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Simulation model of a new solar laser system of Fresnel lens according to real observed solar radiation data in Helwan of Egypt



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Abstract A new simulation model of a new solar pumped laser system was tested to be run in Helwan in Egypt (latitude $\varphi = 29^{\circ}52'N$, longitude $\lambda = 31^{\circ}21'E$ and elevation = 141 m) 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. Two cases of this model are tested; the first one is the model consisting of a Fresnel lens and a two-dimensional Compound Parabolic Concentrator (CPC), while the other is the model consisting of a Fresnel lens and a three-dimensional Compound Parabolic Concentrator (CPC). The model is fed by real actual solar radiation data taken in Helwan Solar Radiation Station at NRIAG in the various seasons in order to know the laser power got from such a system in those conditions. For the system of Fresnel lens and 2D-CPC, an average laser output power of 1.27 W in Winter, 2 W in Spring, 5 W in Summer and 4.68 W in Autumn respectively can be obtained. Accordingly, the annual average output power for this system is 3.24 W. For the system of Fresnel lens and 3D-CPC, an average laser output power of 3.28 W in Winter, 3.55 W in Spring, 7.56 W in Summer and 7.13 W in Autumn respectively can be obtained. Accordingly, the annual average output power for this system is 5.38 W.

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1. Introduction

One of the most interesting applications of solar energy is to generate the laser beam directly. Using the idea of concentrating the sun light, one can get the optical energy needed to excite the laser material in order to generate the laser beam. This kind of application is called *Solar Laser*.

The idea of the solar laser depends on concentrating the solar radiation in order to obtain a pumping intensity greater

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than the threshold level needed to generate the laser. For such purposes, optical concentration devices are used such as the three-dimensional parabolic concentrator (paraboloidal concentrator (3D-PC)), spherical concentrator (SC), Fresnel lens (FL), solar towers, and solar mirror arrays. With the help of the two- or three-dimensional non-imaging concentrators e.g. compound parabolic concentrators, conical concentrator, and V-trough concentrator, one can increase the concentration level to a higher one to attain the approximately the theoretical energy level.

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 ceramic 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.

Abdel-Hadi (2012) developed a simulation model of solar pumped laser system with a concentration system consisting of a Fresnel lens and a trough (2-dimensional) Compound Parabolic Concentrator (CPC). The Fresnel lens was in quadratic form and its dimensions were chosen to be 60 cm × 60 cm. The model was tested to the observed data of solar radiation in Helwan which is a town 35 km south of Cairo. The solar radiation records were taken by a manual solar radiation station and applied to this model. The results showed that 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.

In the present work, the same procedure has been adopted as in the work of Abdel-Hadi (2012). After constructing the automatic solar radiation station in October 2010 on the rooftop of the National Research Institute of Astronomy and Geophysics (NRIAG), it became easier to record more data of solar radiation. So, we applied the new recorded data on our model and got new results according to the actual solar radiation status. Then, we changed in the model itself by substituting the two-dimensional CPC by a three-dimensional CPC to test the increase of the output laser power obtained from this system.

2. Model scenario

The same model scenario adopted in the previous work is also adopted in this work (Abdel-Hadi (2012)). 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.

Table 1 shows the parameters of the Fresnel lens chosen in this model.

Two cases of the Compound Parabolic Concentrator (CPC) were chosen in this model: 2D-CPC and 3D-CPC. The acceptance angle of both of them was chosen to be 45°. Figs. 2 and 3 show the geometry of the 2D-CPC and 3D-CPC used as secondary concentrators respectively, while Table 2 shows the parameters of both of them.

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

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

where A_a is cross-sectional area of the crystal (rod) and γ_l is the loss per pass in the laser. The other parameters are shown in Table 3.

