Proc. Indian Acad. Sci. (Chem. Sci.), Vol. 110, No. 3, June 1998, pp. 335–349.

Side pumping technique model for laser pumped by solar energy

M A MOSALAM SHALTOUT[a]*, M MEDHAT[b] and Y A HADI[a]
[a] National Research Institute of Astronomy and Geophysics, Helwan, Cairo, Egypt
[b] Department of Physics, Faculty of Science, Ain Shams University, Abbassia, Cairo, Egypt

Abstract. A model of side pumping technique for a system of solar concentrators was performed for laser generation. Measurements for the total solar radiation in the hot desert area near Helwan which is south of Cairo by 30 km, of latitude 30°N and longitude 31°E were carried out. The instruments were installed on the rooftop of the National Research Institute of Astronomy and Geophysics (NRIAG). The measurements indicate that the annual average of the global solar radiation is 5·21 kWh/m^2/day, direct solar radiation is 6·26 kWh/m^2/day, diffuse solar radiation is 1·86 kWh/m^2/day, the clearness index K_t is 0·61, and the diffuse fraction K_D is 0·37. The performance of the laser rod and the performance of the system as a whole were tested. Finally, the measurements of solar radiation were applied to the model to obtain the behaviour of the laser output in different seasons, assuming that the concentrator system tracks the sun.

Keywords. Imaging optics; nonimaging optics; solar concentrators; parabolic dish concentrator; compound parabolic concentrator (CPC); solar laser; solid state laser rod; Nd:YAG laser; side pumping technique.

1. Introduction

Laser is one of the most interesting of man's discoveries and is an ideal beam ofter read about in science fiction. By the discovery of laser, man had a monochromatic, coherent and direct beam with a single wavelength. Although laser was wonderful, the required energy for achieving it was very high both technically and commercially. The technique by which laser is produced is called pumping, and the way in which this technique takes place are many, like electrically, chemically and optically. Pumping means exciting the lower level atoms to excited states called higher ones and then going to meta-stable states in which the laser will be ready to lase. We can give the energy of pumping by the ways mentioned before.

Good thinking of optical pumping is to expose the laser medium to a concentrated solar radiation. This means that we are now talking about something called the *solar laser*.

Shortly after the invention of the laser, investigators began dreaming of directly converting sunlight, an incoherent, broadband source, into laser radiation, a coherent, monochromatic source. These dreams were quickly realized, but the efficiencies of typical sun-pumped lasers have been restricted to less than one percent. The chief reason for the low performance is that lasers have high thresholds: the amplifying medium must contain high power per unit volume before any lasing can take place. The idea of directly converting broad-band solar radiation into coherent and narrow-band laser radiation is almost as old as the laser itself. Any laser material that can be optically

---

*For correspondence

pumped can also be used, in principle, as a solar laser. If lasers are needed in remote locations where sunlight is abundant and other forms of energy are scarce, a solar laser would seem to be a natural choice. A solar-pumped laser requires a concentrating solar collector that tracks the sun. The laser head and its associated optics are then placed near or at the focus of the collector.

Gas, liquids and solid lasers have all been considered as candidates for solar lasers. Of these, the solid lasers appear to be most attractive because of their inherent high energy density and compactness, their relatively low pumping threshold, and their potential for efficient solar-to-laser power conversion.

To support the development of solid-state solar lasers for space and other applications, it is necessary to verify experimentally the performance projections and to demonstrate what conversion efficiencies can be achieved. These were some of the objectives of our experiment. Others were to demonstrate the facility of building and testing a solar-pumped solid-state laser and the simplicity and reliability of such a device.

Solar laser is one of the novel branches in recent technology got by a marriage of two sciencies namely solar energy and laser physics. This branch suggests that the desirable laser for use in space communications, industries, medicine, photometry, etc. would be one that derives all its power from the sun.

Side pumping technique for solar laser means that the input solar radiation which is concentrated by the solar concentrator system can be applied to the side of the lsaer rod, i.e., if we want to increase the input radiation (and reasonably the output one), we have to use a laser rod of relatively large exposed surface area and of course a concentrator system of high level of concentration ratio, to exceed the level of the threshold pumping power which is the minimum power which has to be provided to the laser to begin to lase.

