



High Intensity Laser Power Beaming Architecture for Space and Terrestrial Missions

Taysir Nayfeh
Cleveland State University, Cleveland, Ohio

Brian Fast
Orbital Research, Inc., Cleveland, Ohio

Daniel Raible
Glenn Research Center, Cleveland, Ohio

Dragos Dinca
Northrop Grumman Information Technology, Cleveland, Ohio

Nick Tollis and Andrew Jalics
QinetiQ North America, Cleveland, Ohio

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA STI Help Desk at 443-757-5803
- Telephone the NASA STI Help Desk at 443-757-5802
- Write to:
NASA Center for AeroSpace Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320



High Intensity Laser Power Beaming Architecture for Space and Terrestrial Missions

Taysir Nayfeh
Cleveland State University, Cleveland, Ohio

Brian Fast
Orbital Research, Inc., Cleveland, Ohio

Daniel Raible
Glenn Research Center, Cleveland, Ohio

Dragos Dinca
Northrop Grumman Information Technology, Cleveland, Ohio

Nick Tollis and Andrew Jalics
QinetiQ North America, Cleveland, Ohio

Prepared for the
2010 Advanced Space Propulsion Workshop
cosponsored by the Air Force Research Laboratory, the NASA Jet Propulsion Laboratory, and the
NASA Glenn Research Center
Colorado Springs, Colorado, November 15–17, 2010

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

Acknowledgments

The Industrial Space Systems Lab team would like to express their thanks to Bernie Sater, Greenfield Solar, for the advice given to the ISSL from years of experience developing the Vertical Multi-Junction (VMJ) cells. Jim Soeder, Ray Beach, Fred Wolff and the NASA Glenn Research Center for supporting the efforts of the Industrial Space Systems Laboratory (ISSL). Ken Edwards and the Eglin Air Force Research Laboratory for the research partnership with the ISSL in further developing this technology. Hobson Lane, Bob Rice, and Northrop Grumman's Space Technology division for the time and support given to the ISSL during the demonstration. NASA's Space Communications and Navigation (SCaN) program for supporting the publication and presentation of this research.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076-1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at <http://www.sti.nasa.gov>

High Intensity Laser Power Beaming Architecture for Space and Terrestrial Missions

Taysir Nayfeh
Cleveland State University
Cleveland, Ohio 44115

Brian Fast
Orbital Research, Inc.
Cleveland, Ohio 44103

Daniel Raible
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Dragos Dinca
Northrop Grumman Information Technology
Cleveland, Ohio 44130

Nick Tollis and Andrew Jalics
QinetiQ North America
Cleveland, Ohio 44135

Abstract

High Intensity Laser Power Beaming (HILPB) has been developed as a technique to achieve Wireless Power Transmission (WPT) for both space and terrestrial applications. In this paper, the system architecture and hardware results for a terrestrial application of HILPB are presented. These results demonstrate continuous conversion of high intensity optical energy at near-IR wavelengths directly to electrical energy at output power levels as high as 6.24 W from the single cell 0.8 cm² aperture receiver. These results are scalable, and may be realized by implementing receiver arraying and utilizing higher power source lasers. This type of system would enable long range optical “refueling” of electric platforms, such as MUAV’s, airships, robotic exploration missions and provide power to spacecraft platforms which may utilize it to drive electric means of propulsion.

Introduction

In the 20th century, it is inarguable that the use of wireless technologies has revolutionized the telecommunications industry. The effects of wireless systems are apparent in the development of space base assets that are used to communicate across the world. However, the direct use of wireless technologies has not had a significant impact on the power industries. A few applications have attempted to enter into this field on a small scale. For example, the use of inductive power transmission has been used for charging circuits in small hand held devices, and the use of microwave transmission has been the primary means of investigating the transmission of large amounts of power over longer distances. However, inductive power transmission is only effective over relatively short distances (cm) and microwave transmission is only effective over modest distances due to the decrease in the radiated energy density as a function of distance. The ability to transmit optical energy longer distances (km or more) via high intensity lasers makes it an attractive option for wireless power transmission. The primary challenge

with High Intensity Laser Power Beaming (HILPB), and the one currently under investigation, is the receiver's ability to efficiently convert the impinging optical energy to electrical energy under high levels of irradiance.

The primary driver that has kept wireless power transmission from entering the market, as a mainstream enabling technology, is the cost per watt. However, there are several potential aerospace applications where HILPB would be one of only a few technologies that could be capable of accomplishing the specific mission. Two near term missions that have identified HILPB as a potential enabling technology is the Air Force's desire to develop a perpetual flight UAV and NASA's desire to explore the far side of the Moon. Each of these missions will require a significant amount of energy to be delivered remotely, which is a difficult problem.

The proposed HILPB system consists of two halves, one for transmitting energy and one for receiving the energy. The ability to accurately transmit optical energy over long distances with lasers in a controlled fashion already exists in systems such as the Airborne Laser (ABL), Tactical High Energy Laser (THEL) and free space laser communication systems for both terrestrial (aerial, ground, and maritime) and space environments. Lasers provide a means of beaming high intensity optical energy over long distances with narrow beam divergence. The primary missing component for HILPB has been the receiver which would provide the ability to effectively convert the photonic energy directly to usable electrical energy.

In this paper, the results of the proposed architecture for developing a HILPB system are presented. At the core of the HILPB system is the power receiver which will convert the high intensity optical energy to electrical energy. The system also includes the necessary electronics for conditioning the energy for storage in lithium-ion polymer (LiPo) batteries or for powering an electric motor. Initial lab results are presented to validate the ability for the receiver to dissipate the thermal loads while efficiently converting the high intensity optical energy to electrical energy.

