with other forms of renewable energy. Terrestrial solar power system are best located in areas of high sunlight, which are typically remote from the major cities and consumers. Similarly wind power systems are best placed in areas of high prevailing wind speeds, which again are often remote from the users.

Geothermal power also is only available at locations where the hot springs are at or near the Earth's surface, which again are often remote from the users.

Hydro-electric power is limited to locations with ample water and deep valleys, most such areas have already been developed. The cost to transmit power over land by wire increases as a function of distance, and is typically ~$1M per Mw per kilometer. SBSP rectennas can be located close to consumers without the geographical restrictions of other renewable energy sources.

A1.2 CONVERSION EFFICIENCY

Microwave conversion efficiency is much high than for laser systems.

Two types of microwave transmitter devices are available for microwave use, either solid state monolithic Solid State Amplifiers (SSPAs) and Tubes such as Klyston tubes. SSPAs currently have efficiency (depending on frequency) in the 70% range DC to RF and with some investment could be optimized further to perhaps 80%. Klystons tubes already have 80% efficiency and could perhaps be pushed to 90% or better. SSPAs have the advantage that they weigh much less than tubes.

The ultimate efficiency of microwave transmitters is not known, because none have been fully optimized for wireless power applications. Most microwave transmitters are used in telecommunications applications, where a general requirement is the ability to change frequency to transmit in different channels. Also, the ability to support high bandwidth signal modulation is usually required. These requirements compromise the efficiency of the devices. In the telecommunications field, efficiency, although import ant, is a secondary criterion versus the core functionality of supporting the channelization and modulation. A modest investment would be required to design amp0lifiers which are fully tuned and optimized, and it is impossible to predict the ultimate efficiency which could be obtained.

On the receive side, the rectennas comprises an array of multiple dipole elements, each connected to a diode rectifier built around a Schottky barrier diode. The rectifier circuits can be over 90% efficient for RF to DC conversion.

Laser efficiency is improving, but presently is at best ~20% DC to Photons ―wallplug efficiency. Small diode lasers have now reached 60% DC to Photon efficiency, however these devices emit incoherent light, and hence cannot be scaled up into arrays, due to mutual interference. Diode lasers are mostly commonly used as a source to ―pump special tuned media to make them ―lase in a coherent manner. This pumping step introduces another inefficiency. Kare [5] claims that laser pumps have been recently demonstrated at 80%. This in concert with a diode pump would result in an overall efficiency of perhaps 50% at best.

Other forms of laser might be possible. One interesting approach might be to use a white light or solar pumped lasers. Such devices have been built and tested. They employ Iodine or Niodinium Chromium Ytrium Aluminum Garnet (YAG) type lasing media. Yabe in Japan [6] has demonstrated white light laser for recovering Magensium from sea water. The largest white light laser built to date is at a 1 MW facility in Uzbekistan [7, 13]

Table-2 Typical sizing Parameters for Laser SBSP at GEO

Wavelength	Transmit Mirror Diameter	Receiver Diameter	Receiver Area	Power at 1 KW / sq m	Power at 0.1 KW / sq m
1 micron	3 metres	29 metres	661 sq metres	661 KW	66.1 KW
500 nm	2 metres	21 metres	342 sq metres	342 KW	34.2 KW
100 nm	0.93 metres	9.3 metres	68 sq metres	68 KW	6.8 KW

A1.3 STRATOSPHERIC AIRSHIP

A novel approach to combining the benefits of lasers and microwaves is the use of a Stratospheric Airship relay. This allows a system to be scaled down to much smaller sizes than for a pure microwave system. Dickinson [4] proposed an airship relay system from Earth to space, in principle a similar system could be developed for beaming power from space to Earth.

The concept involves establishing an electrically propelled airship to an altitude of 20,000 metres above Earth sea level. At this altitude the airship would be above most of the atmosphere, and all of its weather. A laser beamed down from a spacecraft to the stratospheric airship would suffer very little attenuation, and for safety advantage an eye safe wavelength would work well.   The airship would receive the laser radiation and convert it to electricity using either Photovoltaic (PV) or thermo-dynamic conversion. Some of this power would be used to drive electric motors to keep the airship on station, and counteract wind forces.

Most of the electricity would then be converted to microwave radiation for onward transmission to rectennas on the Earth's surface. Because of the relatively small distance (20km versus 36,000 km), a system using 2.5 GHz would require only modest transmit antenna sizes and thus could work well with quite small rectenna (See Table-3 below). For an airship based system, the rectennas would be small enough to be mobile, and could be installed on demand anywhere. For example, such portable rectennas could be flown into areas which have suffered recent natural disaster, e.g. flood, hurricane, earthquake, where the primary power supply has been knocked off line.

