Solar Pumped Lasers for Free Space Laser Communication

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Keywords: Solar Pumped Lasers, Multi-Frequency, Free Space Laser Communication.

Abstract: Solar Pumped Lasers (SPL) is a kind of lasers that can transform solar light into laser directly, with the advantages of least energy transform procedure, higher energy transform efficiency, higher reliability, and longer lifetime, which is suitable for use in unattended space system, for solar light is the only form of energy source in space. In order to exploring the possibility of using SPL for free space laser communication, multi-frequency SPL is investigated and solar pumped laser amplification is initiated. The first demonstration of SPL used in free space laser communication is also conducted in our group.

1 INTRODUCTION

Solar pumped laser (SPL) is a special kind of lasers, that can transform broad-band, incoherent solar light into narrow-band, coherent laser directly, with the advantages of least energy transform procedure, higher energy transform efficiency, higher reliability and longer lifetime. It is suitable for application in unattended space system, such as space laser communication, space to earth wireless power transmission and space laser propulsion(Mori et al.,2006; Guan et al.,2017; Oliveira et al.2016; Yabe et al., 2008).

SPL has a comparable long research history as lasers itself. Shortly after lasers was invented in 1960, solar light was considered as the pumping source of solid state lasers, for all solid state lasers were light-pumped and solar light is the mostly common light source we encountered in daily life. SPL was first demonstrated by Z. J. Kiss from RCA Laboratories in 1963(Kiss et al., 1963), a Dy^{2+}: CaF_2 crystal was cooled in liquid nitrogen and pumped by solar light. Shortly thereafter, systems using solar light to pump different kinds of laser mediums were considered. Among various laser mediums (solid, liquid and gaseous), solid state lasers appear to be most competitive because of stable performance, lower pumping threshold, and potential efficient of solar-to-laser power conversion. The first Solar-pumped solid laser was reported by Young from the American Optical Company in 1966(Young, 1966), 1W of continuous wave laser output was obtained at room temperature via a Nd:YAG crystal. In 1988, Weksler and Shwartz from Weizmann Institute of Science, Israel, through a compound parabolic concentrator (CPC) obtained 60 W CW output power of laser from a Nd:YAG rod with a slope efficiency about 2%(Weksler and Shwartz, 1998) . In 2007, T. Yabe from Tokyo Institute of Technology demonstrated an 18.7 W/m^2 laser output from a Cr^{3+}, Nd^{3+} co-doped YAG ceramic with Fresnel lens as the primary solar light concentrator, corresponding to a total slope efficiency of 2.9%(Yabe et al., 2007). In 2011, Liang from Universidade NOVA de Lisboa, Portugal, 19.3 W/m^2 laser collection efficiency was achieved from a Φ4×25mm Nd:YAG rod, which is pumped by a 0.64 m^2 Fresnel lens(Liang and Almeida, 2011). T. Yabe's group reported a SPL with 120 watts CW output in 2012(Dinh et al., 2012). They used a 4 m^2 Fresnel lens as first solar energy collector and a Φ6mm Nd:YAG rod, the collection efficiency was 30W/m^2. For further thermal management, grooved Nd:YAG laser rod was firstly used in SPL in 2014(Xu et al., 2014). Zhao´s group from Beijing Institute of Technology achieved 27 W laser power by utilizing a Φ6×95mm Nd:YAG grooved rod pumped by a 1.03 m^2 Fresnel lens, corresponding to a slope efficiency of 9.0%. The grooved Nd:YAG rod offered better heat dissipation and reduced the thermal lens effect, compared with that of unpolished rod, leading to a superior efficiency and beam quality. In 2017, D. Liang and J. Almeida used the heliostat-parabolic mirror system to pump a Nd:YAG rod and obtained a collection efficiency of 31.5 W/m^2(Liang et al., 2017). The highest collection efficiency of 32.1W/m^2, for the time being, was achieved by Beijing Institute of Technology, using a

Zhao, C., Zhang, H., Guan, Z., Cai, Z., He, D. and Wang, Y.
Solar Pumped Lasers for Free Space Laser Communication.
DOI: 10.5220/0007569702680275
In *Proceedings of the 7th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2019)*, pages 268-275
ISBN: 978-989-758-364-3

grooved and bonding Nd:YAG/YAG crystal rod and a Fresnel lens as the primary concentrator(Guan and Zhao, 2018).

