Demonstration of Eye-Safe (1550 nm) Terrestrial Laser Power Beaming at 30 m and Subsequent Conversion into Electrical Power Using Dedicated Photovoltaics

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Abstract — We report on the successful demonstration of terrestrial laser power beaming across a distance of 30 m at an eye-safe wavelength of 1550 nm. Using novel photovoltaic convertors based on III-V semiconductors an optical to electrical power conversion efficiency of 45±1 % at 1 kW/m^2 and room temperature was achieved. Such an energy delivery system could prove extremely useful as a future energy source specifically in regions and targets where conventional energy delivery systems are un-deployable.

Index terms — photovoltaics, homo-junction, laser power beaming

I. INTRODUCTION

The feasibility of harnessing solar power via space based laser power beaming (LPB) has been investigated in detail on several occasions in the past under concerted studies [1]. In the presence of competing technologies utilizing microwave power beaming, space based solar power (SBSP) via LPB has been received with mixed interest under overall system cost and efficiency considerations [2]. While the microwave power beaming system currently offers a higher end-to-end efficiency compared to LPB [3], it is plagued by interference with signals from other communication satellites together with a larger receiver foot-print limiting its maneuverability and directional energy delivery which is the primary advantage in a LPB based system [4]. Recent technological breakthroughs in efficient high power fibre lasers [5] and photovoltaics [6] have now reached a juncture where the concept of SBSP via LPB can be realized in practice with an overall system efficiency of 10% or more [7].

SBSP via LPB utilizes high power lasers, either directly solar pumped or indirectly pumped by diode lasers which are in-turn driven by electrical energy generated by on-board solar cells on a satellite (sun-synchronous [1]), to beam down optical power to Earth (or any other target location) with a high pointing accuracy and stability, where it is converted to electrical power using dedicated photovoltaics. Recent advances in diode pumped fibre lasers offer very high pointing accuracy and stability [8] while emitting radiation at very high powers [4]. Conversion of beamed optical power into electrical energy can be achieved using dedicated photovoltaics (i.e. laser power convertors (LPCs)) which can convert optical radiation at a single wavelength into electrical energy with very high efficiency unlike conventional solar cells [9]. This is because a photovoltaic cell demonstrates maximum optical to electrical conversion efficiency when illuminated by monochromatic light with a wavelength closely corresponding to the chosen absorbing material band-gap energy [10].

It should be noted that such a LPB system coupled with dedicated LPCs not only finds use in SBSP but is also useful for several other terrestrial optical power delivery applications [11]. In particular, such a system can be used for terrestrial line-of-sight optical power delivery, remote powering of unmanned areal vehicles and subcutaneous equipment [12]-[14]. Fibre-optic power delivery systems can be used with dedicated LPCs to transfer power in places where conventional wiring is not feasible due to the presence of explosive or volatile substances susceptible to electromagnetic interference [15].

The choice of wavelength for a free-space LPB system mainly depends on two important considerations: (1) eye- and skin-safety and (2) absorption and attenuation of optical radiation when passing through the atmosphere or any other channel (such as an optical fibre). It is now well known that radiation at wavelengths longer than 1.4 µm is safe for both human eyes and skin up to a power density of 1kW/m^2 (1 sun equivalent) [17]. The minimum attenuation optical transmission windows within the Earth's atmosphere are around 1.55 µm and 2.1 µm in the near- and mid-infrared respectively [18].

Ultra high power high brightness fibre lasers have now been demonstrated at both 1.55 µm and at 2.1 µm [19]. Thus, to cater to the applications mentioned above, a pv-cell optimized for maximum conversion efficiency at 1.55 µm and 2.1 µm is required. We have developed novel III-V based high-efficiency laser power convertors (LPCs), optimised specifically for converting monochromatic laser radiation at the eye-safe wavelength of 1.55 µm into electrical power [20,21]. It should be noted that a dedicated pv-cell for 2.1 µm will fundamentally have lower conversion efficiency due to the lower photon energy at 2 µm compared to 1.55 µm [22].

In order to estimate the feasibility of LPB for SBSP we have performed terrestrial LPB experiments at a distance of 30 m which we report below. Further long range terrestrial demonstration experiments are currently being planned.

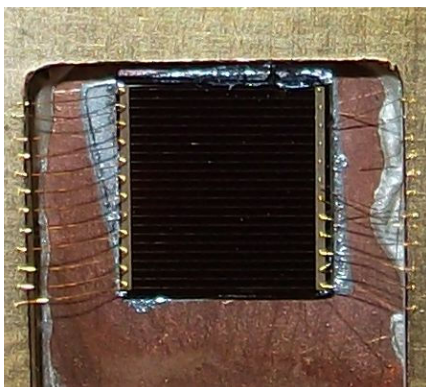

Fig 1. Top-view of the 5 mm x 5 mm dedicated laser power converter (LPC) designed and developed at Surrey (details in reference [20]).