Table-3 Parameters for 20km distance Wireless power transmission, e.g. from Stratospheric Airship

	Transmit Antenna	Rectenna	Rectenna Area	Power at 1 KW	Power at 0.1
Frequency	Diameter	Diameter	sq-metres	/sq metre	KW / sq metre
2.5 GHz	24.2 metres	242 metres	46,000 sq-m	46 MW	4.6 MW
5.8 GHz	15.9 metres	159 metres	19,818 sq-m	19.8 MW	1.2 MW
38 GHz	6.2 metres	62 metres	3,032 sq-m	3 MW	300 KW

A1.4 SAFETY HAZARDS

Lasers present safety hazards to the human eye, and can cause blindness. Short wavelength lasers (less than 1.4 microns) can burn the retina of the eye. Long wavelength lasers (>2 microns) burn the cornea at the front of the eye, and rapidly cause cataracts. Damage to the cornea can be corrected by various surgical procedures, even transplants, but these are expensive. Damage to the retina is permanent, causes partial or total blindness, and cannot be corrected by current medical technology.

In the USA, laser safety is regulated by the Food and Drug Administration (FDA).

There is a wavelength range of laser light known as ―eye –safe (in the range of 1.4 microns to 2 microns) where eye damage is minimized, but still possible. Lasers at the wavelength of 2 microns are relatively eye-safe, and can penetrate large distances through air.

Microwave safety primarily is thermal in nature. At high enough intensity, microwaves can damage or destroy thin blood vessels, and the cornea of the eye. Sensitive membranes such as the ear drum are also susceptible. For these reasons, most western countries have established maximum exposure safety levels to protect the general public and workers. In the USA, the Federal Communications Commission (FCC) regulates exposure to microwaves, via enforcing IET Bulletin 65 [3].

In the US system it establishes two safety levels for human exposure, one level of the general public, and another higher level for workers. For locations where humans are physically precluded by physical barriers from entering a zone of high microwave radiation, there is no upper limit. For example, microwave ovens contain very high levels of microwave radiation, but human are prevented from being exposed by the door and cabinet. Consequently, if there is a physical barrier surrounding the rectenna, such as a tall fence sturdy fence topped with razor wire, then there is no limit to how much the radiation intensity can be. It must be guaranteed that levels OUTSIDE of the rectenna area are below the public safety limits.   Aircraft flying through the beam might be a concern, but a metallic fuselage should be sufficient protection to the human occupants. It would be advisable to restrict the airspace above rectennas to prevent aircraft from flying through.

There might be some concern of birds flying through the beam. A possible safety measure might be to overlay a beam of 94 GHz to cover the same area as the primary power beam. 94 GHz is known to inflict non-lethal pain on human skin and is used as a nonlethal ―"Active Denial System" weapon by the US military, developed by Raytheon it is called ―Silent Guardian [8]. Tests should be done to see if it is as effective on birds. Such a field at 94 GHz might deter birds from entering the main beam, and motivate them to fly around it instead.

A1.5 COMPARISON OF SBSP WITH PRESENT POWER SOURCES

Space Based Solar Power has all the benefits of terrestrial renewable energy, without their considerable limitations.

Specifically:
1. Unlike coal and nuclear plants, SSP does not compete for or depend on scarce fresh water resources.
2. Unlike coal, oil, gasoline (petrol), LNG, ethanol, and bio-fuel plants and engines, SSP emits no CO2
3. Unlike bio-ethanol or bio-diesel, SSP does not compete for increasingly valuable farm land (and water) nor does it depend on natural-gas-derived fertilizer. Bio-fuels contribute to increasing food prices and shortages.
4. Unlike nuclear power plants, SSP produces no hazardous waste, does not proliferate nuclear weapons, nor provide potential for terrorists to hijack nuclear material.
5. In the event of natural disasters such as Earthquakes or Tsunamis there is no possibility of meltdown, nor release of radioactive or toxic substances.
6. Unlike coal and nuclear fuels, SSP does not require environmentally problematic mining operations.
7. SBSP can provide energy independence for the nations that develop it, eliminating a major source of national competition for limited Earth-based energy resources and dependence on unstable or hostile foreign oil providers.
8. SBSP can be easily "exported" anywhere in the world.

The primary challenge of SBSP of course is the very high cost compared to most forms of terrestrial power. Baseload power in most of the world today is provided mostly by coal, however that produces high carbon emissions, and ideally should be phased out and eliminated as soon as possible. The other primary baseload power source around the world is nuclear, with its inherent environmental and safety concerns. SBSP cannot compete with those sources on price, but if the world is willing to pay a premium price for electricity in order to save the Earth's rapidly degrading environment, then only SBSP has the reliability and scalability to provide most or all of the world's electricity. As time goes on, with economies of scale, the cost of electricity from SBSP will steadily decline.