Winston and Welford[1] showed how paraboloidal mirrors of short focal ratio and similar systems can have their flux concentration enhanced to near the thermodynamic limit by the addition of nonimaging compound elliptical concentrators (CEC). Weksler and Shwartz[2] obtained very interesting results in their work experimentally. They scanned the focal plane of the primary concentrator to estimate the best position for fixing the absorber. Also, they constructed a complete system of side pumping technique for solar laser using a laser rod of the type of Nd:YAG. This system was also provided by a cooling system which is a pyrex cooling sleeve and a 1% solution of potassium chromate in water. The obtained performance curves showed that more than 60 watts of output power was readily obtained from this solar-pumped Nd:YAG rod with a slope efficiency exceeding 2%. Also, Brauch and his co-workers[3] constructed a similar system with different dimensions and studied experimentally the effect of the operating temperature on a number of physical quantities like the power, divergence, and stress-induced birefringence. The coolant used was either room temperature water or pressurized liquid nitrogen. They also used two types of solid state laser rods which were the Nd:YAG and Nd:Cr:GSGG (neodymium- and chromium-doped gadolinium scandium gallium garnet) and the two types were Moalam Shaltout and his co-workers[4] carried out an end pumping technique model for laser pumped by solar energy in Egypt in which the concentrated solar radiation is delivered onto one end of the laser rod. They used a parabolic dish concentrator as a primary concentrator and a conical concentrator as a secondary one. They worked on the optimum values and obtained good results for laser generation using solar energy. They used two methods for this; the first is when the secondary concentrator was filled with air which has a refractive index of unity, while the other is when the secondary concentrator was filled with sapphire which has a refractive index of 1·76. They made a comparison between them to obtain the better one scientifically and economically.

In this model, we used a system of two-stage concentrator. The primary concentrator is of the type of parabolic dish concentrator which can reach to a concentration level up to 40,000 times theoretically in its focus, while the secondary concentrator is of the type of compound parabolic concentrator (CPC) which is a nonimaging optical one and can increase the concentrated solar radiation by a factor of 1·5 [5]. This system of concentrators will deliver the concentrated solar radiation to the absorber of the CPC concentrator which is, in our model, the Nd:YAG laser rod of length 7·5 cm which matches the lateral extent of the focal spot. If this pumping radiation exceeds the threshold pumping power, the laser will lase. The laser itself was introduced into a cooling system. It is inserted in a pyrex cooling sleeve, and one percent solution of potassium chromate in water was used as a coolant. The pyrex and the potassium chromate both helped to block UV radiation and protect the rod from solarization.

2. Working on the optimum

To attain the maximum performance and concentration from the parabolic dish, we have to work on the optimum values for its parameters. The main one is its rim angle ϕ_r which, in our case, will take the value of 44·8665°, which gives a value geometrical concentration ratio C of $1{\cdot}14 \times 10^4$ times. Accordingly, the focal number (F-ratio) takes the value of 0·609.

3. Model scenario

Two cases of this model have been studied. The normal one, in which no subsidiary matter filled the secondary concentrator (CPC), i.e. this concentrator was filled by the air (the refractive index of air is $n = 1$, and the other case is one in which a material of a refractive index more than unity fills the CPC. We have chosen sapphire which has the index of refraction $n = 1{\cdot}76$. We know that the concentration ratio of a three dimensional concentrator has to be multiplied by the value of refractive index n, i.e. the resultant concentration ratio will be increased, which will make the delivered radiation to the laser rod be a higher one. Figure 1 shows a schematic of side pumping technique model. Figure 2 shows the laser system, the resonator, and the cooling system.

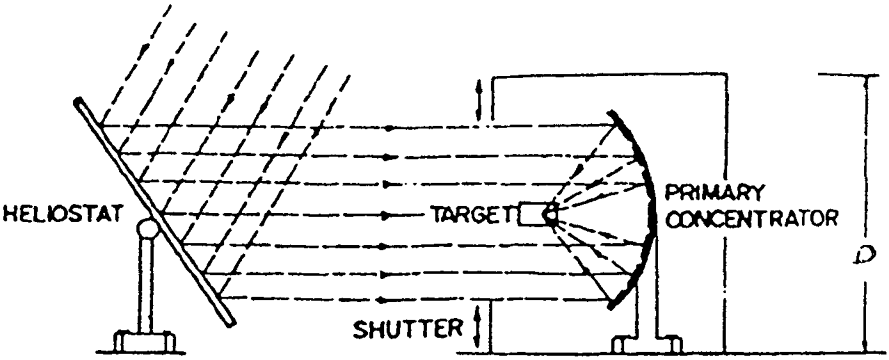

Figure 1. Schematic of side pumping technique model.

