



National Research Institute of Astronomy and Geophysics NRIAG Journal of Astronomy and Geophysics

www.elsevier.com/locate/nrjag



Simulation model of a new solar pumped laser system of Fresnel lens in Helwan of Egypt

Yasser A. Abdel-Hadi *

National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Cairo, Egypt

Received 15 October 2012; accepted 12 December 2012

Available online 7 March 2013

KEYWORDS

Solar laser;
Solar concentrator;
Fresnel lens;
Compound parabolic concentrator (CPC)

Abstract A simulation model of a new solar pumped laser system is tested to be run in Helwan in Egypt as an example of an industrial polluted area. The system is based on concentrating the solar radiation using a Fresnel lens on a laser head fixed on a mount tracking the sun during the day and powered by a DC battery. The model is fed by real solar radiation data in the various seasons in order to know the laser power got from such a system in those conditions. The results showed that the output laser power obtained from this system can be up to 6.2 W in spring, 6.8 W in summer, 2.2 W in autumn and 0.4 W in winter.

© 2013 Production and hosting by Elsevier B.V. on behalf of National Research Institute of Astronomy and Geophysics.

1. Introduction

Solar laser is one of the most interesting fields of research. It is one of solar energy applications. It was a dream of mankind to convert the sunlight, which is an incoherent, broadband radiation into laser radiation which is coherent and monochromatic. This dream began to be realized shortly after the invention of the laser. The scientists made progress in reducing the cost of production of lasers by reducing the pumping energy. Among the laser materials, solid state lasers remain the easiest to use and the most widespread in this field.

Solid state lasers require an optical excitation source for pumping the upper laser levels. Classical lasers use pulsed or cw discharge light sources, while modern devices use laser diodes which are very efficient, but – at present – very expensive pumping devices. The overall efficiency of discharge lamp pumped lasers varies from a fraction of one percent to approximately 4% (50% efficiency of the discharge lamp and 8% efficiency of the optical laser system). The efficiency of diode pumped lasers is in the order of 15–20% in respect to the electric input power (Koechner, 1992).

Abdel-Hadi (2006) developed a solar concentration system consisting of a Fresnel lens and a Compound Spherical Concentrator (CSC). The concentrated radiation was 267.14 W which equals $6.8 \times 10^6 \text{ W/m}^2$. This power could generate a laser beam of 2.552 W which could be translated into an intensity of $6.458 \times 10^4 \text{ W/m}^2$ with a slope efficiency of 0.028 according to the simulation model developed for this concentration system.

Ohkubo (2009) developed a solar-pumped 100 W class laser that features high efficiency and low cost owing to the use of a Fresnel lens and a chromium co-doped neodymium YAG cera-

* Tel.: +2 01000556473.

E-mail address: yasser_hadi@yahoo.com.

☆ Peer review under responsibility of National Research Institute of Astronomy and Geophysics.



Production and hosting by Elsevier

mic laser medium. A laser output of about 80 W was achieved with combination of a 4 m² Fresnel lens and a pumping cavity as a secondary power concentrator. This output corresponds to 4.3% of conversion efficiency from solar power into laser, and the maximum output from a unit area of Fresnel lens was 20 W/m², which was 2.8 times larger than previous results with mirror-type concentrator.

Liang and Almeida (2011) developed a solar pumped laser system irradiated by a Fresnel lens using a Cr:Nd:YAG ceramic medium. The incoming solar radiation from the sun was focused by a 0.9 m diameter Fresnel lens. The output power produced from this system was 12.3 W of cw laser corresponding to 19.3 W/m² of intensity.

2. Model scenario

In order to test the ability of developing a solar laser system in Helwan which is 35 km south of Cairo, the capital city of Egypt, a simulation model was developed and applied for the system developed by Abdel-Hadi (2006) according to the radiation and weather conditions there.

A Fresnel lens is fixed on an optical bench as shown in Fig. 1. The concentrated solar radiation will be focused on a compound parabolic concentrator (CPC). This system will direct the radiation into the Nd:YAG laser crystal. The crystal has total reflective coating from the side of contact while there is a high reflective mirror as an output coupler aligned to the system on the optical bench. A water-based cooling circulation is connected to the crystal in order to eliminate the heat caused by the concentration and the laser pumping process. The whole optical bench is set on a mount with a tracking motor which can let the system follow the position of the sun during the daytime. The parameters of the Fresnel lens are given in Table 1, while the parameters of the compound parabolic concentrator (CPC) are given in Table 2.