Power Receiver

The proposed architecture for the HILPB receiver is developed around the photovoltaic ability to directly convert optical energy to electrical energy. Unfortunately most optical to electrical devices have been developed for solar applications which are limited to converting the equivalent of approximately one sun of broadband optical energy. However, in an attempt to develop more cost efficient photovoltaic systems, specialized cells have been developed that can convert optical energies greater than one sun for use with concentration systems. For HILPB applications the most relevant characteristics of the cells are the maximum input irradiance the cells can convert, spectral response, thermal performance capability, sensitivity to energy variations, and how these characteristics affect the overall design and performance of the HILPB system.

The current HILPB receiver has been developed around a silicon based Vertical Multi-Junction (VMJ) photovoltaic cell (Ref. 2) developed at the NASA Glenn Research Center (GRC). The VMJ cell (0.8 cm² area) has been flash tested in the GRC solar simulator to withstand 2500 suns of broadband optical energy while producing 40.4 W electrical output from nearly 211 W/cm² irradiance levels with a nominal voltage of 24 V under these transient conditions. The VMJ cell is an integrally bonded series-connected array of miniature silicon junction unit cells, as shown in Figure 1. The illuminated face of the cell is oriented at the side of the p⁺nn⁺ junctions, and so it is also referred to as an "edge illumination" multi-junction cell. Because of the series connected junctions, one small 40-junction VMJ cell (0.8 cm² area) can output a nominal 24 V under load. This eliminates the need to construct series stacks of conventional photovoltaic cells in an array to interface with downstream electronics, resulting in a significantly more compact and practical receiver. The number of junctions in a VMJ cell can easily be varied during the design and manufacturing process to accommodate the bus voltage requirements of the end application.

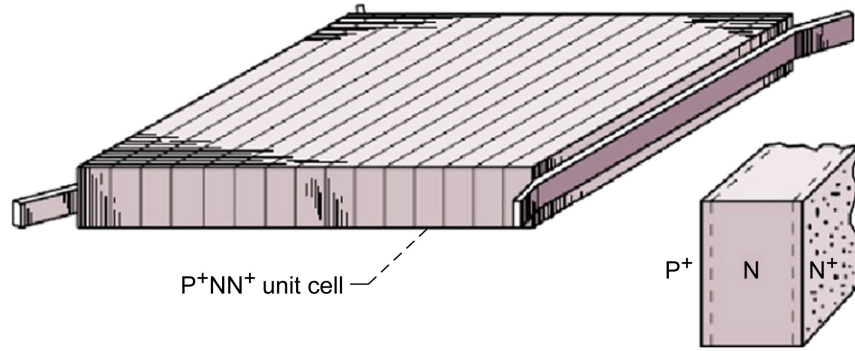


Figure 1.—40-junction VMJ silicon photovoltaic.

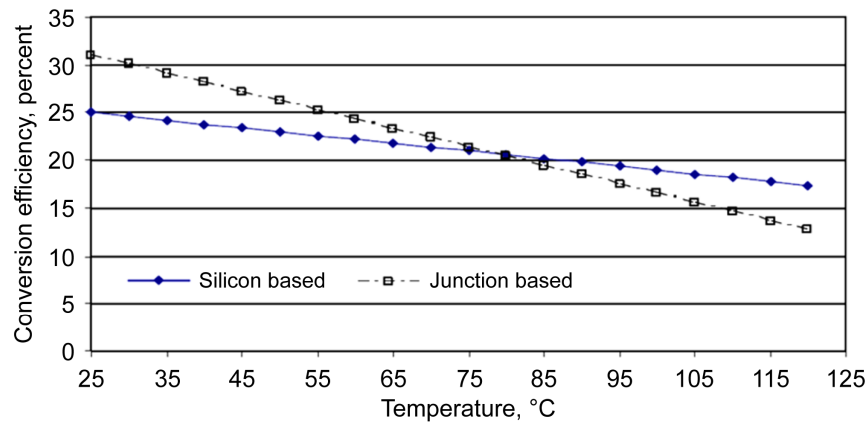


Figure 2.—Silicon VMJ temperature derating.

The unique design of the VMJ cell has several advantages. First, since the cell is edge illuminated, the need for electrical contacts on the illuminated face is eliminated. This allows for a greater unobstructed convertible surface area for the photonic energy to enter the cell. Since the junctions are vertical, the cell thickness is not limited by the thickness of the silicon wafer, but can be adjusted during manufacturing to optimize performance. Through the depth of each junction, there is an equal probability that an excess carrier can be generated from the impinging energy, increasing the chance for a photonic collision to occur. This produces an improved spectral response at low and high frequencies (Ref. 2). Second, the series connections of the junctions provide high compatibility with most loads. This also creates a very high reverse voltage breakdown immunity, which reduces the need for adding bypass protection diodes that are typical in paralleled photovoltaic arrays. In a reverse biased experiment, a 40-junction VMJ cell was able to withstand a 6 kV potential (the limit of the test equipment) with only minimal leakage current.

The semiconductor material selected to construct the VMJ cell will significantly affect the overall system architecture by determining the characteristics of the power receiver's spectral and thermal response. For this study a silicon VMJ cell was used due to the high technology readiness level (TRL) and availability, however in the future other materials may be considered that may tailor the system performance for a particular application. The thermal response of a silicon VMJ cell is such that for every 10° of temperature increase the output power will degrade by less than 1 percent, as shown in Figure 2.