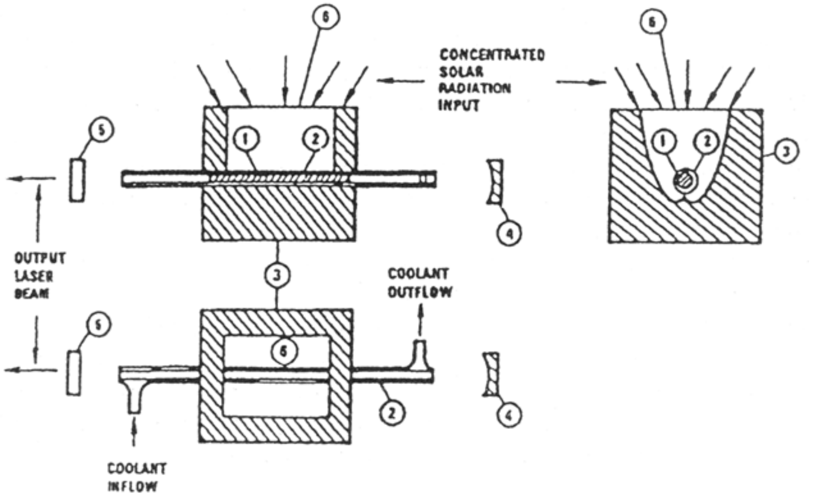

Figure 2. Three cross sections of the laser head and resonator. Upper right-hand side: axial view with the laser rod (1), cooling sleeve (2), and secondary concentrator (CPC) (3) cross sections. Upper left-hand and lower left-hand sides: side and plane views, respectively, identifying the laser resonator mirrors (4 and 5) and the CPC aperature (6) that was placed at the focal plane of the solar furnace.

Table 1. The parameters of the primary concentrator (Parabolic Dish) used in the case of side pumping technique model.

Parameter	Symbol	Value
Rim angle	ϕ_r	44·8665°
Diameter	D	9·69 m
Focal length	f	5·896365 m
Focal ratio	F	0·609
Concentration ratio	C	$1{\cdot}14 \times 10^4$ times
Reflectivity	r	0·7
Interception factor	γ	0·85
Efficiency	η	0·665

The parabolic dish parameters are summarized in table 1 while the CPC ones are summarized in table 2, and the laser cavity ones are summarized in table 3.

The solar radiation is believed to be delivered and concentrated into the parabolic dish concentrator and then delivered to the compound parabolic concentrator (CPC) as a secondary one in which the concentration can reach to a higher level (about 1·5 times the radiation coming from the parabolic dish one). Finally the CPC wraps the radiation onto the laser head which is of a Nd:YAG type of crystal as mentioned previously. After reaching the threshold level, the laser will emit from the end of the crystal although the pumping technique is side one.

We have formulated a simple model for solid-state solar pumped lasers. One can think about this model in the following way: the radiation enters the aperture of the parabolic dish concentrator and their values have to be multipled by the value of the

Table 2. The parameters of the secondary concentrator (CPC) used in the case of side pumping technique model.

Parameter	Symbol	Value
Acceptance angle	θ_a	35°
Concentration ratio	C	1·743 times.
Reflectivily	r	0·7
Concentration ratio in the case of a cylindrical absorber	C_t	1·427 times
Height	H	7 mm
Efficiency	η	0·763

Table 3. The parameters of the laser rod and the resonator used in the case of side pumping technique model.

Parámeter	Symbol	Value
Rod length	La	7·5 cm
Rod diameter	Da	$6{\cdot}25 \times 10^{-3}$ m
Absorption coefficient	α	0·59
Quantum efficiency	η_q	0·63
Pumping efficiency	ε	0·67
Overlap ratio	η_{ovp}	0·14
Loss across the rod	γ_l	0·025
Fluorescence of the crystal (saturation flux)	I_s	12·5 W/mm^2
Slope efficiency	η_s	0·02
Transmissivity of the output coupler	T	0·05

concentration ratio of the concentrator and its efficiency. After this, the output radiation from this primary concentrator will enter the secondary one which is the compound parabolic concentrator (CPC) and will also accordingly have to be multiplied by its values of concentration ratio and efficiency. The resultant radiation will hit and irradiate the laser rod which is fixed as an absorber of the CPC and when their values overtake the threshold value of the laser, the laser radiation will be emitted.

The threshold pumping power of the laser rod can be calculated from the formula,

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

where A_a is the cross-sectional area of the rod which is equal to $\pi D_a^2/4$.