The Nd:YAG laser is by far the most commonly used type of solid-state laser. Neodymium-doped yttrium aluminium garnet (Nd:YAG) possesses a combination of properties un-

Table 1 Parameters of the used Fresnel lens.

Parameter	Value
Dimensions	60 cm × 60 cm
Aperture area	0.36 m ²
Focal length	0.75 m

Table 2 Parameters of the used CPC.

Parameter	Value
Acceptance angle	45°
Concentration ratio	1.414

iquely favourable for laser operation. The YAG host is hard, of good optical quality, and has a high thermal conductivity. Furthermore, the cubic structure of YAG favours a narrow fluorescent line width, which results in high gain and low threshold for laser operation. In Nd:YAG, trivalent neodymium substitutes for trivalent yttrium in the lattice, so charge compensation is not required (Koechner, 1992). The parameters of the Nd:YAG laser crystal are given in Table 3.

The threshold pumping power of the laser rod can be calculated from Eq. (1) (Weksler and Schwartz, 1988).

$$P_{th} = \frac{A_a I_s}{\eta_q \eta_{ovp} \alpha} \left(\frac{2\gamma_l - \ln(R)}{2s} \right) \quad (1)$$

where A_a is cross-sectional area of the crystal (rod). The other parameters are defined in Table 3.

We can also calculate the value of the slope efficiency (the efficiency above the threshold) using the Eq. (2).

$$\eta_s = \eta_q \eta_{ovp} \alpha \epsilon \left(\frac{T}{(2\gamma_l - \ln(R))} \right) \quad (2)$$

where the value η_q is the quantum efficiency (the mean wavelength of absorbed radiation divided by the lasing wavelength) which can be calculated from the Eq. (3) (Weksler and Schwartz, 1988).

$$\lambda_q = \frac{\lambda_s}{\lambda_L} \quad (3)$$

The laser output power P_{out} can be written as:

$$P_{out} = (A_a I_s) \frac{T}{(2\gamma_l - \ln(R))} \left[g_0 - (\gamma_l - \ln(\sqrt{R})) \right] \quad (4)$$

where I_s is the saturation flux, T and R are the output mirror transmission and the reflectivity, respectively, g_0 is the small signal gain; and γ_l is the loss per pass in the laser (Winston et al., 1992).

Table 3 Parameters of the used Nd:YAG laser crystal.

Parameter	Symbol	Value
Fluorescence of the crystal	I_s	12.5×10^6 W/m ²
Quantum efficiency	η_q	0.63
Overlap ratio	η_{ovp}	0.14
Absorption coefficient	α	0.59
Pumping efficiency	ϵ	0.67
Rod length	l	7 mm
Rod diameter	d	2 mm

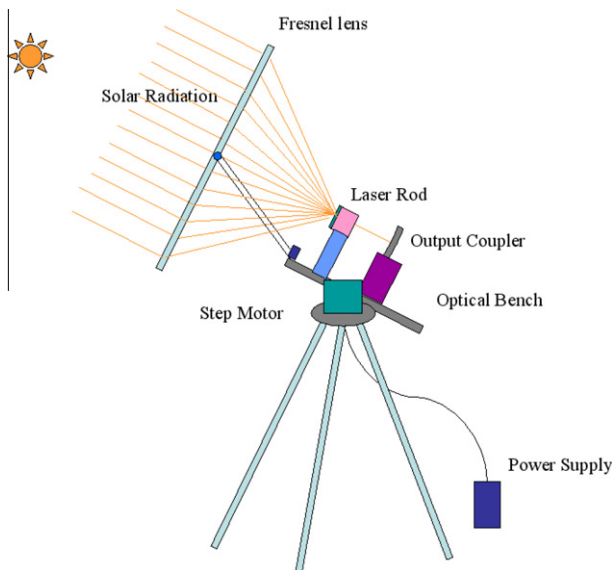


Fig. 1 The total solar laser system.