The technology maturity and efficiency of SPL has arrived at a stage for application in a suitable situation. And free space laser communication is probably the best chance for SPL to be used, for solar light is the only form of energy source in space. 1064nm wavelength laser has become one of a major wavelength for laser communication. In 2007, Germany launched TerraSA R-X satellite for scientific and commercial purposes, where laser communication terminal were used for inter-satellite laser communication with a laser band of 1064nm(Liu, 2007.). Switzerland Contraves Space Centre designed OPTEL high-performance laser communication terminal series with 1064nm wavelength, which use 808nm laser diode as the pump source and Nd:YAG as the gain medium(Baister et al.). Therefore we consider using Nd:YAG crystal and its 1064nm wavelength as our selection.

In order to increase the data rate of laser communication system, multi-wavelength or multi-frequency operation of the lasers is demanded, completed by the technology of wavelength division multiplexing(WDM). The possibility of multi-wavelength and multi-frequency operation for solar pumped both Nd:YAG lasers and amplifier are investigated in the paper. One to three-frequency operation of solar pumped Nd:YAG laser is realised in experiment. A new bonding Nd:YAG slab amplifier is designed and initial experiment is performed. Based on the solar pumped Nd:YAG lasers, the first solar pumped free space laser communication system is demonstrated.

2 SOLAR PUMPED MULTI-LONGITUDINAL MODE LASERS

In free space laser communication systems, the total data rate is equal to the data rate of one frequency channel multiply the number of frequency channels. Data rate is improved either by increase the date rate of single frequency channel or by increase the number of frequency channels. To increase the number of frequency channel have two methods, the first one is to oscillate simultaneously more wavelengths in a certain laser medium, and the second one is to oscillate simultaneously more longitudinal modes within a single emitting wavelength, while keeping the frequency separation suitable for frequency discrimination.

For the mostly used laser medium Nd:YAG, there are several emitting wavelengths around 1064nm, and their emitting cross section are comparable with its of 1064nm, means the possibility of lasing separately under certain conditions, such as the wavelength of 1052nm, 1062nm, 1065nm, and 1074nm.

For a particular wavelength, such as 1064nm, its linewidth of florescence (0.45nm) will allow multi-longitudinal mode oscillating simultaneously, with each longitudinal mode represents a frequency channel. Indeed, Nd:YAG laser is usually oscillating in multi-longitudinal mode without mode selecting design. But, the multi-longitudinal mode output here means to get the demanded number of longitudinal mode output from a specially designed laser.

2.1 Design and Experimental Setup

Nd:YAG crystal is a four-level system, the most important wavelength of 1064nm at room temperature is generated by the two-level transition, $^4F_{3/2}\rightarrow{}^4F_{11/2}$, and the average fluorescence linewidth of the transition is 120GHz. The broadening of the spectrum of solid laser gain medium is mainly due to uniform widening caused by lattice thermal motion and no-uniform widening caused by lattice defects. Nd:YAG crystal is of good quality and isotropic, and dominated by uniform widening in the whole temperature range. The uniform broaden line has a Lorentz line shape, the closer to the gain curve centre frequency, the higher gain the longitudinal mode obtained. According to the principle of resonator longitudinal mode selection, the number of the lasing longitudinal mode m is determined by the width of gain curve $\Delta\nu_D$ of the laser medium and the longitudinal mode spacing $\Delta\nu_q$ of the resonator, written as:

$$m = \left(\Delta\nu_D/\Delta\nu_q\right) + 1 \qquad (1)$$

And

$$\Delta\nu_q = c/2nL \qquad (2)$$

Where c is the vacuum speed of light, n is the refractive index of laser medium at certain wavelength, and L is the geometry length of the resonator. From equations (1) and (2), we can calculate the resonator length for a given number of m. In fact, for a small number of m, L is small too, and the laser rod is in fact a disk. For *m=1,2,3*, *L* will be 0.8mm, 1.1mm, and 2.4mm, respectively.