We can also calculate the value of the slope efficiency (the efficiency above the threshold)[6] using the equation,

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

where the value η_q is the quantum efficiency (the mean wavelength of absorbed radiation divided by the lasing wavelength [2] and can be calculated from (2),

$$\eta_q = \frac{\lambda_s}{\lambda_L} \tag{3}$$

and η_{ovp} is the overlap of laser absorption with the solar spectrum and can be calculated from the equation,

$$\eta_{ovp} = \frac{\int_{a.b} g_\lambda d\lambda}{\int_0^\infty g_\lambda d\lambda} \tag{4}$$

where g_λ is the standard solar spectral irradiance. Note that,

$$\int_0^\infty g_\lambda d\lambda = I_o \tag{5}$$

λ_s in (3) is defined as the mean absorbed and intensity weighted solar radiation wavelength, i.e.,

$$\lambda_s = \frac{\int_{a.b} g_\lambda \lambda d\lambda}{\int_{a.b} g_\lambda d\lambda} \tag{6}$$

with a.b. sign under the integral indicating once again that the integration is performed over the laser absorption bands only. The laser output P_{out} can be written as,

$$P_{out} = (A_a I_s)\frac{T}{(2\gamma_l - \ln R)}[g_o - (\gamma_l - \ln\sqrt{R})] \tag{7}$$

where I_s is the saturation flux; T and R are the output mirror transmission and reflectivity, respectively, g_o is the small signal gain; and γ_l is the loss per pass in the laser.

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

$$P_{out} = \eta_s(P_{in} - P_{th}). \tag{8}$$

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. The experimental data can be plotted graphically giving a straight line at correlation [2]. From the intercept of this line with the $(-\ln R)$ axis, the round trip loss across the rod can be determined; while from the slope of this line the pumping efficiency can be determined. It was found that the round trip loss across the laser rod is $2\gamma_l = 0{\cdot}05 \pm 0{\cdot}01$. Also, the pumping efficiency was obtained to be $\varepsilon = 0{\cdot}76 \pm 0{\cdot}1$ [2] [2].

The output results of this model were then plotted in a graph representing the relation between the input solar radiation power on the laser rod and the output laser power according to this input. Also, the performance of all of the system has been studied graphically. After this testing of the model, we have applied it to the observed data taken at Helwan, which is a town near Cairo, the capital of Egypt, in the different seasons to study the behaviour of the output laser during the year.

A solar radiation station fixed on the rooftop of the National Research Institute of Astronomy and Geophysics (NRIAG) at Helwan was used for taking the measurements of the solar radiation components such as the global, direct and diffuse ones. These measurements have been recorded by using a pyranometer for the global and diffuse components and a pyrheliometer for the direct one. These instruments were fabricated in the Eppley laboratory (EPLAB) in USA. Helwan is an industrially polluted town and the pollution affects the insolation levels of the solar radiation components. The measurements indicate that the annual average of the global solar radiation is 5·21 kWh/m^2/day, direct solar radiation is 6·26 kWh/m^2/day, diffuse solar radiation is 1·86 kWh/m^2/day, clearness index K_t is 0·61 and the diffuse fraction K_D is 0·37.

Figures 3 and 4 represent the output laser power and irradiance according to the input ones, while figures 5 and 6 represent the output laser power and irradiance according to the incident solar radiation on the primary concentrator. Also figures 7 and 8 show the hourly variation of the output laser power and irradiance during the day in the different seasons of the year. All these curves represent the case in which the secondary concentrator (CPC) was filled with air which has a refractive index of unity.

In the same manner, figures 9 and 10 represent the output laser power and irradiance according to the input ones, while figures 11 and 12 represent the output laser power and irradiance according to the incident solar radiation ones on the primary concentrator. Also, figures 13 and 14 show hourly variations of the output laser power and irradiance during the day in the different seasons of the year. All these curves represent the case in which the secondary concentrator (CPC) was filled with sapphire which has a refractive index of 1·76.

The filling of the secondary concentrator by a material of a refractive index more than unity can increase the concentration level of this concentrator to a higher value which can be calculated by multiplying the geometrical concentration ratio of the concentrator by the refractive index of the material. This fact is provided with selecting a material which has an optical absorption band which does not overlap the solar radiation band.

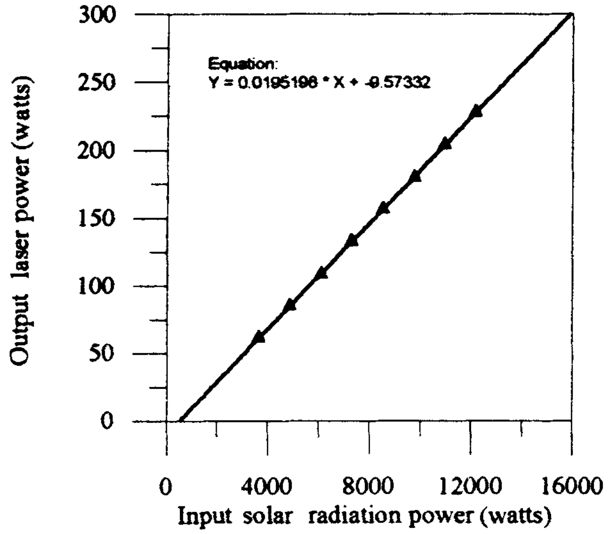

Figure 3. Performance of a direct solar-pumped Nd:YAG rod laser with side pumping technique in the case of a CPC filled with air concentrator.

