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Enhancing Lunar Operation Architecture Through Increasing Efficiency of Wireless Power Delivery

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Abstract

As NASA and other space agencies plan to establish a sustained presence on the Moon, an electrical power delivery network on the lunar surface has become a critical infrastructure element of the overall lunar operation architecture. It is not practical to deliver physical cables for power distribution to the lunar surface. Some assets such as rovers and remote posts are also expected to operate in the permanently or partially shadowed regions of the Moon, so a solar power generation solution is not feasible requiring power to be transmitted to the location that may be a moving or non-permanent station. Accordingly, most of the currently proposed operation architecture include wireless power transfer (WPT) as the main means of distributing power. WPT is a technology that allows energy to be transported from one location to another without the use of wires. One type of wireless power transfer is laser wireless power transfer (LWPT) where it has advantages over the more traditional microwave WPT. The efficiency of LWPT can be further increased by using polychromatic lasers that are tuned to the optimum absorption wavelengths of a multi-junction solar cell. The major benefit for lunar assets would be no requirement for a specialized LWPT receiver to distribute power, while power generation can utilize sunlight when able. The higher efficiency also results in reduction of other required resources, allowing significant enhancements to the lunar operation architecture. This paper outlines preliminary test results that show that high solar cell efficiency can be achieved using a multi-junction GaAs solar cell and polychromatic laser setup and how the lunar operation architecture can be enhanced using polychromatic LWPT method.

Keywords: wireless power transfer, laser power transfer

Acronyms/Abbreviations

Electromagnetic (EM)
Laser Wireless Power Transfer (LWPT)
Wireless Power Transfer (WPT)

1. Introduction

There are a few different methods proposed for wireless power transfer (WPT). Each of the proposed methods currently being actively researched have varying hardware requirements, resulting in different impacts on the lunar operation architecture [1]. The power transmitters and receivers, based on their performance limitations, play a defining role on how the lunar surface operations will be conducted to include the power distribution system for the moon [2-4]. Therefore, if the required specialized equipment can be reduced, it will have a significant impact on the overall operation architecture [5]. In addition, the power transfer efficiency will also play a substantial element in reducing the required resources.

Theoretically, the entire electromagnetic (EM) spectrum may be utilized to accomplish wireless power transfer, but two regions of the EM spectrum for experimentation have dominated research in the last few decades: microwaves and visible light/near IR. Microwaves are useful because of their ability to penetrate the Earth's atmosphere with minimal attenuation. Microwaves have several disadvantages [6-8], though, including the need for a large, dedicated receiver. On the other hand, visible/near IR wavelengths are useful in space because of the ability to use photovoltaic cells as a receiver, thereby allowing systems to harvest energy from both the Sun and WPT systems. In the vacuum environment of space or the Moon, laser wireless power transfer (LWPT) has the potential to beam power to satellites and systems. LWPT could result in a significant cost reduction by reducing the need for batteries and providing a constant and reliable source of energy on the Moon [9].

Modern solar cell technology uses multiple junctions to more efficiently use the entire solar spectrum, in order to harvest photons of different wavelengths within the solar spectrum. Ideally, each junction will be activated by part of the spectrum to generate electricity, so more junctions means more power. Due to the limitation of manufacturing, most multi-junction solar cells are limited to three layers. Within each layer, materials of different bandgap energies are used in order to react to photons of different energy. For a multi-junction cell, wavelengths of green, red, and IR will activate each layer, thereby increasing the voltage and power generated by the solar cell. Figure 1 displays the interaction of the wavelength energy to the junction of the solar cell.

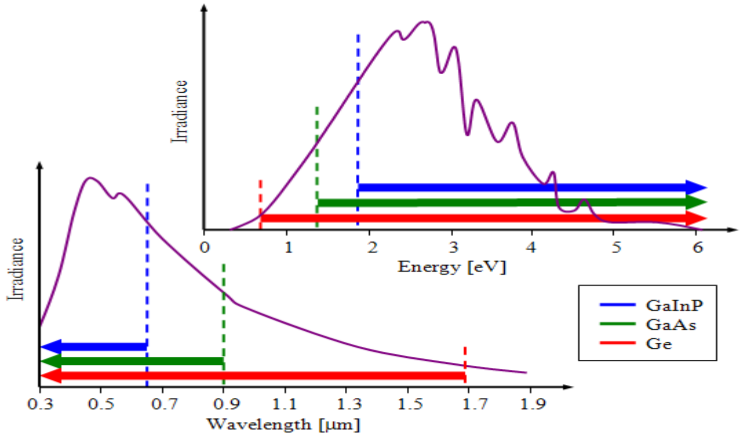

Fig. 1. Solar Spectrum reactance with the triple junction solar cell (colors arbitrarily assigned) [10]