The experimental setup of multi-longitudinal mode laser is shown in fig.1. It is composed of solar light collecting system, the laser medium and the temperature control system. The solar light collecting system consists of focusing lens, coupling lenses, and large aperture fibre. The solar light is focused and coupled into the large aperture fibre firstly, and after transmitted in the fibre, it is coupled into the laser medium by the second coupling optics. The purpose of using fibre as light transmitter is because of its flexibility. The size of the laser medium is Φ6×0.8～2.4mm, with its two surface form the resonator. One surface is coated with AR coating @808nm and HR coating @1064nm, as the pump light entrance, another surface is coated with PR coating @1064nm, as output coupler. The laser medium is temperature controlled by a TEC cooler.

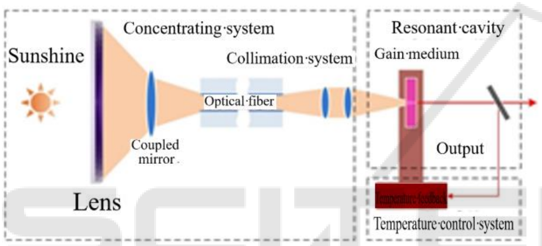

Figure 1: The experiment setup of solar-pumped multi-frequency lasers.

2.2 Experimental Results

Before pumped by solar light, the multi-frequency laser is firstly pumped by an 808nm LD indoors. The output transverse mode is monitored by a laser beam analyser, and the longitudinal mode is monitored by a F-P spectrum analyser. From the measurement result of the laser beam analyser, TEM_{00} output from the multi-frequency lasers is ensured.

The longitudinal mode of output laser for different length of resonation is show in Fig.2, which corresponding to one longitudinal mode, two longitudinal modes and three longitudinal modes, respectively.

For the single longitudinal mode output, the linewidth is measured based on the fibre delayed homodyne beat note method, and result is show as Fig.3. From where, one can see, 16KHz of linewidth is obtained. For the two longitudinal mode output, the spacing of the longitudinal mode is 74.4GHz. For the three longitudinal mode output, the spacing of the longitudinal mode is 34.3GHz. In the experiments of two frequencies and three frequencies, the measured frequency spacing is a little bit smaller than theoretical prediction raising from thermal expansion of the laser medium.

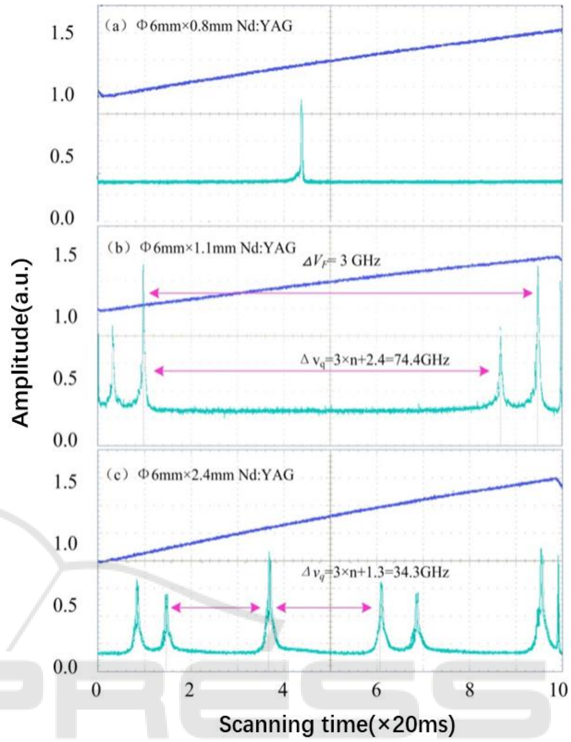

Figure 2: The output longitudinal mode from LD pumped different length of resonator lasers.

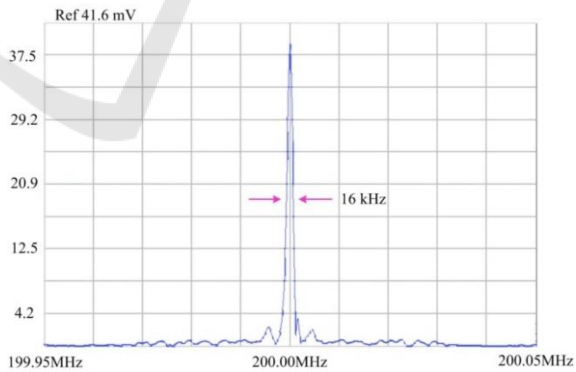

Figure 3: The linewidth of single frequency output based on the measurement method of fibre delayed homodyne beat note.