II. THE EXPERIMENT

The terrestrial power transfer experiment was performed in an aircraft hangar at EADS ASTRIUM Space Transportation, Bremen, Germany where a diode pumped high power fibre laser was beamed at the dedicated LPC across a distance of 30 m. A diode pumped fibre laser (P_{max} ~ 50 W, M^2~1.05, wall-plug efficiency = 12.5 %) from IPG photonics was used [23]. The dedicated LPC developed at Surrey is based on lattice-matched InGaAsP/InP and incorporates a pn-homojunction together with elements for photon-recycling and efficient carrier extraction, see Fig 1. The laser beam in the experiment was expanded (from beam waist 4 mm to 12 mm) using a beam-expander (Thorlabs BE03M-C) in order to reduce and control the power density incident on the LPC for the power density dependent tests. The LPC mounted on a copper heat-spreader was temperature controlled (fixed at 21 C) during the experiment.

As seen from Fig 2, the plot for the conversion efficiency vs. incident optical density at 1.55 um, the maximum conversion efficiency (45±1 %) for the LPC is achieved at 1 kW/m^2 ([13, 24]) beyond which the conversion efficiency droops due to an increased thermal load and series resistance losses [10, 20]. The fill-factor at 1 kW/m^2 was 75 ± 1 %. As the LPC conversion efficiency saturates around 1 kW/m^2, even in the absence of thermal effects [20], increasing the incident radiation intensity increases the thermal load on the LPC thereby reducing its efficiency via temperature dependent carrier recombination mechanisms [24]. It should be pointed out that the LPC characteristics reported here match very well with the characteristics measured in the laboratory [20].

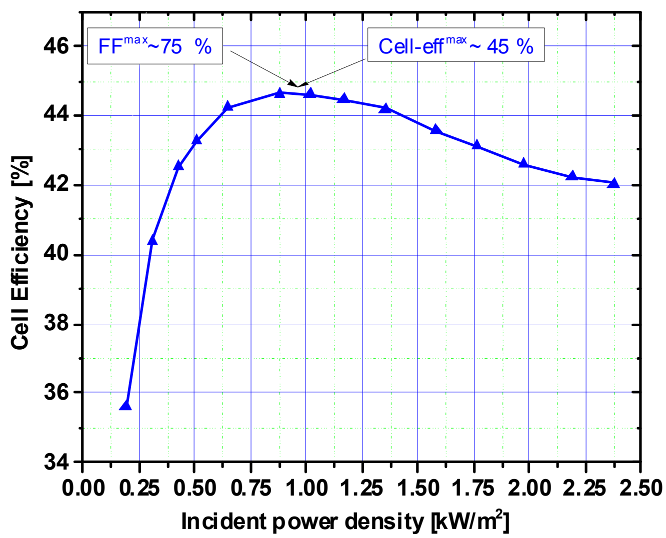

Fig 2. Dependence of LPC conversion efficiency on incident power density at 1550 nm. A maximum conversion efficiency of 45±1% is achieved at ~ 1 kW/m^2 (corresponding fill-factor (FF) is 75 ±1%) beyond which the conversion efficiency drops due to an increased thermal load. The calculated conversion efficiency is corrected for the Gaussian beam shape of the laser radiation. The LPC junction temperature was fixed at 21 C during the experiment by controlling the temperature of the sub-mount.

III. CONCLUSION

In conclusion, we have demonstrated eye-safe (1550nm) terrestrial laser power transfer across a distance of 30 m. The maximum optical to electrical conversion efficiency obtained is 45 ±1% (Fill-factor: 75 ±1 %) at a power density of 1 kW/m^2. Beyond 1 kW/m^2 the conversion efficiency droops due to an increased thermal load on the

LPC. Further design optimization of our LPC design is expected to scale the efficiency beyond 50 % at 1 kW/m^2. The end-to-end (electrical to optical and back to electrical) system efficiency is currently limited mainly by the diode pumped fibre laser's wall-plug efficiency (12.5%). In order to maintain the maximum achievable LPC conversion efficiency 1 kW/m^2 at even higher power densities from our LPB system, especially while using LPC arrays, improved LPC thermal management schemes would be required which are currently being studied. Such a LPB system will prove extremely useful as a future (green and safe) energy source specifically in regions and targets where conventional energy delivery systems are un-deployable. A SBSP via LPB system presents various technological and economic challenges. This terrestrial LPB demonstration (at 30 m) provides a useful first step towards a successful realization of an efficient SBSP delivery system for future energy generation and delivery.

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