Optical Waveguide System for Solar Power Applications in Space

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ABSTRACT

In this paper we will discuss an innovative optical system for solar power applications in space. In this system solar radiation is collected by the concentrator array which transfers the concentrated solar radiation to the optical waveguide (OW) transmission line made of low loss optical fibers. The OW transmission line directs the solar radiation to the place of solar power utilization such as: the thermochemical receiver for processing of lunar regolith for oxygen production; or the plant growth facility where the solar light is used for biomass production.

Keywords: Solar Thermo-Chemical Material Processing, Solar Plant Lighting, Lunar Regolith

1. INTRODUCTION

Using native lunar materials for production of propellant, construction blocks or other building materials is attractive because it can significantly reduce the cost for exploring and living on the Moon. For in-situ resource utilization (ISRU) on the moon, solar power is a readily available heat source. For this reason, the solar furnace for materials processing has been widely studied in the past. For most of the past solar furnace experiments, high intensity solar radiation, concentrated by parabolic reflectors, was applied to the materials in the furnace directly or through a window. In such an arrangement it was often difficult to achieve ideal heating of the raw materials because solar power is concentrated in a high temperature spot which can cause uneven heating and vaporization of some material components [1,2]. Because of these difficulties in controlling the process environment, some processing cycles must employ electric heating at the expense of significant power inefficiency. In order to realize viable in-situ resource utilization, we need an innovative solar thermal system which can effectively supply solar thermal power to material processing plants on the moon.

Sustaining long duration space travel or extended stay in planetary colonies will ultimately require plant (crop) production systems to provide food and bioregenerative life support. Plants would also be useful for transit missions, where a relatively small crop growing system could provide fresh vegetables and fruits to supplement the crew’s diet and provide a source of bio-available nutrients, which may be an important counter measure to radiation exposure [3]. Lighting is one of the most critical enabling technologies for plant production in human planetary missions, and provision of power and cooling for plant lighting can contribute more than 50% of the equivalent system mass (ESM) for a bioregenerative life support system using traditional electrical lighting approaches [4, 5]. To date, electrical lighting has been used for most of the enclosed plant chamber studies for bioregenerative research to provide uniform environments for comparative crop testing [6]. However, the low efficiency and high heat generation of electric lighting add thermal control challenges and make these systems inefficient and massive. For plant growth to play an important role in the human exploration of space, we need an innovative concept that will make the plant lighting system efficient, compact and lightweight.

In this paper we will discuss development of the optical waveguide solar power system for thermochemical material processing and plant lighting in space. Specific applications we will discuss are: (1) thermochemical processing of lunar regolith for oxygen production; and (2) solar lighting for plant production in space.

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2. OPTICAL WAVEGUIDE SOLAR THERMAL SYSTEM FOR MATERIAL PROCESSING

Schematic representation of the solar thermal system for material processing is given in Figure 1. In this system, solar radiation is collected by the concentrator array which transfers the concentrated solar radiation to the optical waveguide (OW) transmission line made of low loss optical fibers. The OW transmission line directs the solar radiation to the thermal receiver for thermochemical processing of lunar regolith for oxygen production on the lunar surface. Key features of the proposed system are:

1. Highly concentrated solar radiation (~ 4 ×10³) can be transmitted via the flexible OW transmission line directly to the thermal receiver for oxygen production from lunar regolith;
2. Power scale-up of the system can be achieved by incremental increase of the number of concentrator units;
3. The system can be autonomous, stationary or mobile, and easily transported and deployed on the lunar surface; and
4. The system can be applied to a variety of oxygen production processes.

Figure 1. Solar thermal system for oxygen production from lunar regolith.

The OW solar thermal system was originally developed for lunar materials processing with NASA/JSC funding support from 1994 to 1996 [7, 8]. Figure 2 shows the photo of the ground test model developed in this program. The system consists of three major components: the concentrator, the solar power transmission line, and the thermal reactor. The concentrator consists of multiple-facet parabolic concentrators with nonimaging secondary concentrators attached to optical fiber cables. Four parabolic aluminum concentrators (50 cm) were machined by a diamond tool to an accuracy of 17 nm. The optical waveguide cables are composed of step-index, multimode fused silica-core optical fibers.

Figure 2. The ground test model of the OW solar thermal power system.
The OW solar thermal system shown in Fig. 2 was used for hydrogen reduction of lunar regolith during 1996. In this program, hydrogen reduction of JSC-1 was demonstrated at 832°C. A summary report on the oxygen production process is given in the final report of the program [7], and in a recent conference paper [9]. A more complete analysis of the experiment is given in a recent publication [10].