The output power of LD and thereafter the solid state lasers is adjusted by tuning the pumping electric current of LD. The output power of different resonator length versus the pumping current is show in Fig.4.

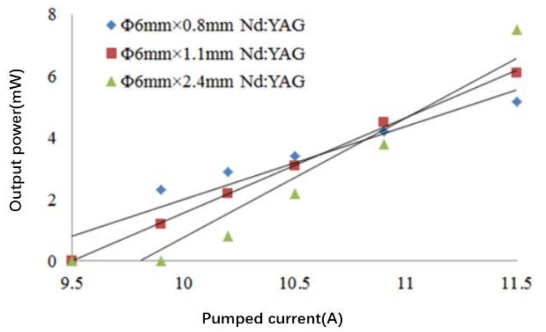

Figure 4: The output power of different resonator length lasers versus pumping current.

After complication of indoors experiment, solar pumped experiment outdoors is performed. The picture of experimental facility is show in Fig. 5.

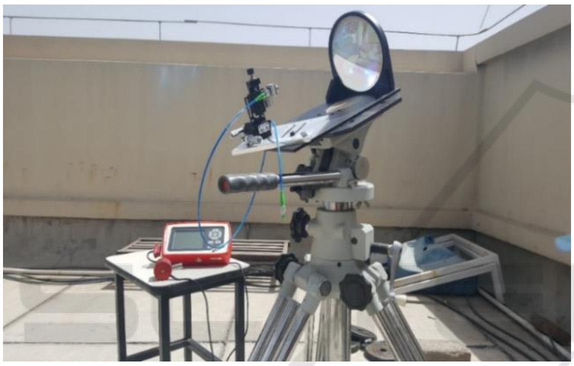

Figure 5: The picture of solar pumped multi-frequency lasers experimental facility.

The experiment is performed in Beijing under clear (with light cloud) weather, with measured solar radiation density of 770W/m^2. The output power of different resonator length lasers versus pumping solar power is show in Fig.6. Under the complexity outdoor environment, SHR wavelength meter (SOLAR LASER SYSTEM Co., ltd) is used to replace the F-P interferometer as the frequency (wavelength) measurement instrument, with the measurement precision of 0.012nm around 1064nm. Fig.6 showed the three wavelength output and the measured data for each wavelength. The output wavelength is 1064.754nm, 1064.877nm and 1065.011nm, respectively, corresponding to frequency of 281414.406GHz, 281449.906GHz and 281482.406GHz. Also, the measured frequency (wavelength) spacing is a little bit different from theoretical prediction, raising from thermal expansion of the laser medium. The output power of each frequency is different, with higher power in the central frequency, for which obtaining higher gain compared with the another two frequencies.

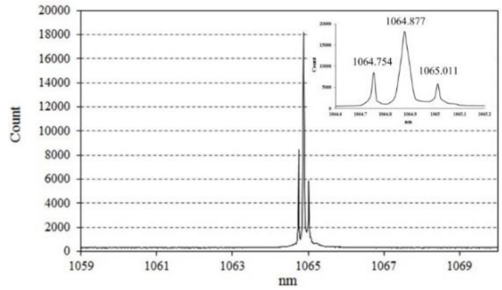

Figure 6: The three wavelength output and measured data for each wavelength.

3 SOLAR PUMPED ND:YAG SLAB AMPLIFIER

Another way to use the solar pumped lasers for free space laser communication is to amplify simultaneously multi-frequency seed lasers by the same solar pumped amplifier. A new bonding slab solar pumped amplifier is designed and initial experiment is performed.