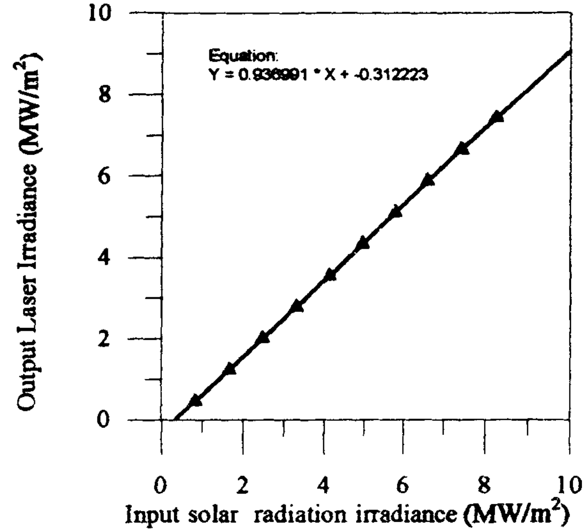

Figure 4. The output laser irradiance against the input solar one (in the case of a CPC filled with air concentrator).

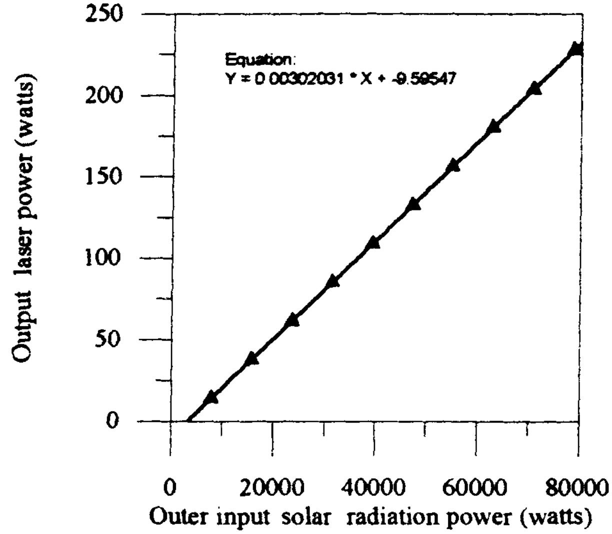

Figure 5. Output laser power against incident solar radiation one on the primary concentrator (in the case of an air-filled secondary concentrator of side pumping technique).

This model obtained by the side pumping technique gives best results. We can say that 60 kW of incident power on the primay concentrator can give about 171·62 W of laser power as an output in the case of an air-filled CPC and 309·32 W in the case of the a sapphire-filled one in the side pumping technique. This can be translated to 764 W/m^2 which can give 5·59 MW/m^2 in the first case, and 10·08 MW/m^2 in the second one. This level of insolation is easy to obtain in Egypt and accordingly the system operation will be a great success from both the practical and economical point of view.

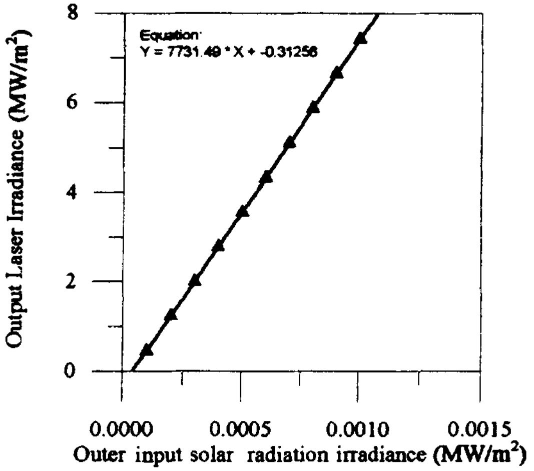

Figure 6. Output laser irradiance against incident solar radiation one on the primary concentrator (in the case of an air-filled secondary concentrator of side pumping technique).