### 2.1 Component Improvement

Since we demonstrated the first oxygen production feasibility in 1996, we made an effort to improve the OW technology by improving each component of the system. Among the system components, we focused our attention on the following key components: (i) secondary concentrator; and (ii) receiver interface with oxygen production process. The reason for choosing the secondary concentrator and the receiver interface with the thermochemical process as key components is that the operation requirements for these components will dictate the system configuration for the lunar-based oxygen production plant.

The secondary concentrator attached to the inlet of the optical fiber cable acts as the funnel to inject the concentrated solar radiation into the optical fiber cable. It plays two roles: (i) further concentrates the solar radiation collected by the primary dish concentrator; and (ii) injects the focused solar radiation into individual optical fibers with minimal loss. In previous programs PSI used the quartz secondary concentrator in which the solar ray from the primary concentrator is further concentrated by the conical quartz secondary concentrator. In the present program we developed and tested a precision machined reflective matrix secondary concentrator in which a matrix of miniature reflective non-imaging concentrators injects the solar flux into individual optical fibers.

We prepared a test optical fiber cable with the reflective matrix secondary concentrator and tested it with the PSI 20-inch concentrator. An overall transmission efficiency of 69% was measured. In our previous tests conducted with conical quartz secondary concentrator, transmission efficiency was in the range 45–50%. By developing the new reflective matrix secondary concentrator, we have improved the transmission efficiency by 20%.

Based on the results we obtained in recent programs, we can make a realistic prediction for the improvement of the component technology in the future. Table 1 lists a summary of the component efficiencies in our previous programs, those achieved in the recent program [11] and those expected in the future. The method of how we achieve the projected improvement is also given in the table.

<table>
<thead>
<tr>
<th>Component</th>
<th>1996-2005</th>
<th>May 2007</th>
<th>Space-Based Operational System</th>
<th>Improvement Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concentrator</strong></td>
<td>0.722</td>
<td>0.858</td>
<td>0.936</td>
<td></td>
</tr>
<tr>
<td>Reflectivity</td>
<td>0.82</td>
<td>0.975*</td>
<td>0.975**</td>
<td>• Apply protected silver coating.</td>
</tr>
<tr>
<td>Intercept factor</td>
<td>0.88</td>
<td>0.88</td>
<td>0.96</td>
<td>• Use high slope accuracy reflector. Absence of atmospheric scattering helps.</td>
</tr>
<tr>
<td><strong>Optical Fiber Cable</strong></td>
<td>0.52</td>
<td>0.691</td>
<td>0.812</td>
<td></td>
</tr>
<tr>
<td>Front Fresnel refl.</td>
<td>0.965</td>
<td>0.965</td>
<td>0.983</td>
<td>• AR coating (400–850 nm)</td>
</tr>
<tr>
<td>Fiber fill factor</td>
<td>0.734</td>
<td>1.0</td>
<td>1.0</td>
<td>• Already accomplished</td>
</tr>
<tr>
<td>Integral fiber trans.</td>
<td>0.77</td>
<td>0.742</td>
<td>0.84</td>
<td>• Improve inlet optics and use high purity fibers</td>
</tr>
<tr>
<td>Back Fresnel refl.</td>
<td>0.965</td>
<td>0.965</td>
<td>0.983</td>
<td>• AR Coating (400–850 nm)</td>
</tr>
<tr>
<td><strong>System Efficiency</strong></td>
<td>0.38</td>
<td>0.592</td>
<td>0.760</td>
<td></td>
</tr>
</tbody>
</table>

* Coating the protected silver on the existing PSI concentrator surface is assumed.
** Reflectivity of the Cassegrain concentrator will be $0.975 \times 0.975 = 0.950$, as it involves the second reflector. In this case, the concentrator efficiency will become 0.9126.
2.2 Regolith Melting Capability

A series of solar powered JSC-1 melting experiments was conducted in 2007. Figure 3 shows two PSI solar concentrators melting JSC-1. The non-imaging optics arrangement is shown in Fig. 4. Figure 5 shows three quartz rods focusing solar radiation on the JSC-1 surface. The JSC-1 melt zone is visible in the figure. In these regolith melting experiments, the temperature of the melt was measured by Type-C (W5%Re–W26%Re) thermocouples. Figure 6 shows the vitrified JSC-1 after the experiments.

Figure 3. Two PSI solar concentrators for melting JSC-1.

Figure 4. Two non-imaging optics focusing solar power on the JSC-1 surface.