Based on Van Dyke’s simulations, a triple junction cell of InGaP/GaAs/Ge reacts best to wavelengths of 555 nm, 860 nm, and 1510 nm, respectively [11]. Based on PV theory, the top layer has the highest band gap energy, thus producing the most voltage but the least amount of current for a given input level. In order to optimize the power generated, the ratios of the input wavelengths are 50% for green, 40% for red, and 10% for the IR wavelength. Thus, the consumption of power at the laser transmitter will be different for each wavelength, netting a power transmission savings since not all lasers need to transmit the same level of power. The drive of this research is to match the incoming spectrum to this solar cell activation energy. This matching means more efficient power generation due to a proper energy photon activating each layer. He predicts over 51% efficiency to be achievable [11]

While not tested as part of this experiment, another expected benefit of spectrum matching to the solar cell will be a decrease in operating temperature, since only optimal photons will interact with the cell. Photons of higher than needed energy can create electricity but the excess energy is converted to heat. By matching the energy input to the activation energy, less heat will be generated. A cooler cell means a more efficient cell. Future research will investigate this potential benefit.

2. Experiment Setup

A sun simulator powered by LEDs was used to conduct the experiment. This simulator uses LEDs at various spectrum ranges. These LEDs can be toggled on or off, and the power levels can also be varied. Figure 2 shows the general setup, and an example of the LED power output control is also shown in the Figure. Figure 2 also shows an example of a full AM0 spectrum output, as can be seen in the spectrum output on the monitor. The output from the solar cell “target” was measured by measuring the load resistance, voltage generated, and current generated by the solar cell. A triple-junction solar cell (SpectroLab’s UTJ) was placed at 7 cm distance from the light source where the illumination was deemed optimum by the manufacturer of the solar simulator, as shown in Fig. 3. The UTJ cell used in this experiment has approximately 8 cm x 4 cm in size. One issue with the setup was that the area of the solar cell that receives the full input spectrum is limited to the center of the cell. Figure 2 shows this clearly where only the center portion of the target area is properly illuminated by the full input spectrum. To promote a complete illumination of lights from all input spectrum over the entire test area, a screen with a 3 cm x 1 cm slit was placed over the solar cell, as shown in Fig. 4. This ensures that the entire illuminated area is receiving the same amount of light in the desired spectrums.