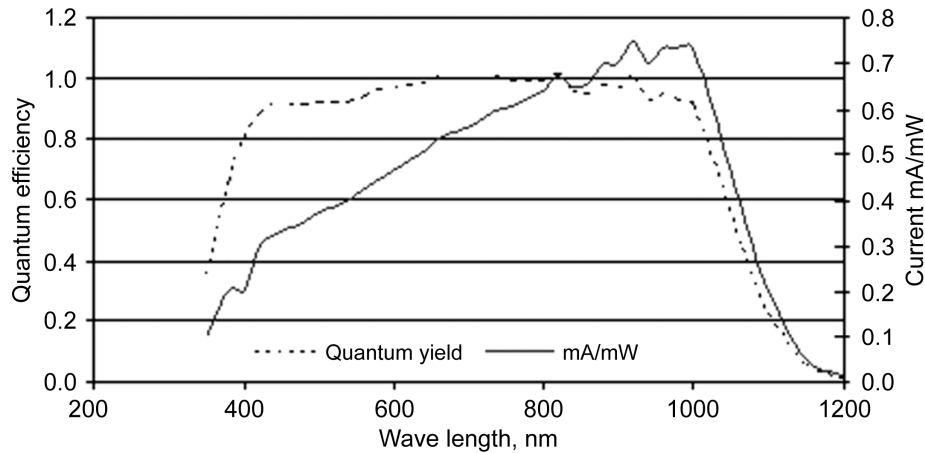


Figure 3.—Silicon spectral response.

The frequency response of silicon, shown in Figure 3, illustrates that a standard IR laser with a wavelength in the vicinity of 1 μm would be ideally suited for maximizing the output performance.

A limiting factor in the performance of the VMJ cell under HILPB conditions is the energy profile of the incident light. Since the cell is made up of series junctions, it is ideal to have uniform illumination across the entire convertible surface. A single or group of weaker junctions, resulting from relatively less illumination, will limit the overall output from the cell. In other words, since the cell is a series arrangement of junctions, the maximum output current will be limited by the weakest junction's contribution. This creates a significant problem for HILPB, since the very nature of the propagation of a laser beam is not uniform, but fundamentally transverse electromagnetic Gaussian (TEM_{00}) in profile (Ref. 3). This is a primary issue that will require further investigation when optimizing the system performance.

The design and construction of the power receiver addresses four main issues. First, the receiver needs to provide sufficient thermal dissipation in order to handle the excess, electrically unconvertible, energy. Second, the materials in the power receiver must have similar coefficients of thermal expansion to avoid stress fracturing during thermal cycling. Third, the electrical paths and connections in the receiver must feature low resistivities in order to maintain good end-to-end power efficiency. Lastly, the receiver must provide electrical isolation for the VMJ cells as well as the electrical routing and the interconnections.

The prototype of the HILPB receiver includes a high performance thermal management system. One of the primary challenges with HILPB is how to efficiently remove the undesirable thermal energy from the VMJ cell. The first part of the thermal management system was determining how to mechanically attach the cell to the rest of the receiver while providing good thermal conductivity along with electrical isolation. The current design is constructed from a series of epoxies and substrate materials. A cross-sectional illustration of the optical receiver is shown in Figure 4. The VMJ cell is mounted to a substrate with a boron nitride filled epoxy resin (Ref. 5). The resin features a good thermal conductivity ($1.5 \text{ W/m}^{\circ}\text{K}$) and a relatively high operating temperature (approximately 200°C). In the center of the stack up is the polished aluminum nitride substrate. Aluminum nitride offers very good thermal performance ($175 \text{ W/m}^{\circ}\text{K}$), low coefficient of thermal expansion and good dielectric strength. Aluminum nitride is commonly used as a substitute for the standard FR4 fiberglass in printed circuit board (PCB) construction for better thermal conductivity in high power circuits. These characteristics render it ideal for the power receiver application. The substrate is mounted to the copper heat pipe unit using another layer of the boron nitride epoxy resin.

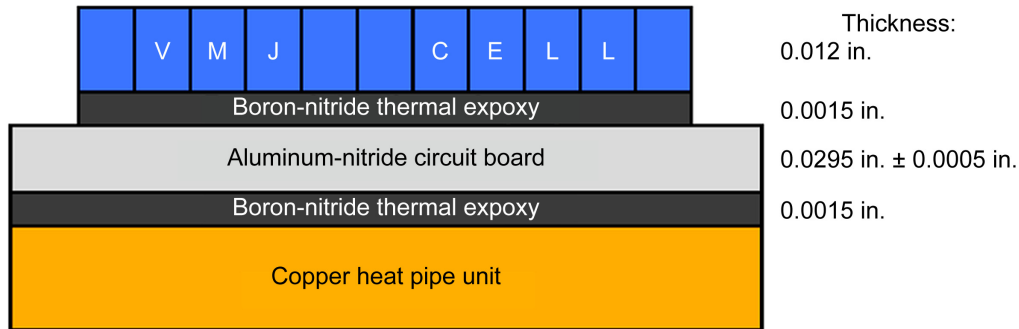


Figure 4.—Cross-sectional stackup of the power receiver.

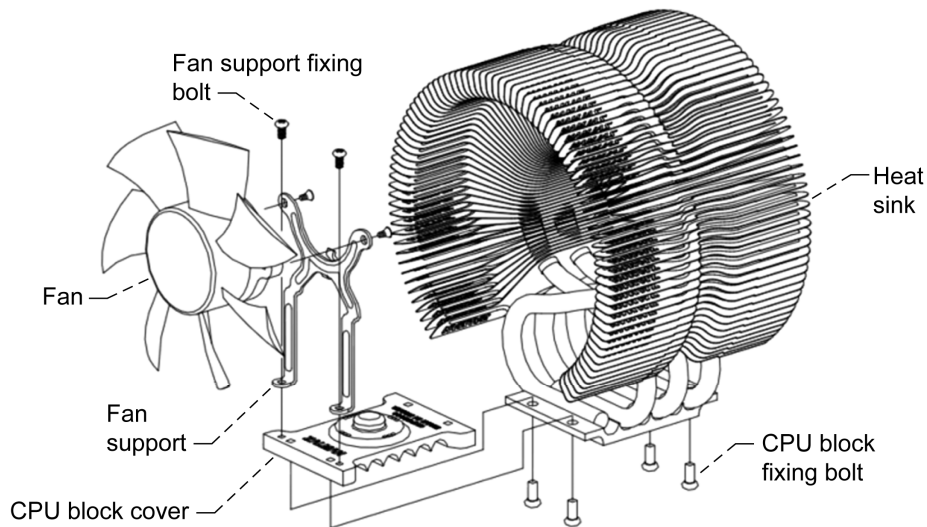


Figure 5.—Zalman heat pipe unit.