Figure 5. Three quartz rods focusing solar power on the JSC-1.
In Fig. 7 we plot the melt surface temperature we measured. It is shown that we have achieved 1800 °C, the temperature necessary for the Carbothermal process. Note that these temperature readings (except for the lowest temperature: 1368 °C) were taken without the radiation shield. With the radiation shield, the melt zone becomes thermally more homogeneous and creates a larger melt. It is important to note that Fig. 7 conclusively demonstrated the capability of the OW solar thermal system to melt the lunar regolith at temperatures necessary for the carbothermal reduction process which requires a very high temperature.

2.3 Current Program

During the past two years, PSI has developed a first generation ground-based demonstration model of the solar thermal system for oxygen production from lunar regolith [12]. The ground-based demonstration unit is shown in Figure 8. The system consists of:

1. A single solar concentrator array equipped with seven 27-inch concentrators and a solar tracking system;
2. Optical fiber cable which transmits the solar radiation (PAR) from the concentrator array to the oxygen production reactor; and
3. Reactor interface optics to inject the high concentration solar radiation into the oxygen reactor.

The solar thermal system was designed, manufactured, integrated and tested at PSI. All components functioned as planned. Based on the test results, it is projected that the solar thermal system will deliver to the carbothermal reactor 700 ~ 900W of solar power, depending on the solar flux intensity at the test site. The measurement made at PSI during a cloudy day with low solar flux (direct flux ~800W/m²) yielded 700 W. At a typical solar flux at San Ramon, CA (direct flux ~880W/m²), output will be about 800W. At a high altitude location close to the equator, the direct solar flux intensity will be ~1000W/m². In this case the power output from the system will be 900W.
The flux intensity created by the quartz rod was measured for the low solar flux (direct flux \( \sim 800 \text{W/m}^2 \)). The intensity was 137 W/cm\(^2\) averaged over the 1 cm diameter on the plane perpendicular to the rod axis. The plane is 4 cm away from the rod tip. For a typical solar flux at northern California (direct flux \( \sim 880 \text{W/m}^2 \)), the flux intensity will be 150W/cm\(^2\). This flux intensity will be sufficient to heat the regolith surface to 1800°C.

At the writing of this paper, the ground-based demonstration system is being tested. After the initial testing, the system will be tested at a test site for lunar ISRU program later part of 2009 through 2010.

**3. OPTICAL WAVEGUIDE SOLAR PLANT LIGHTING SYSTEM**

A schematic representation of the solar plant lighting system is given in Fig. 9. In this system, solar light is collected by reflector optics and focused at the end of an optical waveguide cable. The light is filtered by the selective beam splitter to reject non-plant growing spectra (\( \lambda < 400 \text{ nm} \) and \( \lambda > 700 \text{ nm} \)) from the light path to minimize the introduction of heat into the plant growth chamber. The photosynthetically active radiation (PAR) spectra (400 nm < \( \lambda < 700 \text{ nm} \)) are transmitted to the plant growth chamber where the light is distributed uniformly over the plant growth area. The rejected non-PAR solar spectra can be converted to electric power by low band-gap PV cells. The electric power generated in this manner can be stored and used for system operation.

![Schematic of the optical waveguide solar plant lighting system](image)
To evaluate the effectiveness of the system concept described in Fig. 9, we developed a laboratory model system consisting of: 1) the solar concentrator; 2) the optical waveguide cable; and 3) the lighting panel [13].

3.1 Laboratory Model Testing

The laboratory model consisting of the solar concentrator, optical fiber cable and the lighting chamber is shown in Fig. 10. One concentrator of the PSI system was connected to the lighting chamber via an optical fiber cable consisting of 37 fibers (36 fibers connected to the illuminator panel with one fiber for diagnostic measurement). The lighting panel with four reflector troughs was at the top of the chamber. The lighting chamber walls consisted of an acrylic mirror to maximize reflection of the photons delivered inside of the chamber. For the solar lighting experiment, one concentrator in the PSI solar power system delivered about 60 W (equivalent to 124 µmol s⁻¹ of PPF) to the lighting chamber. With an area inside lighting box of 0.145 m², we expected a photosynthetic photon flux (PPF) of 640 µmol m⁻² s⁻¹ assuming the chamber lighting efficiency to be 75%.

![Figure 10. The laboratory model consisting of the solar concentrator, the optical fiber cable and the lighting chamber.](image1)

A photograph of the trough lighting panel inside of the lighting chamber is shown in Fig. 11. Light delivered by the optical fiber using the indirect (side) ports was scattered by the diffuse reflective surface of the troughs before illuminating the lighting chamber.