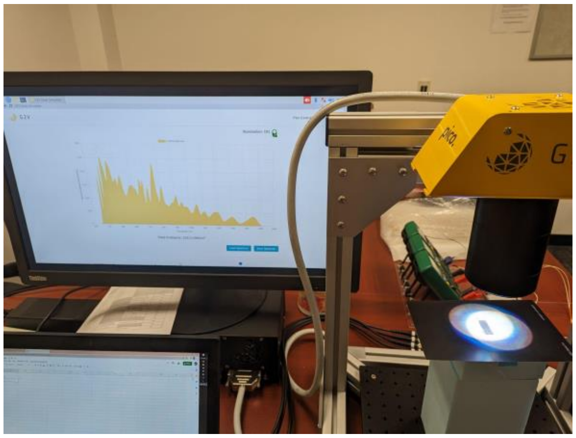

Fig. 2. Depiction of experiment setup using the Pico sun simulator

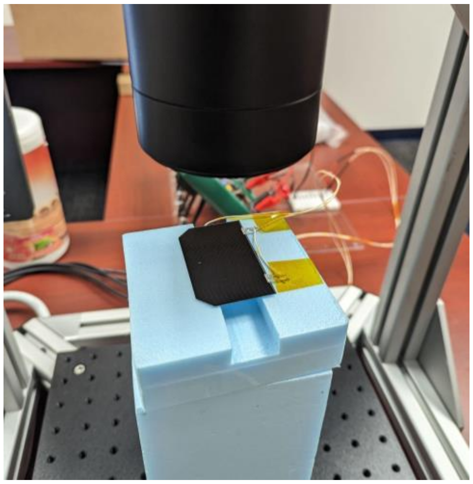

Fig. 3. Close up of the exposed “target” UTJ solar cell

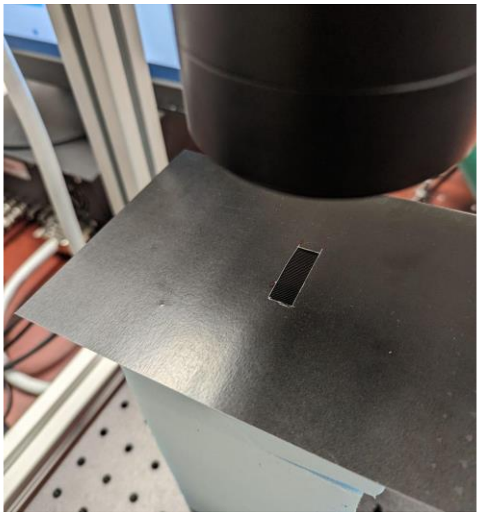

Fig. 4. To ensure illumination area is constant, a screen was placed over solar cell target

3. Results and Discussion

For the initial calibration, a full AM0 light was applied. The load was varied from 0 (closed circuit) to infinity (open circuit) in order to first characterize the solar cell in overall efficiency and peak power point. I-V curve for the full sunlight case is shown in Fig. 5. The peak power occurred with an approximately 50 Ohm load and the peak efficiency was measured at 27%. This corresponds very closely to the manufacturer's established efficiency value of 28%.

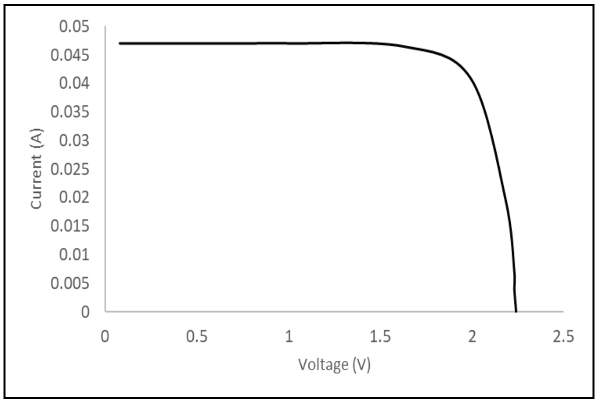

Fig. 5. I-V curve of the experimental setup under full solar spectrum

As previously mentioned, the three optimal wavelengths that result in maximum energy absorption for each of the triple-junction solar cell layer are 555 nm, 860 nm, and 1510 nm. The setup for the experiment utilizes LED lights and not laser lights, and thus emits light in a range of wavelengths. The three ranges used were 506 nm to 538 nm, 814 nm to 873 nm, and 1403 nm to 1556 nm. The output power of each LED can be varied from 0 to 2380 power units (internal setting). The light power output is summarized in Table 1.

Table 1. LED light power output summary for each experiment

Incident Light Configuration	506 – 538 nm	814 – 873 nm	1403 – 1556 nm	Resulting power density
3 wavelengths, equal power	2380	2380	2380	9.9 mW/cm^2
3 wavelengths, Proportional power	2380 (50%)	1905 (40%)	476 (10%)	7.3 mW/cm^2

The first experiment was performed where all three LEDs were outputting maximum power, a setting of 2380. This was the baseline for observing how much improvement in efficiency can be gained by going from the full AM0 spectrum to only the three optimal spectrum ranges. The corresponding spectrum output is shown in Fig. 6. The resulting total power output was 9.9 mW/cm^2.

While this increases the solar cell power generation efficiency, it is not the optimal performance regime. In order for each layer to perform at its peak efficiency, each layer must be activated to produce the same amount of current such that no single layer is "choking" the others and thus decreasing the efficiency. The theoretical power input value for this is approximately 50/40/10% for each of the top/middle/bottom layers of the triple junction solar cell, illustrated in Figure 7. This approximate percentage split was used as the LED lights themselves cannot produce a single-frequency light and thus cannot deliver an exact amount of power at the optimal frequency. The uncertainty from the LED light source is deemed to be greater than a few % difference in the optimal input power ratio. Accordingly, each LED output power was set to the corresponding values to represent the 50/40/10% split. The total resulting power was 7.3 mW/cm^2.

The resulting solar cell efficiencies are tabulated in Table 2. As can be seen, there was a slight increase in solar cell efficiency when the source light was changed from the full sun-light spectrum to the three optimal wavelength ranges. When the three light sources corresponding to the optimal wavelength ranges were modulated to match the optimal power distribution, a significant increase in solar cell efficiency was noted.