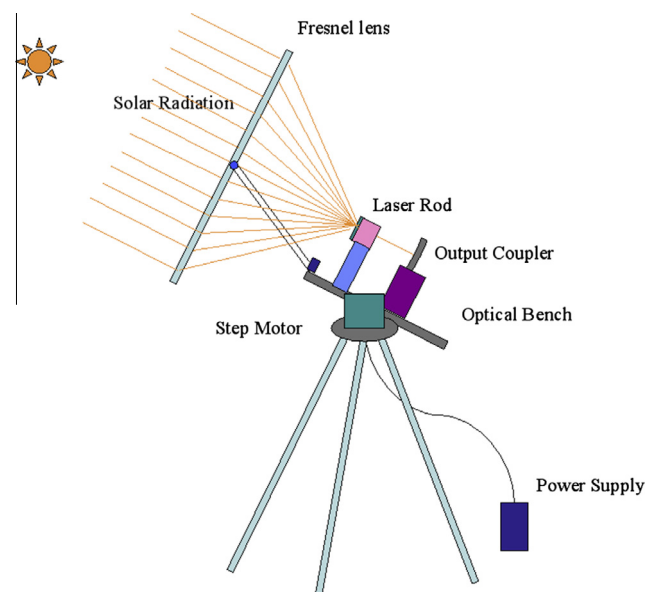


Figure 1 The total solar laser system (Abdel-Hadi (2006, 2012)).

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

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

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

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 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 in Eq. (4):

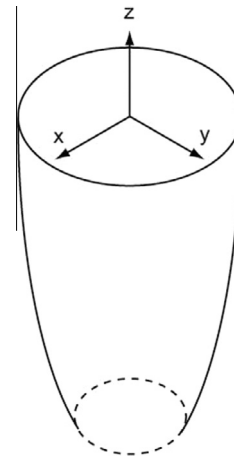
$$P_{out} = (A_o I_s) \frac{T}{(2\gamma_l - \ln(R))} [g_o - (\gamma_l - \ln(\sqrt{R}))] \quad (4)$$

where I_s is the saturation flux, T and R are the output mirror transmission and the reflectivity, respectively, and g_o is the small signal gain (Winston et al. 1992). Putting into a form that is often used when presenting solid-state laser performance data, the output power can also be written as in Eq. (5):

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

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).

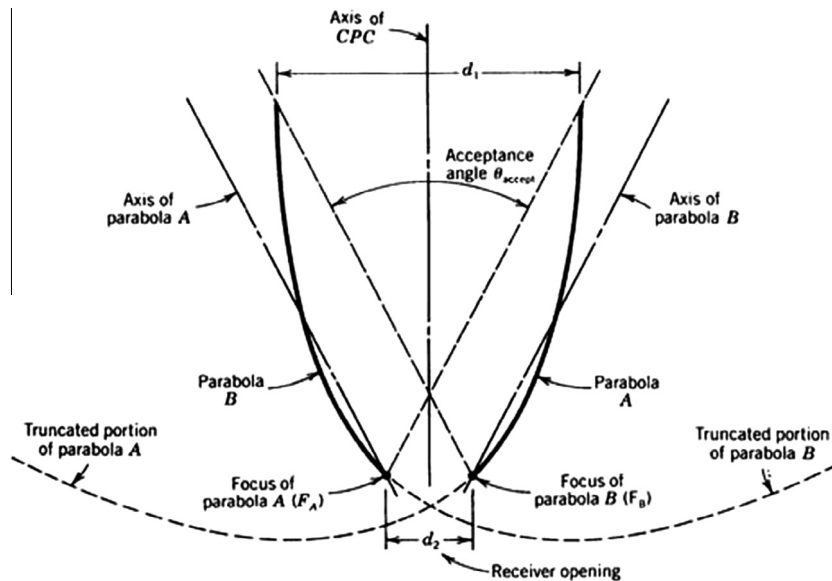
The parameters of the Nd:YAG laser crystal needed in the model are given in Table 3.

**Figure 3** 3D-CPC.**Table 2** Parameters of the used 2D- and 3D-CPCs.

Parameter	2D-CPC	3D-CPC
Acceptance angle	45°	45°
Concentration ratio	1.414	2

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

Parameter	Symbol	Value
Fluorescence of the crystal	I_s	$12.5 \times 10^6 \text{ W/m}^2$
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

**Figure 2** Geometrical design of the 2D-CPC.

Firstly, we tested the two models by applying some arbitrary values of the input solar radiation power. For the first case where we use the two-dimensional Compound Parabolic Concentrator (CPC) as a secondary concentrator, for 1000 W/m^2 of solar radiation (348.075 W and accordingly 492.252 W/m^2 on the Fresnel lens), an output laser power of 8.351 W can be obtained. This output power can be translated to an intensity of $2.108 \times 10^5 \text{ W/m}^2$; for the first case where we use the three-dimensional Compound Parabolic Concentrator (CPC) as a secondary concentrator, and for 1000 W/m^2 of solar radiation (348.075 W on the Fresnel lens), an output laser power of 13.862 W can be obtained. This output power can be translated to an intensity of $3.499 \times 10^5 \text{ W/m}^2$. The conversion efficiency for both systems was found to be 2.7% . Figs. 4 and 5 show the performance of these two systems according to the given parameters, while Eqs. (6) and (7) represent the model fitting equations for both systems respectively.