The electrical paths between the photovoltaic cells were routed with a ferrite-nickel-cobalt alloy wire known as Kovar (Carpenter Technology Corporation) (Ref. 6). Kovar is a material commonly used for bond wires within integrated circuit (IC) semiconductor construction, since its coefficient of thermal expansion is similar to that of silicon. A 6 percent silver plating was added to the Kovar wire, resulting in a low electrical resistance of 31.9 Ω per 1000 ft. The routing wires are electrically attached to the outer two junctions of each VMJ cell with a silver-filled adhesive paste, called Silver Paste Plus (SPI) (Ref. 7). The paste has a high melting temperature (962 °C) and a low electrical resistivity (3×10^{-5} Ω -cm), which meets the demands of the power receiver.

The current prototype focuses on a terrestrial application of providing in-air refueling capability to a perpetual flight electric UAV, and therefore the size and weight constraints of the thermal control system are a significant consideration for the initial proof-of-concept. The anticipated maximum input radiance was to be less than 220 W of optical energy with a desired receiver operating temperature of 60 °C. A small commercial off the shelf (COTS) Zalman microprocessor heat pipe unit, shown in Figure 5 was employed as the primary means of thermal conduction, and modified to maximize surface cooling effect by utilizing the airflow from the propeller. The top mating surface of the unit is finely lapped to provide for maximum thermal transfer. The unit is constructed out of copper, and features three heat pipes that are partially filled with phase change fluid. The heat pipes traverse from the surface plate through a radial array of fins, where airflow is supplied by a small DC fan. This original fan has been replaced by a more powerful motor and propeller commonly used for propulsion on military UAVs, supplied by the Air Force Research Laboratory at Eglin Air Force Base, in order to increase the amount of cooling beyond the manufacturer's specifications.

Material Stack (top-to-bottom)	Thermal Resistance $\Theta_i = (\Delta^\circ\text{C} / \text{W})$
VMJ Cells	$\Theta_1 = 0.02$
Boron-Nitride Epoxy	$\Theta_2 = 0.1905$
Aluminum-Nitride Substrate	$\Theta_3 = 0.0027$
Boron-Nitride Epoxy	$\Theta_4 = 0.0119$
Heat Sink (stock fan at 2,600 RPM)	$\Theta_5 = 0.12$
Heat Sink (stock fan at 1,350 RPM)	$\Theta_5 = 0.16$
Surface Temperature Equals:	
Ambient Temp + Input Power * ($\Theta_1 + \Theta_2 + \Theta_3 + \Theta_4 + \Theta_5$)	

Figure 6.—Thermal analysis of the power receiver.

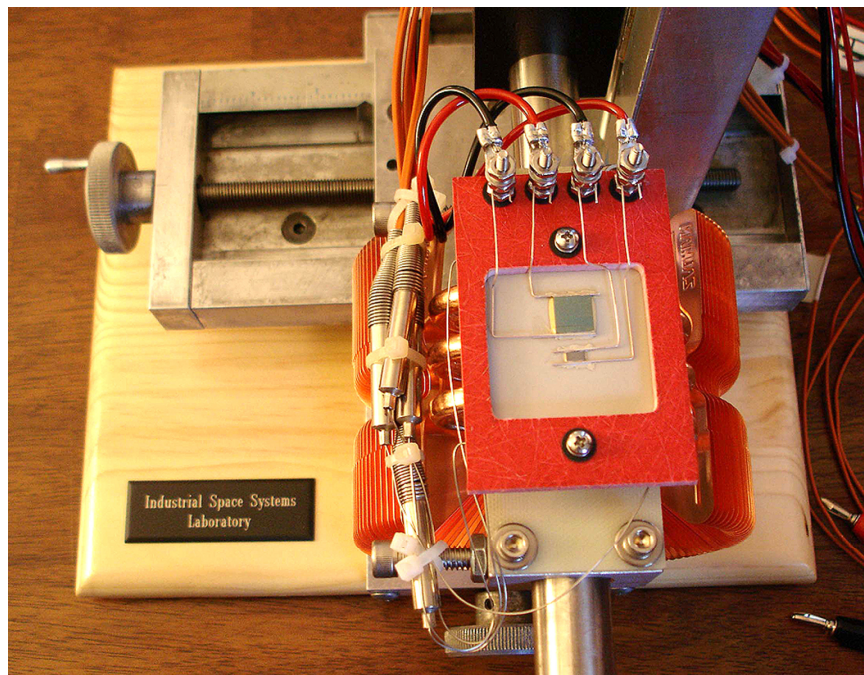


Figure 7.—Overall view of a complete HILPB receiver.

A heat transfer analysis may be performed on the receiver to obtain the theoretical temperature at the surface of the VMJ cell during test as shown in Figure 6. This is accomplished by calculating the thermal resistance for each material in the stack, considering the ambient temperature, surface air velocity generated by the propeller, and the optical input power.