3.1 Design of the Bonded YAG/Nd:YAG/YAG Slab Amplifier

The rod and disk geometry is usually adopted in laser amplifier. For the purpose of solar pump, the matching between focused solar light spot and the laser medium is a new problem. The primary focusing optics used is a larger aperture Fresnel lens, with the size of 1.40m×1.05m and focus length of 1.20m. The measured diameter of focusing spot is 11.2mm, corresponding to the 9.2mrad divergence angel of solar light. The effect area of the Fresnel lens, eliminating shade area of support mechanic is 1.03m^2.Based on above consideration, a new slab crystal amplifier is designed, with the size of 18mm×12mm×5mm. The slab is bonded with YAG/Nd:YAG/YAG to form the sandwich structure, show in Fig.7.

The upper layer is YAG crystal, with thickness of 1mm, the middle layer is Nd:YAG crystal, with thickness of 3mm, and the bottom layer is YAG crystal, with thickness of 1mm. The entrance and exit windows for seed laser are coated with AR coatings@1064nm（T>99.8%）. The seed laser travels in zigzag rout inside the gain medium. The front (except the part of seed laser entrance and exit) and rear surface of the crystal are coated with HR

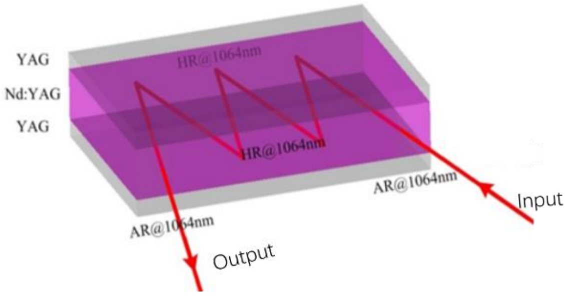

Figure 7: Bonded YAG/Nd:YAG/YAG crystal structure and its coatings at each surfaces.

coating@1064nm. The upper surface of the crystal is coated with AR coating@300-900nm (T>95%), for solar light to irradiate. The bottom surface of the crystal is coated with HR coating@300-900nm (T>95%), for remaining solar light re-absorption. The bonding crystal is favourable for protecting the coatings under high temperature and increase the utilization of pump solar light.

3.2 Initial Experimental Result of the Solar Pumped Laser Amplifier

The experimental setup of the solar pumped laser amplifier is show in Fig.8, which is composed of Fresnel lens, seed laser, bonded slab laser crystal, and temperature control system.

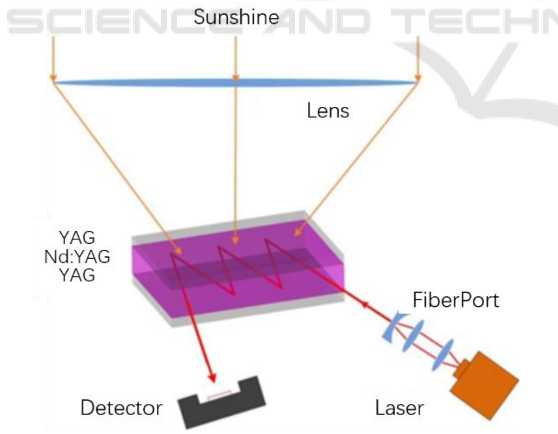

Figure 8: The experimental setup of the solar pumped laser amplifier.

A 1064nm single mode seed fibre laser is firstly aligned through a fibre port and then enter into the laser crystal with a certain angle. After four times of reflection inside the crystal, the amplified laser emitted through the exit.

The beam profile of the seed laser, of the laser after four times of reflection inside the crystal, and of the laser after amplification are show in Fig.9(a), (b), and (c), respectively, showing the beam quality remain the same after amplification.

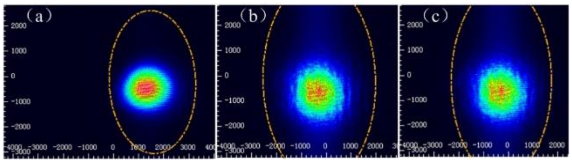

Figure 9: Comparison of the beam profile of the seed laser(a), of the laser after four times of reflection inside the crystal(b), and of the laser after amplification(c).

The gain of solar pumped laser amplifier versus pumping solar power is show in Fig.10. The max gain is 1.25, much lower the theoretical simulation.