![Figure 11. The trough illuminating panel for indirect light delivery.](image2)
Photosynthetic Photon Flux (PPF)

We conducted solar lighting tests with fibers from the concentrator were inserted into the plant illuminator panel. Thus, fibers were integrated with the illuminator panel sideways. The solar power transmitted to the lighting chamber was about 60W including the non-PAR spectral component. We also added another configuration in which an additional 36 fibers were inserted into the panel.

PPF was measured with the LI-COR Quantum Sensor. The uniformity and the flux intensity of the PPF in the lighting chamber are compatible with plant lighting requirements. Solar lighting levels of 800–1500 µmol m-2 s-1 were measured in the lighting chamber. The lighting efficiency, i.e., the efficiency of photon delivery in the lighting chamber, was 75 ~ 85% for the “indirect” lighting whereby the light delivered by the optical fibers was reflected by the diffuse reflective illuminator panel. Efficiencies higher than 95% were observed for the “direct” fiber lighting. For direct lighting, the light from the optical fibers illuminates the chamber without going through diffuse reflection. Having designed and tested illumination devices, we have developed a technology basis of how to improve uniformity and efficiency.

Lighting Spectra

We measured the lighting spectra using the LI-COR spectral radiometer. Our first test was to see if there is a significant difference between the spectra in the lighting chamber and those of the direct sun. There was no major difference in the PAR range between the two sets of spectra except for a slight difference at 475–550nm, due to attenuation of the fused silica optical fiber.

The solar spectra with and without the spectral rejection filters were studied. Figure 12 shows the solar spectra and the PAR spectra. The blue line indicates the PAR spectra delivered into the plant growth chamber. The red line shows the solar spectra not admitted into the plant growth chamber. This shows that it is possible to reduce thermal input to the plant lighting chamber.

![Figure 12. PAR spectra (blue line) introduced in the plant growth chamber.](image)

3.2 Current Program

During the last two years, PSI has developed an engineering prototype of the solar plant lighting system for NASA/KSC [14]. Figure 13 shows the photos of the solar plant lighting system.
The system shown in Figure 13 consists of:

1. Two units of solar concentrator array each of which is equipped with three 27 inch concentrators and a solar tracking system;
2. Optics to reject solar spectra that do not contribute to plant growth;
3. Optical fiber cable which transmits the photosynthetically active radiation (PAR) from the concentrator array to the plant growth chamber; and
4. Plant lighting panel to distribute the PAR uniformly over the plant growth area.

The OW solar plant lighting system was designed, manufactured, integrated and tested at PSI. All components functioned as planned. Based on the test results, the solar plant lighting system will deliver to the plant lighting chamber #13 the PPF at 1500 µmole/s. The system efficiency of the present Phase II system is 39%. Higher system efficiency, at about 60%, can be achieved readily using available components.

At the writing of this paper, the solar plant lighting system is installed at NASA/KSC in preparation for long range operations. Several system improvement measures such as corrosion prevention and remote operation capability are being implemented.

4. CONCLUSION

In light of the results reviewed above, we may conclude that the optical waveguide (OW) solar power system is viable and effective solar power system for thermochemical material processing and plant lighting. We conclusively demonstrated that the OW solar thermal system is capable of heating the lunar regolith to the temperatures necessary for thermo-chemical processing of lunar regolith. The regolith stimulant (JSC-1) was heated to 1800–1900°C by the solar thermal power delivered by the PSI concentrator system. The conceptual design work we conducted indicates that the system will be efficient and light-weight when deployed on the lunar surface. To the best of our knowledge there is no basic barrier for successful implementation of the proposed solar thermal technology for oxygen production on the moon.

We have also demonstrated the OW solar power system is viable and effective in application to lighting plant for biomass or crop production. We believe that it is a key enabling technology for regenerative life support for human exploration on long-duration missions. In fact, from the result of the equivalent system mass (ESM) analyses, it is the only realistic system concept by which advanced life support can be implemented for human exploration of space.

For solar thermal application, we have developed a ground-based demonstration system for carbothermal oxygen production from lunar regolith. At the writing of this paper the system is going through initial testing. After the initial testing, the system will be tested at a test site for lunar ISRU program later part of 2009 thorough 2010.

As for plant lighting application, we developed an engineering prototype of the solar plant lighting system and installed the system at NASA/KSC. The system is being prepared for long range operation at the KSC site.
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