With an ambient laboratory temperature of 20 °C, the original manufacture's cooling fan running at 2,600 rpm, an estimated 30 percent optical-to-electrical conversion efficiency for the VMJ cells (70 percent thermal load assuming zero reflectivity) and an input radiance of 130 W, the above equation yields a theoretical surface temperature of 51.4 °C. With an input radiance equal to 220 W, the resulting theoretical surface temperature is 73.15 °C. This is well within the operating limitations of the prototype power receiver for the initial range of tests to be conducted.

The constructed prototype of a HILPB receiver featuring a parallel array of nine photovoltaic VMJ cells is shown in Figure 7. The outer ring is cut from GPO3 electrical grade fiberglass, and serves as a mounting surface for the stainless hardware. Optical mounting blocks have been machined to interface with standard 7/8 in. optical rods, and have been bolted to the heat pipe unit. 1/32 in. channels were milled into the top face of the copper plate, where several thermocouples have been embedded to characterize the thermal profile of the interface between the copper and the aluminum nitride substrate.

There have been a few variations in the geometry of the receivers, each featuring a different number and arrangement of VMJ cells to vary the total convertible surface area. Overall, the receivers have been constructed to support a host of HILPB experiments, some of which will be discussed in subsequent papers.

Power Management and Distribution (PMAD) System

The objective of the PMAD system is to allow the electrical energy from the HILPB receiver to be properly monitored and distributed to the downstream load (propulsion) or the battery pack for storage. The design incorporates an energy storage subsystem which includes specific charger circuitry for the prototype high energy density Lithium-ion polymer (LiPo) batteries, in addition to featuring cell balancing electronics that provide charge/discharge accuracy and safety for the battery pack. An illustrative block diagram of the PMAD system is shown in Figure 8.

Power distribution throughout the system and to the load depends on the available energy from the VMJ cells and the status of the battery pack. This means that the load, in the UAV case the brushless DC motor, may be operated either directly from the VMJ cells through a buck/boost DC-to-DC converter or from the energy storage subsystem. The control circuitry allows either one of these modes to be online or, if desirable, both modes can be offline in which case the motor is turned off. An IRFU5305 field-effect transistor (FET), along with a properly biased high voltage, open-collector driver IC (Texas Instrument's SN7406 series) ensures the correct functionality of the power routing control circuitry.

System monitoring allows tracking of the electrical energy throughout the system, so that power distribution can be accurately controlled and displayed by the on-board controller. Thus, voltage and current measurements are taken at the following points in the system: the input power source at the receiver (VMJ cells), the buck/boost converter's output, and the main output of the energy storage subsystem. The voltage and temperature of each cell in the battery pack are also individually monitored, while the charger circuitry provides additional monitoring capabilities. A total of seven K-type thermal couples are used to monitor the temperature profile of the HILPB receiver and also the

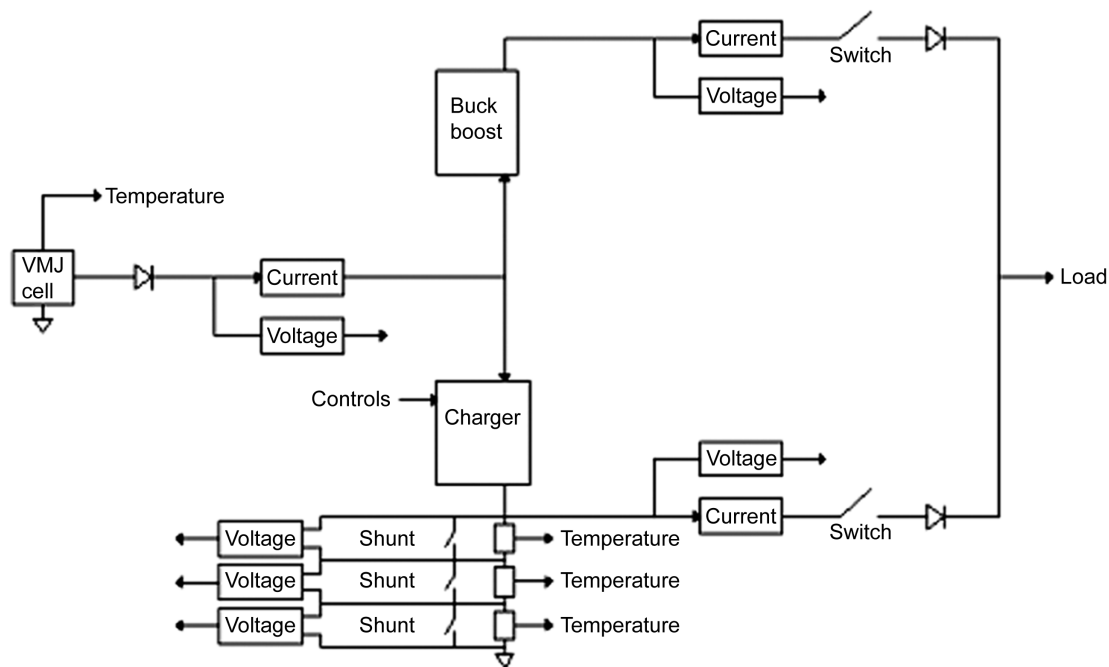


Figure 8.—PMAD system design—block diagram.

temperature of the battery pack. MAX6674, a temperature measurement IC that incorporates cold junction compensation, is utilized to measure temperatures in the range of 0 to 125 °C; these temperatures are monitored once a second (1 Hz).