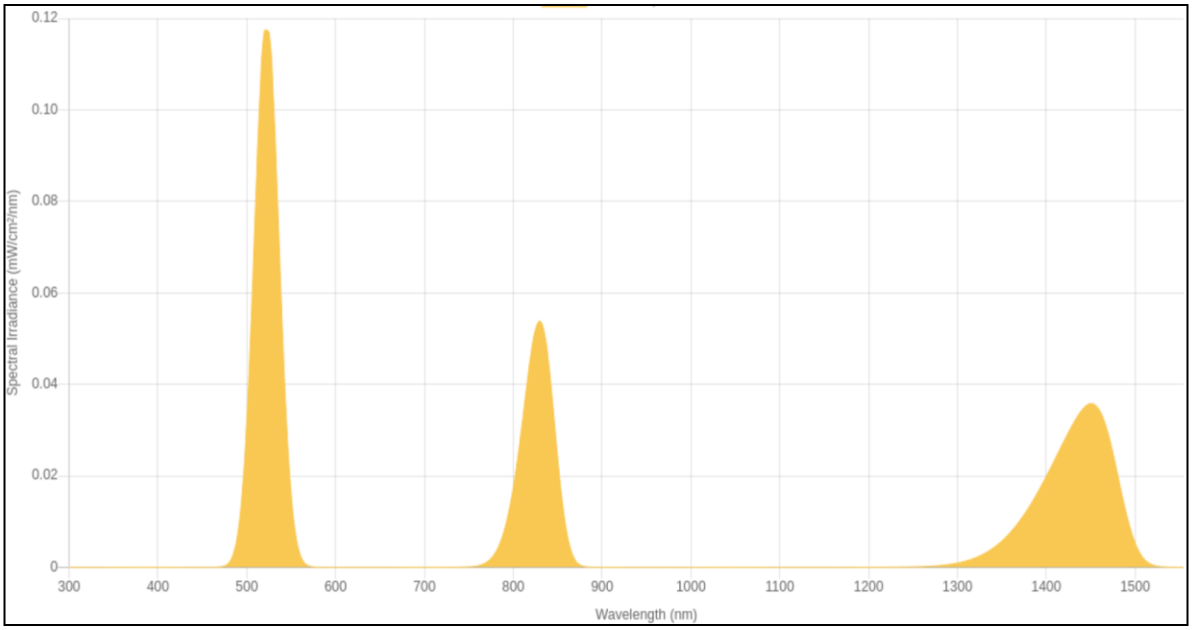

Fig. 6. Spectrum power output where all three LEDs were at their maximum (and equal) output