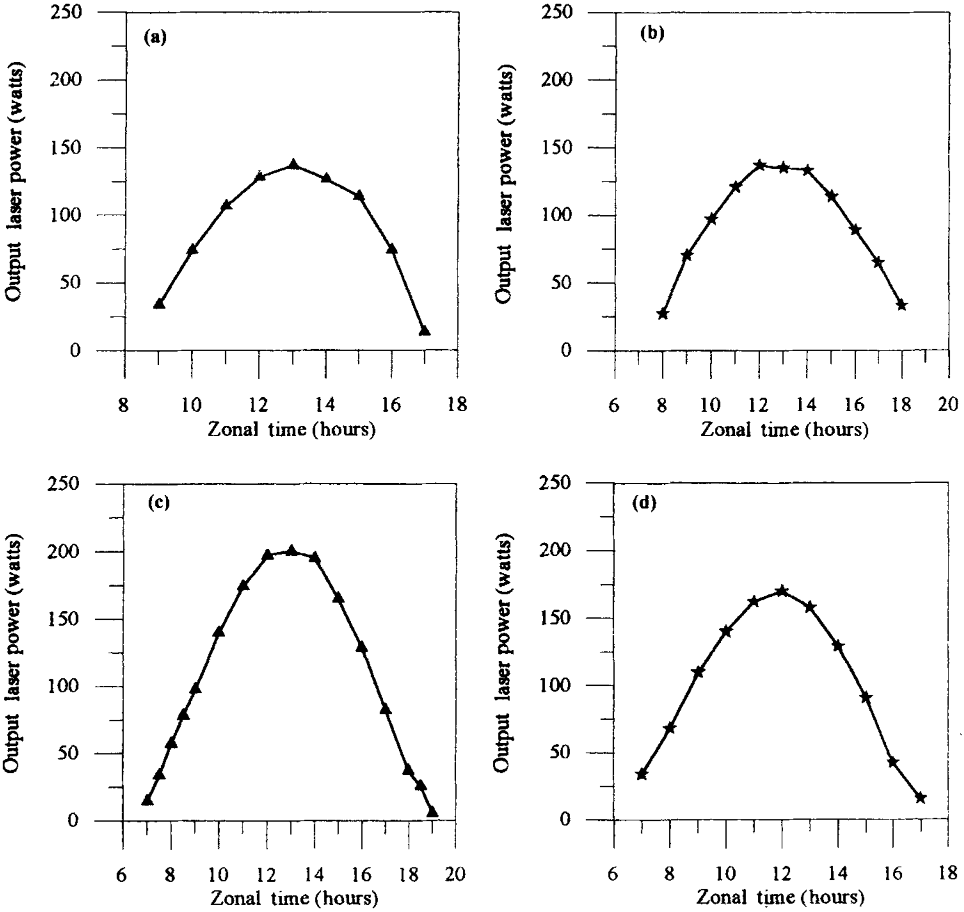

Figure 7. Hourly variations of the output laser power during the day in the case of a CPC filled with air concentrator in (**a**) Winter, (**b**) Spring, (**c**) Summer, and (**d**) Autumn.