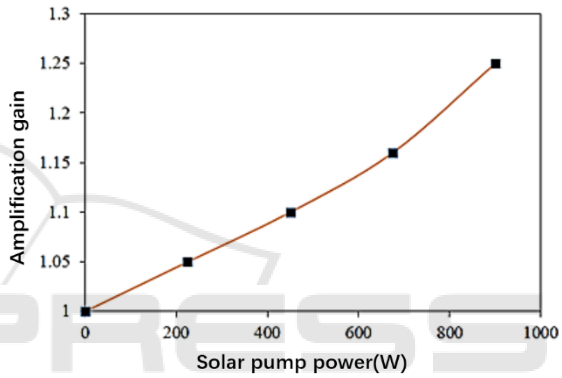

Figure 10: The gain of solar pumped laser amplifier versus pumping solar power.

4 DEMONSTRATION OF FREE SPACE LASER COMMUNICATION USING SOLAR PUMPED LASER

A free space laser communication system with a solar pumped laser as the signal transmitter was demonstrated. A 0.6m × 0.6 m Fresnel lens was used as the primary concentrator to collect the solar light. 6.8 W continuous wave laser power was obtained from a 4 mm diameter grooved Nd:YAG rod. The output intensity was modulated with a video signal via a $LiNbO_3$ Mach–Zehnder optoelectronic modulator. The video signal with a resolution of 1920×1080/frame and the frame rate of 25 Hz was transmitted over five-meter free space in real time with high fidelity. The transmission rate was 125 Mbps and bit error rate was lower than 10^{-6}.

4.1 Experimental Setup of the Free Space Laser Communication System

The free space laser(FSL) communication system was composed of a SPL with fibre coupler, a Mach–Zehnder modulator (MZM), a set of optical transmitting/receiving antennas, an avalanche photo diode (APD), a demodulator and a monitor, as shown in figure 11.

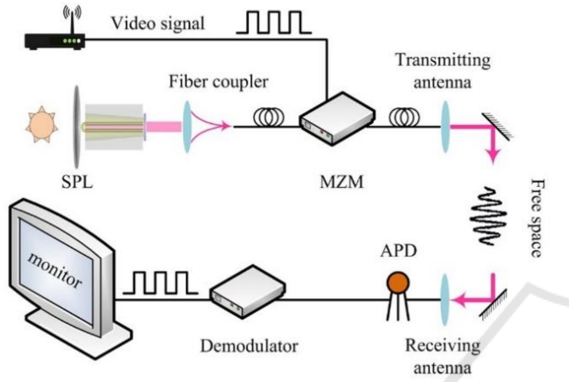

Figure 11: Scheme of the free-space laser communication system. SPL, solar-pumped laser; MZM, Mach–Zehnder modulator; APD, avalanche photo diode.

A more compact SPL was designed to meet the requirements for FSL communication. A 0.6m×0.6 m Fresnel lens which supplied by Shandong Yuying Optical Instrument Co., LTD was used as the primary concentrator. The Fresnel lens was made of Polymethyl Methacrylate (PMMA) material. The focal length of the Fresnel lens was 0.89 m. A conical cavity was used to further concentrate the solar light into the laser rod, a quartz tube filled with cooling water confines the solar light in the crystal. The conical cavity also was cooled by cooling water. The fibre coupling system with a single lens and a multimode fibre was designed. Schematic of the SPL is shown in figure 12.

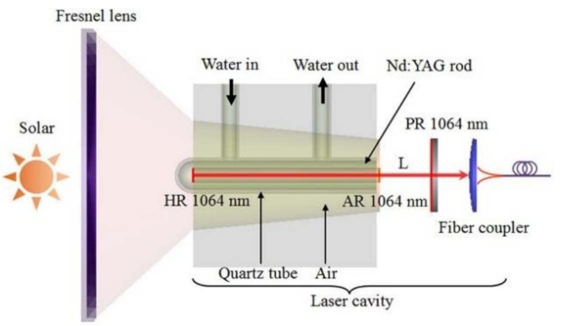

Figure 12: Schematic of the solar pumped laser with Fresnel lens and conical cavity.