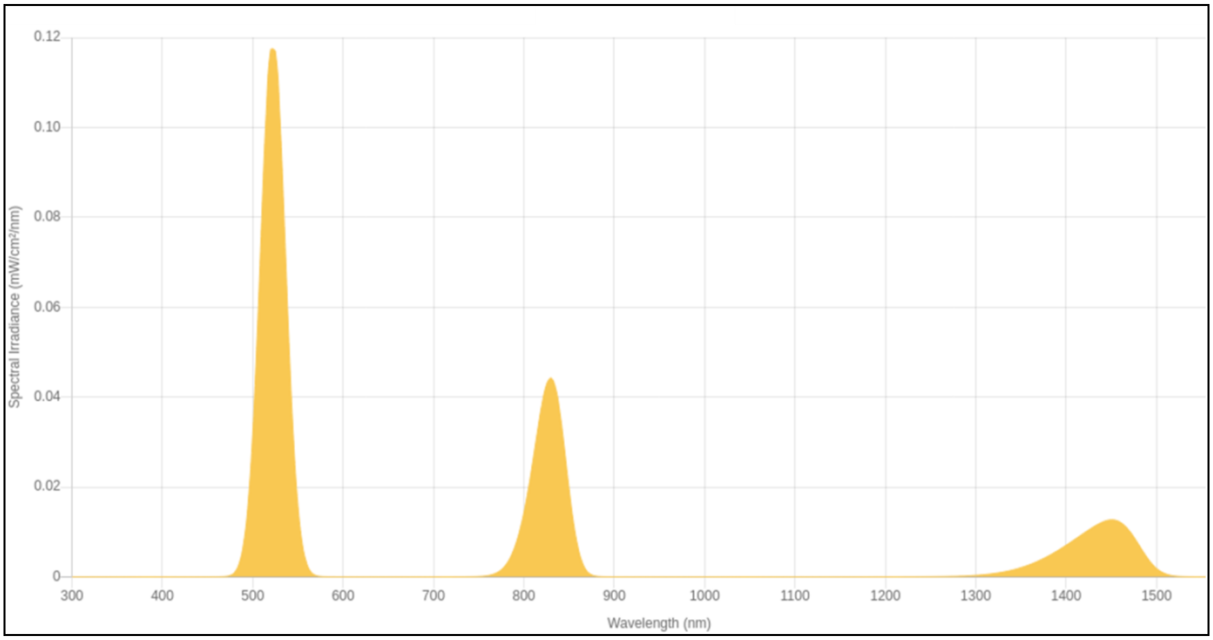

Fig. 7. Spectrum power output where the three LEDs were set to 50/40/10% power output

Table 2. Solar cell efficiency result.

	AM0	3 wavelengths / equal power	3 wavelengths / proportional power
Efficiency (%)	26	27	31

A much higher efficiency was expected for the optimal power distribution experiment, however. There are two factors causing the experiment result to show a much lower efficiency. The first is that the power source is still not optimized to the ideal wavelengths. As LEDs output a range of wavelengths, not all of the power can be concentrated on the peak power wavelength, thus decreasing the overall performance. A second reason is the low power delivery. As the peak output power of the LEDs in this experiment were limited to a low level, each layer of the solar cell may not be properly activated, resulting in choking of the current flow. The result does show a notable improvement in solar cell efficiency and hints at a significant improvement in power delivery with polychromatic lasers set to the optimal wavelengths and powers.

4. Application

Polychromatic lasers set to the optimal wavelengths and power levels have a potential to significantly improve the future wireless power delivery architecture in space. Most space assets are powered by solar power. Accordingly, typical space assets have solar panels for power generation. Therefore, it is hugely beneficial for the wireless power transfer to utilize the existing solar panels on the space assets, instead of requiring a dedicated receiver for the wireless power beaming (microwave power receiver, for example). In this scenario, the space assets with the solar panels can operate normally using their own solar arrays, and when needed, the same solar arrays can be used to receive power from the power beaming source using polychromatic lasers. In theory, these solar panel can convert the received power at over 50% efficiency using the typical triple-junction solar cells, increasing the overall power transfer efficiency between the source and the receiving space assets. Existing space assets can benefit by receiving power beaming without any modification and the future space assets can be made much lighter and smaller by not requiring a separate WPT receiver. Example applications may include satellites that require a continued, full-power operation in eclipse where the power can be delivered to it from either terrestrial or spaceborne sources. Rovers with solar panels on the Moon can operate both on the sun-lit side, as well as on the dark side using the same solar panels.

An additional benefit to using polychromatic laser for WPT is the ability to keep the solar panels at a lower temperature, further increasing the power conversion efficiency. As the sunlight powers solar panels, the energy belonging to the spectrum ranges not absorbed by the solar cells is converted into heat. This heats up the solar panels, further reducing the power conversion efficiency. In the case of the polychromatic laser set to the optimal wavelengths and power level ratio, most of the energy arriving at the solar panel is absorbed and converted into electrical current. This means that the heating of the solar panels can be minimized, resulting in further increasing the efficiency and thus WPT performance. When all these benefits are added together, polychromatic laser wireless power transfer has the potential to greatly benefit the operations of future space assets.

5. Conclusion

As part of the exploration of the moon and beyond becomes reality, the practical distribution of power for space systems can be best served by wireless power transfer. Whether power will be generated using a central power station or beamed from orbit, the ability to distribute the power to where it is needed will have to be critical design for any lunar base. Using a WPT is a logical means to reduce the need to transport materials to the moon.

Using a solar power generation system can take advantage of the sun when visible, supported by a laser power transfer system while in shadow or eclipse. LWPT means that specialized receivers are not needed as compared to microwave technology. By matching wavelength to solar cell band gap energy, a reduction in thermal energy will result in operating at a more optimal temperature. The increase in power received along with the optimal temperature range will maximize the power transferred.

Based on previous work, this paper shows that appropriate wavelength lasers can actually improve the efficiency of a multi-junction solar cell to 31%. This improvement is 20% more than the power generated by the solar spectrum. While still short of the theoretical simulated efficiency of 51%, this practical experiment shows improvements are being made. The next step is to push the limit of the efficiency by using high power lasers to broach the theoretical limit, showing the practicality of a multi-laser power transfer system for lunar power distribution.

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