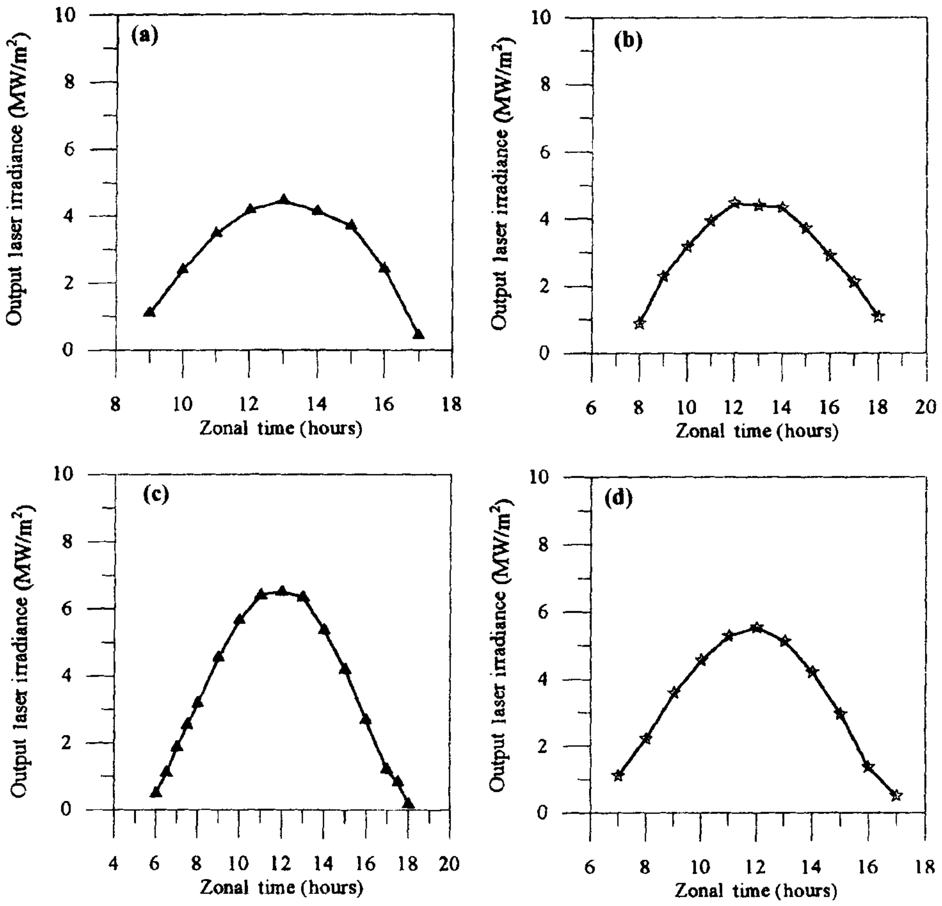

Figure 8. Hourly variations of the output laser irradiance during the day in the case of a CPC filled with air concentrator in (**a**) Winter, (**b**) Spring, (**c**) Summer, and (**d**) Autumn seasons.

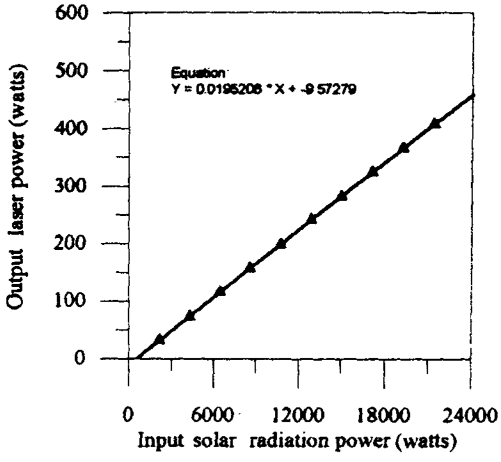

Figure 9. Performance of a direct solar-pumped Nd:YAG rod laser with side pumping technique in the case of a CPC filled with sapphire concentrator.

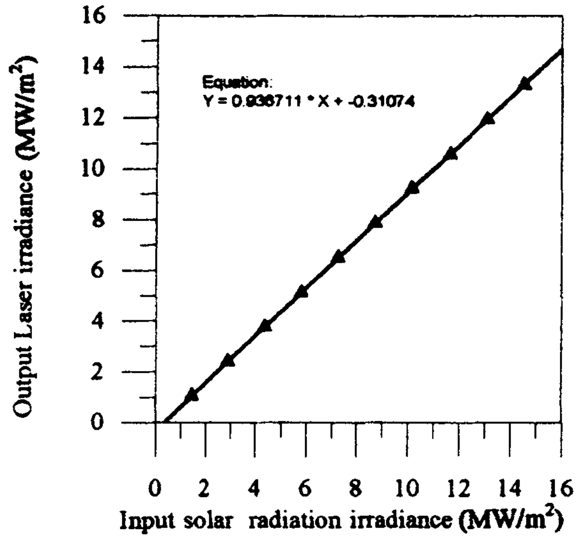

Figure 10. The output laser irradiance against the input solar one (in the case of a CPC filled with sapphire concentrator).

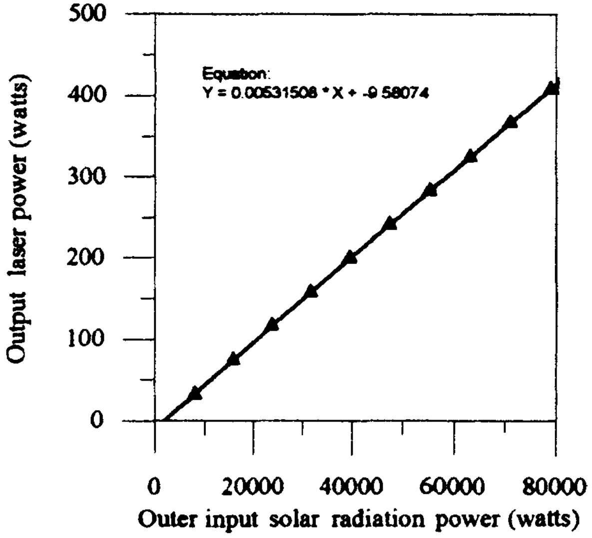

Figure 11. Output laser power against incident solar radiation one on the primary concentrator (in the case of a sapphire-filled secondary concentrator of side pumping technique).