$$P_{out,2D-CPC} = 0.02702P_{in} - 4.95143 \quad (6)$$

$$P_{out,3D-CPC} = 0.02703P_{in} - 4.95195 \quad (7)$$

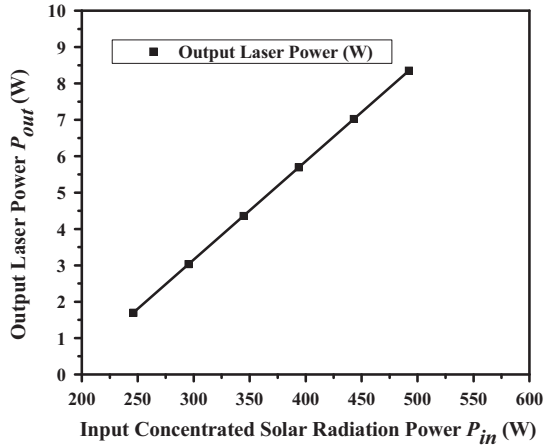


Figure 4 The performance of the solar laser model for a system of Fresnel lens and 2D-CPC.

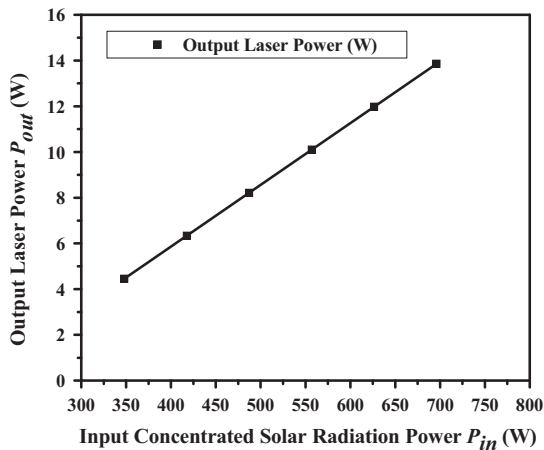


Figure 5 The performance of the solar laser model for a system of Fresnel lens and 3D-CPC.

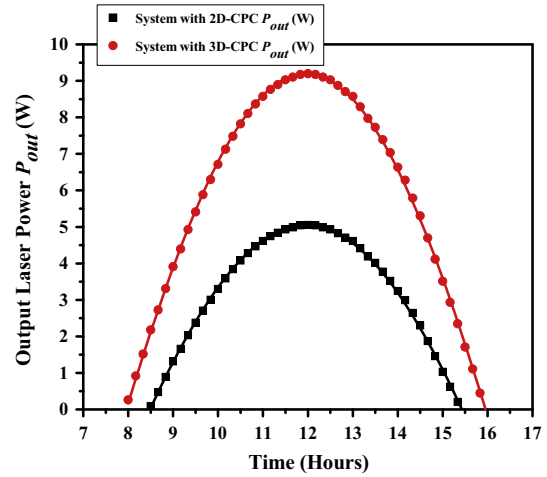


Figure 6 Laser output for the system of Fresnel lens and 2D- and 3D-CPCs.

To compare the output power gained from each one of the two models, we applied the both modelled systems on a real recorded data by the Solar Radiation Station fixed at the National Research Institute of Astronomy and Geophysics (NRIAG) at Helwan ($\varphi = 29^{\circ}52'$ and $\lambda = 31^{\circ}21'$). Fig. 6 shows the calculated laser output for the system having each case of the CPC as a secondary concentrator. Eqs. (8) and (9) represent the model fitting of the curves 2D-CPC and 3D-CPC systems respectively. The maximum difference between the laser output power values in the two cases reaches up to 5 W .

$$P_{out,2D-CPC} = -24.98287 + \left(\frac{430.79684}{11.44457\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{P_{in}-11.95681}{11.44457}\right)^2} \quad (8)$$

$$P_{out,3D-CPC} = -33.28006 + \left(\frac{609.23874}{11.44457\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{P_{in}-11.95681}{11.44457}\right)^2} \quad (9)$$

Fig. 6 and Eqs. (8) and (9) represent an example of an ideal day on which, a whole laser output power of 431 W in the case of using a 2D-CPC and 609 W in the case of 3D-CPC during the day can be obtained.