Current measurements are made possible by utilizing Maxim Integrated Products' MAX4173H, a high-side current sense amplifier. This IC uses an external current sense resistor, the sizing of which optimizes the current sense capability depending on the amount of available current. Hence, MAX4173H produces an output voltage representative of the measured current which is fed to the on board controller through a low noise, unity gain buffer amplifier. A two stage operational-amplifier design is implemented to measure the bus voltage at different stages in the system. The first op-amp stage is used as a high impedance follower, to minimize parasitic current draw or loading down of the bus voltage. The second circuit utilizes another amplifier to precisely scale the bus voltage and provide the appropriate voltage level to a 4-channel, 13-bit analog-to-digital converter (AD7324, a product of Analog Devices, Inc.). The operational amplifiers used in this design are of the Texas Instruments Burr-Brown OPA251 family. A block diagram of the voltage and current measurement circuitry is depicted in Figure 9.

Charging of the battery pack is accomplished by using a highly integrated, multi-chemistry battery charger control IC – MAX1908, manufactured by Maxim Integrated Products, Inc. (Ref. 10). In order to achieve high efficiency, MAX1908 makes use of a buck topology with synchronous rectification. With a few modifications, this battery charger may be configured to charge Li+ batteries at current charge rates as high as 7.5 A. MAX1908 uses analog inputs to control the charge voltage and current, which in turn gives the on board controller flexibility and total control over these tasks; separate internal control compensation loops allow for accurate voltage and current charge of the battery system. In addition, the charger features monitoring capabilities, which are provided as outputs to the main controller. Some of the tasks that can be monitored are: presence of the input-power, the battery-charging current, and the input-power current draw. Furthermore, the charger circuit provides a conditioning charge feature that is dependent on the present state of the battery pack.

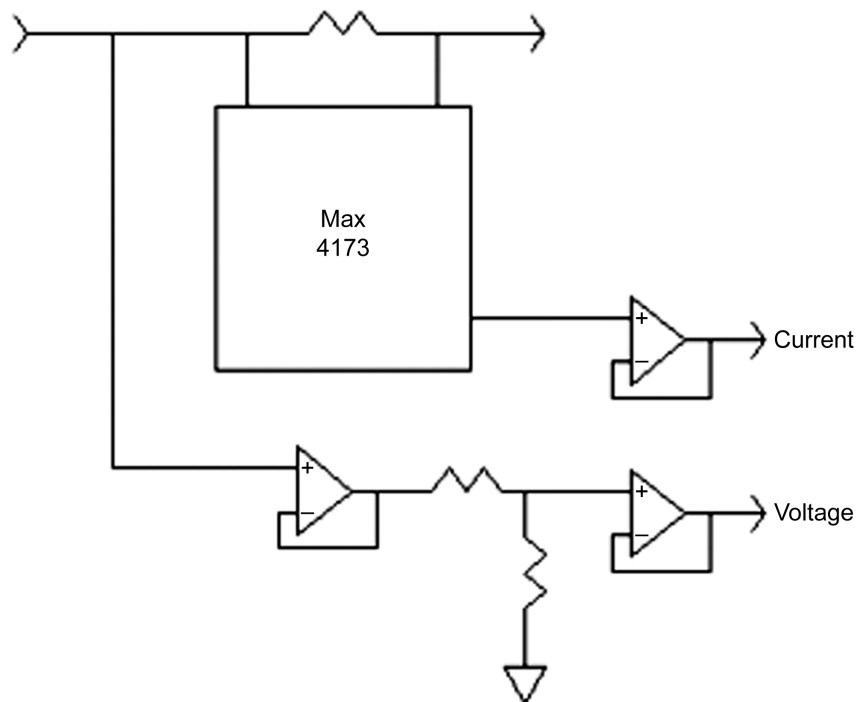


Figure 9.—Voltage and current monitoring—block diagram.

The energy storage subsystem incorporates cell balancing during charging and discharging of the batteries, to ensure that each cell in the battery pack has the same voltage potential while in a fully charged or discharged state. The battery pack is not in a balanced condition if one of the cells reaches the maximum charge state before the other cells. For optimal performance, the voltage difference between the cells cannot be greater than 100 mV at any time during the charge or discharge cycle (Refs. 11 and 12). In case the cells become unbalanced, the battery system's efficiency is affected in two ways. First, the battery system has less capacity during the discharge cycle since the cell that is not fully charged will be drained before the other cells. Second, once the battery system reaches an unbalanced state, the lifetime of the unbalanced cell is significantly reduced.

Prior to balancing the battery pack, each cell's voltage must be recorded. The individual cell voltage is measured by a precision, low drift, instrumentation amplifier (Texas Instruments Burr-Brown's INA118). An accurate cell voltage measurement is ensured by implementing a passive low pass filter with an approximate cutoff of 1.5 kHz to reduce sensitivity to higher frequency noise. The output voltage of the INA118 is then polled by the A/D converter for digitization. Once the cell voltage is obtained, balancing or shunting a battery cell is achieved by redirecting a portion of the charging current (approximately 20 percent) around the cell through a power resistor. The charging current is routed using a power FET (IRLR024N) that is connected in parallel with each individual cell. The FET is controlled by the main microcontroller, which along with the power resistor is used to balance the cells while charging or discharging the battery pack. A block diagram of the energy storage subsystem's functionality is depicted in Figure 10.