The solar light was converged by a Fresnel lens and was focused into the laser head. The input window of the conical cavity was 30mm in diameter and 50mm in length. The inner wall of the cavity was gold plated. The outer diameter of quartz tube was 9mm. These parameters were numerically optimized by TracePro@ software. The grooved rod was cooled by deionized water at 4.5lmin^{-1} flow rate. The focal length of the coupling lens was 100 mm and the diameter of the fibre was 62.5 µm. We use a grooved laser rod for a better heat dissipation effect. The 1.0at% grooved Nd:YAG rod with 4mm diameter, 70mm length, 0.6mm grooved pitch and 0.1mm grooved depth was used.

4.2 Experimental Result of the Free Space Laser Communication System

The solar irradiance in Beijing during the experiment was 930 W/m^2. The Fresnel lens had an effective solar energy collection area of 0.35 m^2. For 326W solar power at the surface of Fresnel lens, output couplers of different reflectivity with same radius of curvature (RoC) of 900 mm were tested individually to maximize the output laser power. Figure 13 shows the results of laser output with respect to various input solar power levels. The maximum output power was 6.8 W corresponding to a slope efficiency of 3.9% when R=97% output coupler was used. The optical-optical efficiency was 2.1%. The maximum output power from the R= 99%, R=95%, and R=97% output coupler were 5.2W, 6.0W, and 6.8W, respectively.

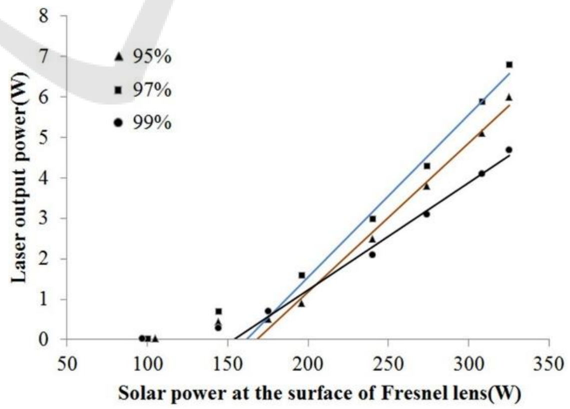

Figure 13: Laser output power versus solar power at the surface of Fresnel lens for three output couplers with different reflectivity.

The video signal from a media player with the resolution of 1920×1080/frame and the frame rate of 25 Hz is transmitted. A $LiNbO_3$ MZM modulates laser intensity with the encoded video signal. The bandwidth of the MZM is 10GHz, and the frequency limit of the video signal carrier is 4 GHz in the experiments. Optical transmitting antenna collimates the output light from the fibre and sends into free space within 40 μrad angle of divergence. Meanwhile, the optical receiving antenna focuses the laser signal onto a high speed APD gain controller, then a data decision circuit, successively. The decoder restores the digital video signal and transmits to a monitor.

During the testing of the free space laser communication system with a distance of 5 meters, a Lecory Labmaster 10-36Zi oscilloscope was used for monitoring the communication system. The bit error rate (BER) was measured lower than 10^{-6}. The video transmission rate was measured higher than 125 Mbps from an eye diagram shown in figure 14.

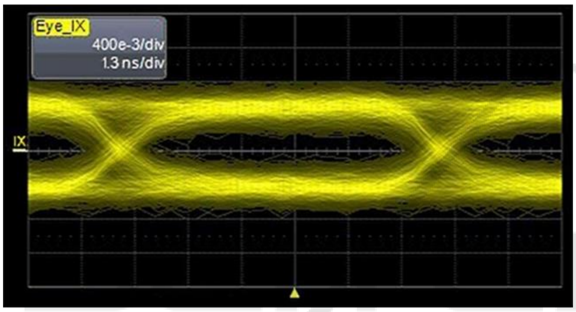

Figure 14: The 125 Mbps eye diagram of the demodulated signals in 1.3 ns/div was measured by oscilloscope.

A real-time, high-fidelity transmission of video signals had been realized in this system. The video signal was divided into two paths: one was transmitted by the free space laser communication system, and the other one directly connected to the display as a comparison. Figure15 shows a snapshot of the video signal before and after the transmission.