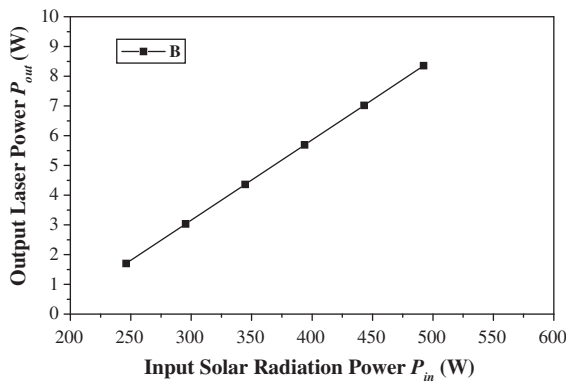


Fig. 2 The performance of the solar laser model.

Put into a form that is often used when presenting solid-state laser performance data, the output power can also be written as:

$$P_{out} = \eta_s(P_{in} - P_{th}) \quad (5)$$

The measured laser threshold power, as a function of the output coupler mirror reflectivity R , can be used to determine both the loss per pass L and the mean pumping efficiency ε (Winston et al., 1992).

As a test of this model, for 1000 W/m^2 of solar radiation (348.075 W on the Fresnel lens and accordingly 492.252 W on falling on the laser rod), an output laser power of 8.351 W can be obtained. This output power can be translated to an intensity of $2.108 \times 10^5 \text{ W/m}^2$. The conversion efficiency for such a system is 2.7%. Fig. 2 shows the performance of this system according to the model parameters.

We applied this model on the real solar radiation data taken in Helwan daily by the solar radiation station which belongs to the Solar and Space Department of the National Research Institute of Astronomy and Geophysics (NRIAG) ($\varphi = 29^\circ 52'$ and $\lambda = 31^\circ 21'$). In order to test the model, we chose some days representing each season of the year and obtained the average values for each of them. Fig. 3 shows the output laser power gained in Helwan according to this model, while Fig. 4 shows the corresponding output laser intensity.

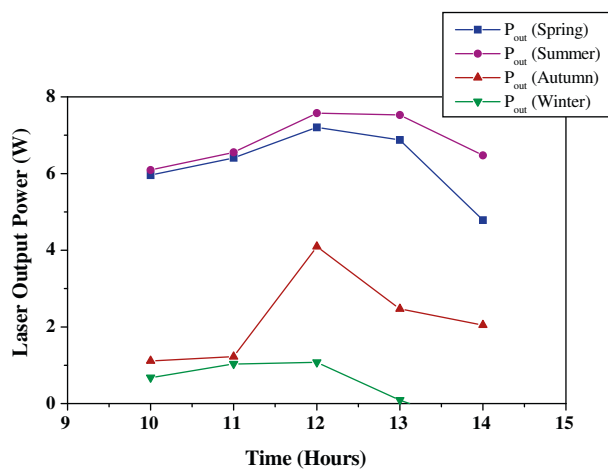


Fig. 3 The output laser power of the solar laser system in some days representing the annual seasons.

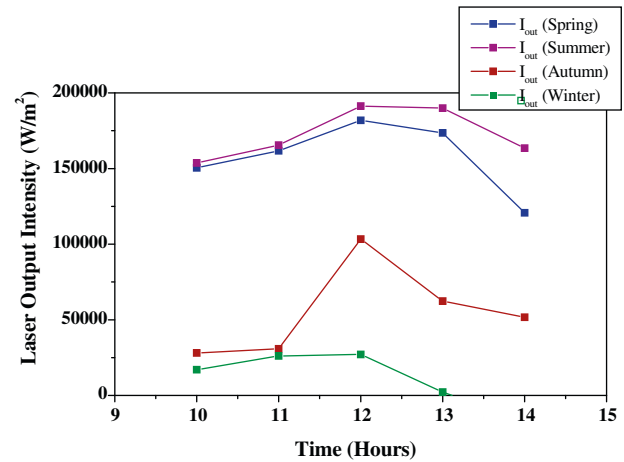


Fig. 4 The output laser intensity of the solar laser system in some days representing the annual seasons.