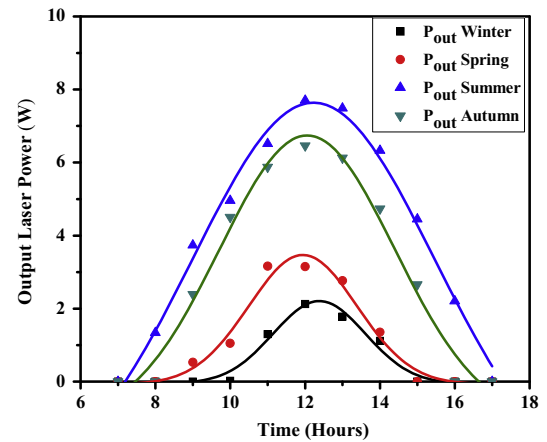


Figure 7 The output laser power obtained in Helwan according to the system of Fresnel lens and 2D-CPC.

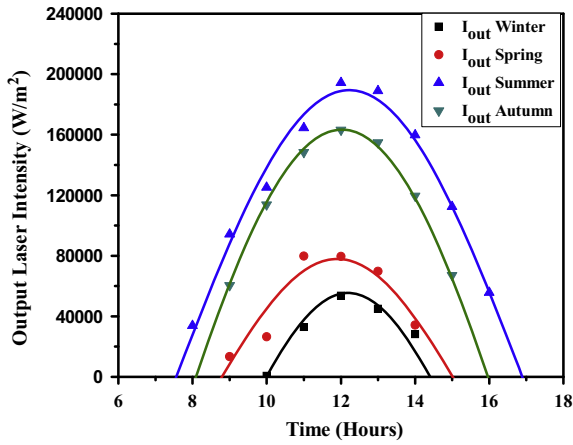


Figure 8 The output laser intensity obtained in Helwan according to the system of Fresnel lens and 2D-CPC.

Finally, we tested the both models according to the real solar radiation data recorded by the mentioned Solar Radiation Station recently in all seasons in 2012. Figs. 7 and 8 show the output laser power and intensity obtained in Helwan according to this model respectively for the system of Fresnel lens and 2D-CPC which are fitted in Eqs. (10)–(17). On the other hand, Figs. 9 and 10 show the output laser power and intensity obtained in Helwan according to this model respectively for the system of Fresnel lens and 3D-CPC which are fitted in Eqs. (18)–(25):

$$P_{out,2D-CPC,Winter} = -0.05803 + \left(\frac{6.98227}{2.45962\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{P_m-12.3779}{2.45962}\right)^2} \quad (10)$$

$$P_{out,2D-CPC,Spring} = -0.07386 + \left(\frac{12.82166}{2.88835\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{P_m-11.94198}{2.88835}\right)^2} \quad (11)$$

$$P_{out,2D-CPC,Summer} = -3.23174 + \left(\frac{88.04286}{6.46261\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{P_m-12.22648}{6.46261}\right)^2} \quad (12)$$

$$P_{out,2D-CPC,Autumn} = -1.14546 + \left(\frac{46.17388}{4.67126\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{P_m-12.05532}{4.67126}\right)^2} \quad (13)$$

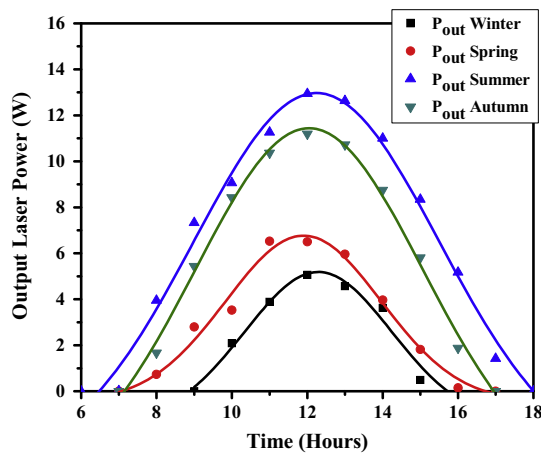


Figure 9 The output laser power obtained in Helwan according to the system of Fresnel lens and 3D-CPC.