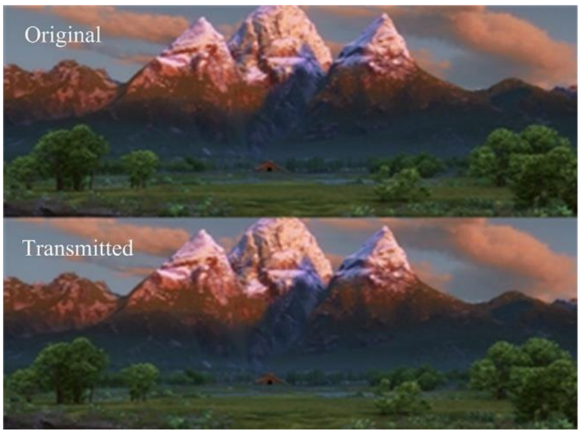

Figure 15: The original and transmitted video snapshot.

5 CONCLUSION

A research works on the free space laser communication system using solar pumped Nd:YAG laser and related research is explored. Based on the advantages of solar pumped laser, a simple, high efficiency, and long lifetime free space laser communication system is feasible in the near future. Multi-frequency output solar pumped laser is realised. The initial progress in the amplification of 1064nm seed laser by solar pump is achieved. A free space laser communication system based on a SPL is built. A high resolution video signal was transmitted by the laser beam in a 5 meters free-space. 125 Mbps bit rate was demonstrated, BER was measured lower than 10^{-6}. The feasibility of using SPL for high rate communication application in free space was demonstrated for the first time.

We hope our research can promote the development of SPLs as well as their applications. Future efforts will be made to increase the number of channel for communication, and increase the data transmission rate.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (61775018).

REFERENCES

Mori et al., 2006. Summary of studies on space solar power systems of Japan Aerospace Exploration Agency (JAXA). *Acta Astronaut. 59 (2006) 132– 138*.

Guan et al., 2017. Demonstration of a freespace optical communication system using a solar-pumped laser as signal transmitter. *Laser Phys. Lett. 14 (2017) 055804*.

Oliveira et al., 2016. A path to renewable Mg reduction from MgO by a continuous-wave Cr, Nd:YAG ceramic solar laser. *Sol, Energy Mater. Sol. Cells 155 (2016) 430–435*.

Yabe et al., 2008. 100 Wclass solar pumped laser for sustainable magnesium-hydrogen energy cycle. *Appl. Phys. 104 (2008) 1–8*.

Kiss et al., 1963. Sun pumped continuous optical maser. *Appl. Phys. Lett. 2 (1963) 93–94*.

Young, 1966. A sun-pumped CW one-watt laser. *Appl. Opt. 5 (1966) 993–998*.

Weksler and Shwartz, 1998. Solar-pumped solid-state lasers. *IEEE J. Quantum Electron. 24 (1998) 1222–1228*.

Yabe et al., 2007. High-efficiency and economical solar-energy-pumped laser with Fresnel lens and chromium

codoped laser medium. *Appl. Phys. Lett. 90 (2007) 261120*.
Liang and Almeida, 2011. Highly efficient solar-pumped Nd:YAG laser. *Opt. Express. 19 (2011) 26399–26405*.
Dinh et al., 2012. 120 watt continuous wave solar pumped laser with a liquid light-guide lens and an Nd:YAG rod.*Opt. Lett. 37 (2012) 2670–2672*.
Xu et al., 2014. High efficiency solar-pumped laser with a grooved Nd:YAG rod. *Appl.Opt. 53 (2014) 3941–3944*.
Liang et al., 2017. Solar-pumped Nd:YAG laser with 31.5 W/m^2 multimode and 7.9 W/m^2 TEM00-mode collection efficiencies. *Sol. Energy Mater. Sol. Cells 159 (2017) 435–439*.
Guan and Zhao, 2018. 32.1 W/m^2 continuous wave solar-pumped laser with a bonding Nd:YAG/YAG rod and a Fresnel lens. *Optics and Laser Technology, 2018, 107:158-161*.
Liu, 2007. Satellite laser communication I link and terminal technology. *Chin J Las34(1),3–10(2007)*.
Baister et al., 2003. The OPTEL Terminal Development Programme-Enabling Technologies for Future Optical Crosslink Applications. *AIAA, space (2003)*.