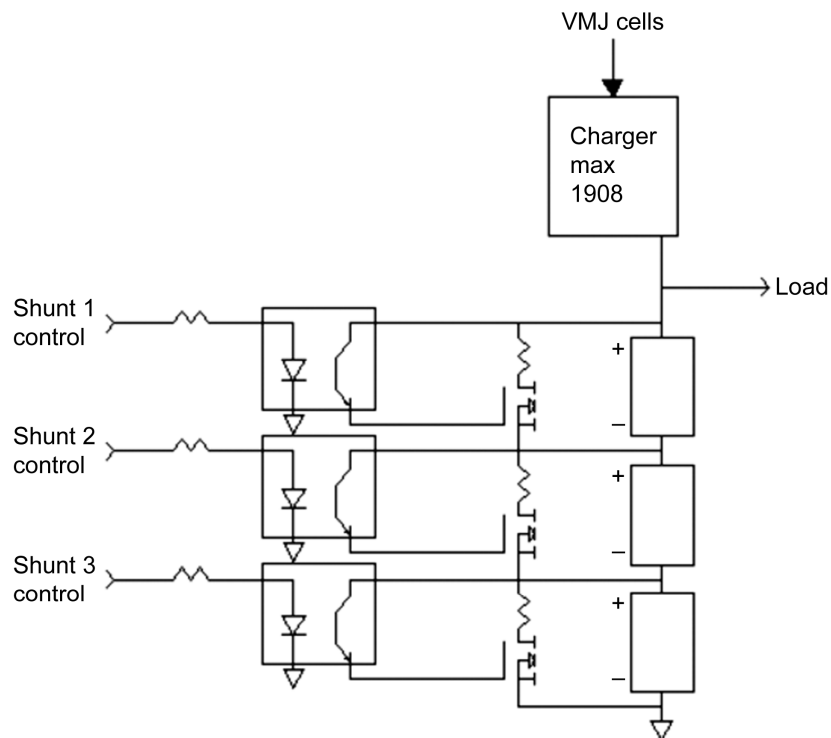


Figure 10.—Energy storage subsystem—block diagram.



Figure 11.—HILPB electronics.

At the heart of the PMAD system is the on board controller, a Xilinx Spartan 3 field programmable gate array (FPGA). In addition to data acquisition, interfacing with the battery charger IC and all of the associated safety tasks previously described, the FPGA is also responsible with controlling the speed of the UAV propeller, controlling some of the PMAD system tasks autonomously, interfacing with a wireless communication channel, and displaying the real-time data to a Liquid Crystal Display (LCD); the LCD is provided for quickly validating the status of the system. The processing for the FPGA has been constructed using a Very High Speed Integrated Circuit (VHSIC) Hardware Description Language (VHDL). The FPGA communicates with a remote computer through a 900 MHz, 9600 BAUD rate, Spread Spectrum wireless module interface manufactured by MaxStream Inc. The complete system electronics have been designed to fit on a 5 by 8 in., four layer printed circuit board (PCB), as shown in Figure 11.

Experimental Results

The presented results validate the ability to dissipate the excess thermal energy, efficiently convert high intensity optical energy to electrical energy, and illustrate the necessity of having uniform illumination across the cell.

These tests were performed in the Northrop Grumman Space Technology (NGST) laser laboratory, using a 975 nm fiber coupled semiconductor laser with a single VMJ cell receiver. The fiber was aligned orthogonal to the face of the receiver using a three axis positioner (see Fig. 12), and the beam was allowed to propagate in free space without any collimation optics added. The inherent divergence of the beam led to an overflow factor with respect to the VMJ cell, which was measured in order to quantify the irradiance level impinging on the face of the photovoltaic cell (quantifying overflow).

The test procedure called for the laser energy to be increased incrementally, while sweeping an I-V curve for the receiver at each set-point. During these tests the propeller was operated to provide cooling to the heat pipe unit, as it would during a test flight. By carefully aligning the receiver to the laser in three axes and increasing the laser power, a peak measurement was obtained. At an input radiant power of 27.1 W, a single VMJ cell was able to continuously generate 6.24 W of electrical power at peak output, for an optical-to-electrical conversion efficiency of 23 percent. These sets of data serve as the first empirical proof of concept for the application of the VMJ technology for HILPB.

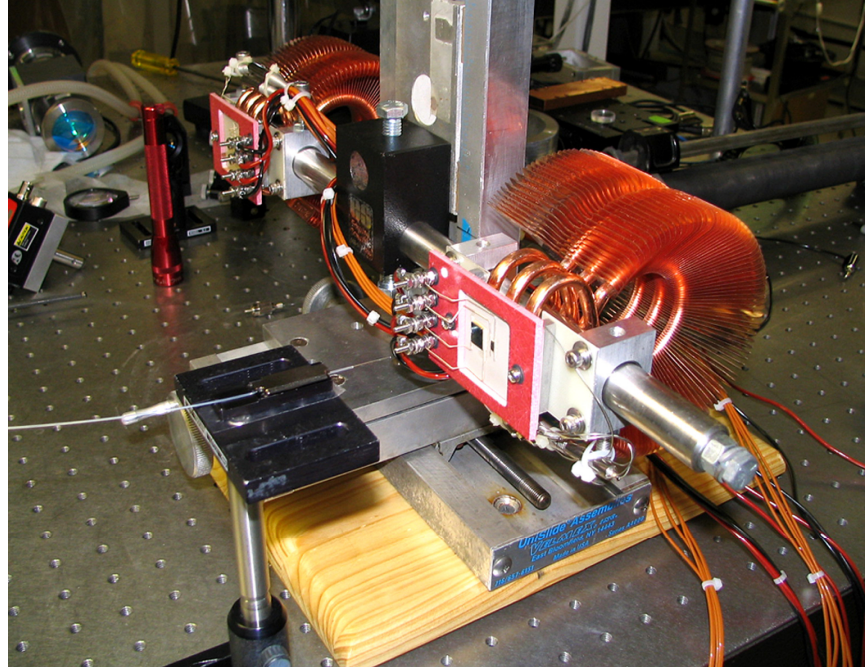


Figure 12.—Optical bench setup during the laser test.