$$I_{out,2D-CPC,Winter} = -187817.0148 + \left(\frac{1.87286 \times 10^6}{6.14325\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{I_m-12.19756}{6.14325}\right)^2} \quad (14)$$

$$I_{out,2D-CPC,Spring} = -163815.61319 + \left(\frac{2.13878 \times 10^6}{7.0604\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{I_m-11.90345}{7.0604}\right)^2} \quad (15)$$

$$I_{out,2D-CPC,Summer} = -328605.16482 + \left(\frac{6.34826 \times 10^6}{9.77724\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{I_m-12.22658}{9.77724}\right)^2} \quad (16)$$

$$I_{out,2D-CPC,Autumn} = -541070.09845 + \left(\frac{9.56516 \times 10^6}{10.83434\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{I_m-12.02759}{10.83434}\right)^2} \quad (17)$$

$$P_{out3D-CPC,Winter} = -1.3855 + \left(\frac{32.03316}{3.88846\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{P_m-12.29131}{3.88846}\right)^2} \quad (18)$$

$$P_{out3D-CPC,Spring} = -0.46754 + \left(\frac{37.39508}{4.12306\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{P_m-11.89891}{4.12306}\right)^2} \quad (19)$$

$$P_{out3D-CPC,Summer} = -3.38973 + \left(\frac{133.23476}{6.49738\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{P_m-12.24386}{6.49738}\right)^2} \quad (20)$$

$$P_{out3D-CPC,Autumn} = -4.16213 + \left(\frac{117.89474}{6.02874\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{P_m-12.04913}{6.02874}\right)^2} \quad (21)$$

$$I_{out3D-CPC,Winter} = -213836.67427 + \left(\frac{2.64862 \times 10^6}{6.14325\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{I_m-12.19756}{6.14325}\right)^2} \quad (22)$$

$$I_{out3D-CPC,Spring} = -179893.56661 + \left(\frac{3.02469 \times 10^6}{7.0604\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{I_m-11.90345}{7.0604}\right)^2} \quad (23)$$

$$I_{out3D-CPC,Summer} = -412941.18546 + \left(\frac{8.9778 \times 10^6}{9.77724\sqrt{\frac{\pi}{2}}} \right) e^{-2\left(\frac{I_m-12.22658}{9.77724}\right)^2} \quad (24)$$

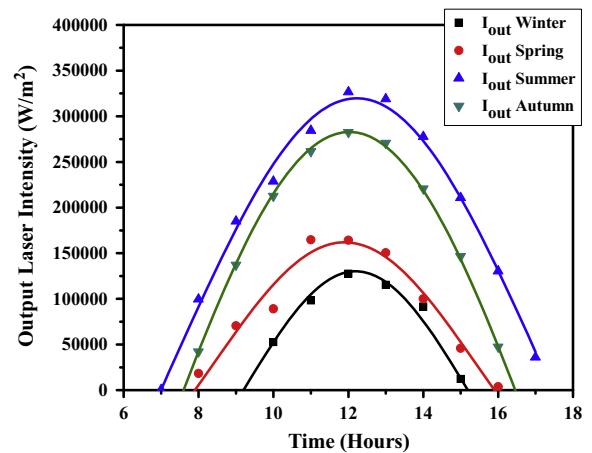


Figure 10 The output laser intensity obtained in Helwan according to the system of Fresnel lens and 3D-CPC.

$$I_{out3D-CPC,Autumn} = -713411.97613 + \left(\frac{1.35272 \times 10^7}{10.83434 \sqrt{\frac{\pi}{2}}} \right) e^{-2 \left(\frac{t_{in} - 12.02759}{10.83434} \right)^2} \quad (25)$$

From the last equations, the width of the Gaussian profile representing the output laser power and intensity takes its maximum in Summer and its minimum in Winter, while it takes its intermediate values in Spring and Autumn.

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 is 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 all cement factories besides 50% from the iron and steel factories pours 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

According to the two cases of models in our work and the recorded solar radiation data recorded by the Solar Radiation Station at the National Research Institute of Astronomy and Geophysics (NRIAG), promising output values of laser can be readily obtained. We selected some typical days representing each season of the year 2012. The selection was based on the criteria that the day has to be around the intermediate days of the seasons and its profile has to be a typical profile (bell-shaped).

For the system of Fresnel lens and 2D-CPC, an average laser output power of 1.27 W in Winter, 2 W in Spring, 5 W in Summer and 4.68 W in Autumn respectively can be obtained. Accordingly, the annual average output power for this system is 3.24 W. These values can represent the values of intensity: 0.32×10^5 W/m² in Winter, 0.505×10^5 W/m² in Spring, 1.25×10^5 W/m² in Summer and 1.18×10^5 W/m² in Autumn respectively. Accordingly, the annual average output intensity for this system is 0.814×10^5 W/m².