Furthermore, SBSP can be economically complementary with existing sources of terrestrial renewable power. For example, in systems which heavily use wind power, e.g. much of Europe and North America, the spot market price for electricity spikes an order of magnitude on days when wind speed falls or drops to zero. SBSP can sell power into these temporary high priced markets. Spot prices for electricity spike for other reasons, for example unexpected changes in weather, e.g. unusually hot summer weather can cause a surge in demand by air conditioning systems.

SBSP can monitor spot market electricity prices, and opportunistically jump in to serve the highest priced market at any given time. Sufficient rectennas will need to be installed around the world to provide SBSP access to all the target markets of interest.

A1.6 NEXT STEPS – THE ROADMAP

LSF believes a series of ground based demonstrators of microwave wireless power transmission is required, at increasing power levels and distances, first starting at 2.5 GHz but increasing to 38 GHz. Transmitter devices (solid state and/or tubes) should be developed to achieve maximized efficiency at 38 GHz.

We also encourage work to improve the efficiency of white light pumped lasers.
It is also necessary to push the state of the art of CW phased arrays Transmit and receive), to increase the size and power level beyond those built to date.

Development of a stratospheric airship for wireless power relay should also be investigated, to determine costs and design parameters.

Appendix-2 Other Applications of Solar Pumped Lasers

A2.1 Laser Powered Stratospheric Aircraft

Besides power beaming to the ground, there are some other potential applications of aircraft in the upper stratosphere supplied by a space based laser. For example;

A2.1.1 – Radar platform

Civilian and military users have potential interest in a long duration or permanent mobile radar platform. This can be for tracking distant objects in remote areas where ground based infrastructure is not existent.

A2.1.2 – Communications platform

Civilian and military users could benefit from a stratospheric communications transponder platform. This can be used for communications services of an intermittent or temporary basis, objects in remote areas where ground based infrastructure is not existent. For example for disaster relief, or to support a Combat Theatre Forward Operating Base.

A2.1.3 Green Cargo Transport

Electrically propelled aircraft, e.g. with turbo props, can travel long distances without the need of any fossil fuel. These would probably be too slow to transport passengers, but could be viable to transporting heavy cargo faster than surface shipping across oceans. Eliminating the need for fossil fuel would help reduce carbon emissions.

A2.1.4 Long Duration Remote Sensing UAVs

Electrically powered UAVs [supplied by space based laser at night] could loiter at high altitude for very long periods of time, effectively indefinitely subject to maintenance needs. These could be remote sensing platforms and carry a variety of instruments for monitoring crops, wildlife, fish movements and weather, amongst other things. They would allow faster response times and better coverage [of a given point] than low Earth orbit remote sensing satellites, which are limited by orbital path to only cover a given area for a few minutes per day.

A2.2 Space Based Applications

A2.2.1 – Space to Space Beaming, e.g. on Earth orbit or orbit around a Moon, planet or asteroid.

Satellites can be placed in "Dawn Dusk" orbit which put them in continuously sunlight. These spacecraft can beam power to satellites in different orbits and provide power to them while in darkness. For example, the International Space Station could be supplied in this way.

A2.2.2 – Space to Surface power beaming

Example: a laser based at the Earth-Moon ELM-1 Lagrange point would be in continuous sunlight 98% of the time, and could supply power to the lunar surface including to a base or lander during the 14 day lunar night. This would eliminate or greatly reduce the need for heavy and expensive power storage equipment. A similar laser at EML2 over the lunar far side would also be useful.

A2.2.3 Surface to Surface power beaming

Example 1: a solar powered laser could be placed on a high mountain location near a lunar pole, such as Malapert Mountain where it would be in nearly continuous sunlight. This solar power laser could beam power to rovers in the permanently or near-permanently shadowed area near the lunar poles which are interesting targets for exploration. The shadowed areas are thought to contain deposits of ice and valuable volatiles, but are difficult to explore due to the lack of sunlight.

Example 2: Exploring into dark lunar [or Martian] lava tubes requires power either via cable or wireless power transmission. Dragging a cable could have problems such as deployment spool seizing, cable snagging on rocks, it could also disturb material which we would prefer to remain pristine. Laser beaming of power to a rover inside a lava tube would have some advantages over dragging a cable.

A.2.2.4 Terrestrial Applications

- High power and high efficient solar pumped lasers have a large potential for other applications, e.g.
- nano-materials production,
- materials processing,
- magnesium cycle of hydrogen production,
- free space laser communications,
- energy transmission.

Especially when these applications are performed in the following environments:

- temporary, mobile or remote areas where grid power is not available or cannot be used, such as:
- deserts
- wilderness areas
- areas of natural disasters [e.g. floods, Tsunamis, earthquakes)
- Arctic or Antarctic
- oceans or at sea
- in the air
- military Forward operating Bases.

A2.2.4.1 – Desalination

There is strong interest in India for the use of SBSP for coastal desalination [15]. Solar pumped lasers would greatly improve the economics of this plan.

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