Helwan is a highly polluted industrial town. Its air pollution causes a reduction in the solar radiation falling on this area. The major sources of pollution at Helwan are due to three types of factors: Cement factories, which include 4 factories distributed from the north in Tura to the south in EL-Tebeen, engineering industries (cars, pipes and tubes factories) and iron and steel factories. Also, the wind plays an important role affecting the quality of the air in Helwan. The major source of the wind directions are from the N and N-E, which represents about 50% of the total direction. This means that the Tura EL-Cement and Helwan Portland cement factories represent 50% of the pollution of Helwan region. The national cement factory and iron steel factories represent about 40% (NW, S, W, S-W directions) of the total pollution at Helwan region. Also EL-Tebeen (S-W from Helwan) is considered to be a very high polluted region because of all cement factories besides 50% from the iron and steel factory pour out in this region. This means that the level of pollution in Helwan region is high in comparison with the international limit, by about 1250–2500% in industrial and populated regions (Rahoma and Hassan, 2010). This pollution level affects the solar radiation and reduces it dramatically.

3. Results and discussion

Applying the model on the real solar radiation data taken in Helwan daily by the mentioned solar radiation station, one can obtain an average laser output power of 6.2 W in spring, 6.8 W in summer, 2.2 W in autumn and 0.4 W in winter. The mean intensity values of the output laser are: $1.6 \times 10^5 \text{ W/m}^2$ in spring, $1.7 \times 10^5 \text{ W/m}^2$ in summer, $5.5 \times 10^4 \text{ W/m}^2$ in autumn and $1.1 \times 10^4 \text{ W/m}^2$ in winter.

We have to say that our simulation model represents a portable easy-made solar laser system and, therefore, the expected output laser power is not high like the bigger more complicated systems. So, our way of development will take place in two directions:

1. We have to increase the dimensions and the parameters of the concentration system in order to increase its concentration power.

2. We have to find other laser materials of parameters which can decrease the threshold pumping power with minimum defection of the lasing process or the beam quality.

4. Conclusion

- Fresnel lens is a well-recommended concentrator type for generating a solar laser. For a system of a simple Fresnel lens of dimensions $60\text{ cm} \times 60\text{ cm}$ and a CPC of suitable dimensions, we can get about 8 W of output laser from a 1 kW/m^2 of solar radiation.
- Applying this model on Helwan using the data measured by the solar radiation station in NRIAG ($\varphi = 29^\circ 52'$ and $\lambda = 31^\circ 21'$) for typical days representing each season, we can get an average laser output power of 6.2 W in Spring, 6.8 W in Summer, 2.2 W in Autumn and 0.4 W in Winter.
- The mean intensity values of the output laser are: $1.6 \times 10^5\text{ W/m}^2$ in spring, $1.7 \times 10^5\text{ W/m}^2$ in summer, $5.5 \times 10^4\text{ W/m}^2$ in autumn and $1.1 \times 10^4\text{ W/m}^2$ in winter.
- The solar radiation data were taken in Helwan which is an industrial polluted town. If we set up the system in a place of a cleaner air, better results could be readily obtained.

References

- Abdel-Hadi, Y.A., 2006. Development of Optical Concentrator Systems for Directly Solar Pumped Laser Systems. Mensch und Buch Verlag, Berlin, Germany.
- Koechner, W., 1992. Solid-state laser engineering, third ed. In: Springer Series in Optical Science, vol. 1 Springer Verlag.
- Liang, D., Almeida, J., 2011. Highly efficient solar-pumped Nd:YAG laser. *Optical Express* 19 (27), 26399–26405.
- Ohkubo, T., 2009. Solar-pumped 80 W laser irradiated by a Fresnel lens. *Optics Letters* 34 (2), 175–177.
- Rahoma, U.A., Hassan, A.H., 2010. Estimate of aerosol optical depth using broadband direct normal observations at highest polluted area in the world. *American Journal of Applied Sciences* 7 (5), 647–655.
- Weksler, M., Schwartz, J., 1988. Solar-pumped solid-state lasers. *IEEE Journal of Quantum Electronics* 24 (6), 1222–1228.
- Winston, R., Cooke, D., Gleckman, P., O'Gallagher, J.J., 1992. Ultra-high solar flux and applications to laser pumping". In: Sayigh, A.A.M. (Ed.), *Proceedings of Renewable Technology and the Environment, the Second World Renewable Energy Congress*, vol. 1. Pergamon Press, Reading, UK, pp. 83–90.