For the system of Fresnel lens and 3D-CPC, an average laser output power of 3.28 W in Winter, 3.55 W in Spring, 7.56 W in Summer and 7.13 W in Autumn respectively can be obtained. Accordingly, the annual average output power for this system is 5.38 W. These values can represent the values of intensity: 0.829×10^5 W/m² in Winter, 0.897×10^5 W/m² in Spring, 1.91×10^5 in Summer and 1.8×10^5 W/m² in Autumn respectively. Accordingly, the annual average output intensity for this system is 1.36×10^5 W/m².

In Figs. 7–10, we can notice that the trend of the laser generated by the solar energy obviously coincides with the trend of the solar radiation values recorded for each season in Helwan. The higher values of the laser power can be generated obviously in the Summer, since the solar radiation values are the highest during the year. As we go to the Autumn, the solar radiation values are still high but a little bit less than those of Summer. So, the generated solar laser values are also a little bit less than those generated in the Summer. The trend of the solar radiation gets lower until it gets its lowest values in the Winter in which the lower values of the laser power can be generated. As we go to the Spring, the solar radiation values get higher values again until they reach their maximum values again in the Summer. So, the generated solar laser starts to get higher values again. It is also obvious to find the values of the generated solar laser in Spring lower than those of Autumn for three main reasons: (1) the solar radiation values take their time to get higher level after the Winter, (2) the effect of the Spring wind blowing in Egypt at that time (Khamaseen) and (3) the solar radiation values take their time to get lower level after the Summer.

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 (Abdel-Hadi (2012)) as follows:

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 deflection of the laser 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 cm × 60 cm and a CPC of suitable dimensions, we can get about 13.862 W of output laser from a 1 kW/m² 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 the following results:
 1. For the system of Fresnel lens and 2D-CPC, an average laser output power of 1.27 W in Winter, 2 W in Spring, 5 W in Summer and 4.68 W in Autumn respectively can be obtained. Accordingly, the annual average output power for this system is 3.24 W. These values can represent the values of intensity: 0.32×10^5 W/m² in Winter, 0.505×10^5 W/m² in Spring, 1.25×10^5 in Summer and 1.18×10^5 W/m² in Autumn respectively. Accordingly, the annual average output intensity for this system is 0.814×10^5 W/m².
 2. For the system of Fresnel lens and 3D-CPC, an average laser output power of 3.28 W in Winter, 3.55 W in Spring, 7.56 W in Summer and 7.13 W in Autumn respectively can be obtained. Accordingly, the annual

average output power for this system is 5.38 W. These values can represent the values of intensity: $0.829 \times 10^5 \text{ W/m}^2$ in Winter, $0.897 \times 10^5 \text{ W/m}^2$ in Spring, 1.91×10^5 in Summer and $1.8 \times 10^5 \text{ W/m}^2$ in Autumn respectively. Accordingly, the annual average output intensity for this system is $1.36 \times 10^5 \text{ W/m}^2$.

- Using 3D-CPC as a secondary concentrator for such a system increases the average output power obtained about 1.7 times that obtained by using the 2D-CPC.
- Some of atmospheric phenomena affect the input power of the solar radiation and accordingly the output laser obtained from the system such as the wind direction and speed and the humidity. These factors can affect the clearness of the sky needed to obtain the solar laser.
- 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.
- Abdel-Hadi Y.A., 2012. Simulation Model of a New Solar Pumped Laser System of Fresnel Lens in Helwan of Egypt. In: The 3rd Arab Conference for Astronomy and Geophysics (ACAG-3), October 8–11, 2012, National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Cairo, Egypt, Published in NRJAG Journal of Astronomy and Astrophysics, vol. 1, pp. 195–198.
- Koehnner, W., 1992. *Solid-State Laser Engineering*. Springer Series in Optical Science, vol. 1. Springer Verlag.
- Liang, D., Almeida, J., 2011. Highly efficient solar-pumped Nd:YAG laser. *Opt. Exp.* 19 (27), 26399–26405.
- Ohkubo, T., 2009. Solar-pumped 80 W laser irradiated by a Fresnel lens. *Opt. Lett.* 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. *Am. J. Appl. Sci.* 7 (5), 647–655.
- Weksler, M., Schwartz, J., 1988. Solar-pumped solid-state lasers. *IEEE J. Quant. Electron.* 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: *Proc. of Renewable Technology and the Environment, the Second World Renewable Energy Congress*, vol. 1, pp. 83–90, Reading, U.K.