Proposed Improvements and Future Work

There are several items in the current design of the HILPB receiver that requires further investigation in order to better understand the optimal system design. The selection of silicon for the VMJ cells is the first and most important consideration. Silicon limits the wavelength of the laser for optimal power conversion at the cell level. The material selection also affects the entire system architecture. The laser source with 980 nm wavelength has safety concerns with respect to eye protection that would need to be addressed. The laser frequency has an effect on the performance and complexity of the laser pointing system. The 980 nm laser has significant beam spread from the fiber aperture that will need to be compensated for along with more significant atmospheric absorption than lasers with different wavelengths. The ability of the laser system to uniformly illuminate the receiver significantly dictates the overall performance, which will need to be investigated in more detail. Finally, the mounting of the cells and the design of the heat sink can be optimized to improve the overall system objectives.

Conclusions

Results of this work demonstrate that it is feasible to continuously beam large amounts of energy at extremely high densities wirelessly to narrow receiver apertures (<1 cm); utilizing VMJ photocell based receivers with high intensity IR laser sources. We believe that this wireless power transmission technology will be an enabler to many applications where conventional means of power distribution and delivery is prohibitive. By utilizing focusing optics, such a system may be able to deliver large amounts of power across hundreds of kilometers, as limited by the diffraction limit of the source aperture. This type of system would enable long range optical “refueling” of electric platforms, such as MUAV’s, airships, robotic exploration and spacecraft employing electric means of propulsion.

The developed HILPB architecture may be used to further investigate ways of optimizing the optical power delivery system. In the future, adjustments will be made to the operating wavelength, laser beam profile, receiver geometry, cell construction, beam modulation and thermal interface to maximize the amount of electrical power at the receiver, while understanding the limitations of the system.

It is the opinion of the Industrial Space Systems Laboratory that the HILPB receiver, when used in conjunction with a fiber laser near 980 nm, provides the starting point for developing an infrastructure capable of beaming energy for aerospace and emergency applications. This proof of concept demonstration shows the feasibility of the VMJ cells to be used with a high intensity narrowband photonic source under steady state conditions. The current TRL of this technology is three, as shown by the experimental demonstration of the critical functionality of the system.

References

1. Sater, B.L. Sater, N.D., "High voltage silicon VMJ solar cells for up to 1000 suns intensities," Photovoltaic Specialists Conference, 2002. Conference Record of the Twenty-Ninth IEEE, Publication Date: 19–24 May 2002, on page(s): 1019-1022, ISSN: 1060-8371, ISBN: 0-7803-7471-1.
2. Goradia, C. | Sater, B.L., "A first order theory of the p/+/-n-n/+/- edge-illuminated silicon solar cell at very high injection levels," IEEE Transactions on Electron Devices. Vol. ED-24, pp. 342–351. Apr. 1977.
3. Alda, Javier, "Laser and Gaussian beam propagation and transformation," University Complutense of Madrid, Madrid, Spain, Encyclopedia of Optical Engineering, 2003.
4. Miwa, K.; Fukumoto, A., "First Principles Calculation of the structural, electronic and vibrational properties of gallium nitride and aluminum nitride," *Physical Review B*, Volume 48 Number 11, September 15, 1993.
5. Bujard, P., "Thermal conductivity of boron nitride filled epoxy resins: temperature dependence and influence of sample preparation," Ciba-Geigy Ltd., Fribourg; Thermal Phenomena in the Fabrication and Operation of Electronic Components: I-THERM '88, InterSociety Conference on; 11–13 May 1988.
6. Liu, G.; Cui, B.; Chen, R.J., "Thermal Expansion Behavior of Copper/Kovar Alloy Composite," Northeast Univ. Technol. (China). vol. 9, no. 4, pp. 498–501. Dec. 1988.
7. SPI Silver Paste Plus datasheet, http://www.2spi.com/catalog/spec_prep/plus_prep.html
8. Daoqiang Lu; Tong, Q.K.; Wong, C.P., "Conductivity mechanisms of isotropic conductive adhesives (ICAs)," *Electronics Packaging Manufacturing, IEEE Transactions on [see also Components, Packaging and Manufacturing Technology, Part C: Manufacturing, IEEE Transactions on]*, vol. 22, no. 3 pp. 223–227, Jul 1999.
9. Horowitz, Paul; Hill, Winfield, "The Art of Electronics," Second Edition, Cambridge University Press, 1989.
10. MAX1908 Datasheet, www.maxim-ic.com
11. Y. Droir; C. Martinez, "The Benefits of Cell Balancing," Intersil® - Application Note (AN141).
12. C. Martinez; Y. Droir; J. Ciancio, "Smart Batteries and the Intersil x3100," Intersil® - Application Note (AN127).

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 01-03-2011		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE High Intensity Laser Power Beaming Architecture for Space and Terrestrial Missions			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Nayfeh, Taysir; Fast, Brian; Raible, Daniel; Dinca, Dragos; Tollis, Nick; Jalics, Andrew			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER WBS 439432.07.01.17.02		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-17672		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITOR'S ACRONYM(S) NASA		
			11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2011-217009		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Categories: 33, 36, and 74 Available electronically at http://www.sti.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT High Intensity Laser Power Beaming (HILPB) has been developed as a technique to achieve Wireless Power Transmission (WPT) for both space and terrestrial applications. In this paper, the system architecture and hardware results for a terrestrial application of HILPB are presented. These results demonstrate continuous conversion of high intensity optical energy at near-IR wavelengths directly to electrical energy at output power levels as high as 6.24 W from the single cell 0.8 cm ² aperture receiver. These results are scalable, and may be realized by implementing receiver arraying and utilizing higher power source lasers. This type of system would enable long range optical "refueling" of electric platforms, such as MUAV's, airships, robotic exploration missions and provide power to spacecraft platforms which may utilize it to drive electric means of propulsion.					
15. SUBJECT TERMS Optics; Photonics; Laser power beaming; Wireless Power Transmission (WPT)					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 17	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) 443-757-5802