4. Conclusions

After filling the secondary concentrator with air which has a refractive index of unity, we find that the performance of the system is good and we can get more than 100 W of output power according to 6 kW of incident power on the laser heat with a slope efficiency of about 2%. This can be translated into 2 MW/m^2 of output laser irradiance according to

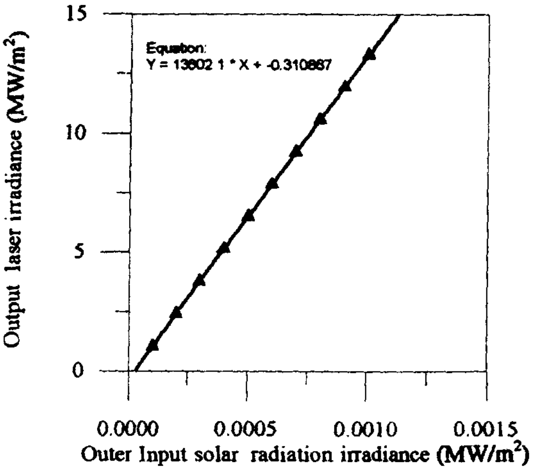

Figure 12. Output laser irradiance against incident solar radiation one on the primary concentrator (in the case of a sapphire-filled secondary concentrator of side pumping technique).

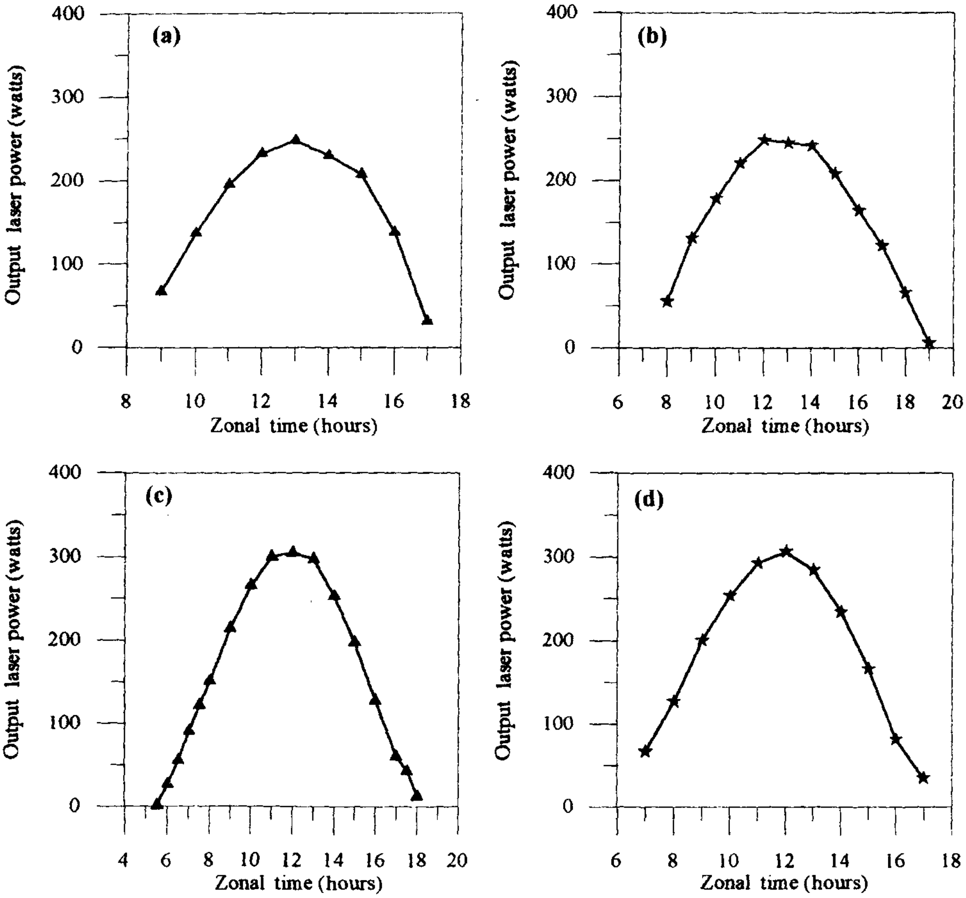

Figure 13. Hourly variations of the output laser power during the day in the case of a CPC filled with sapphire concentrator in (**a**) Winter, (**b**) Spring, (**c**) Summer, and (**d**) Autumn seasons.

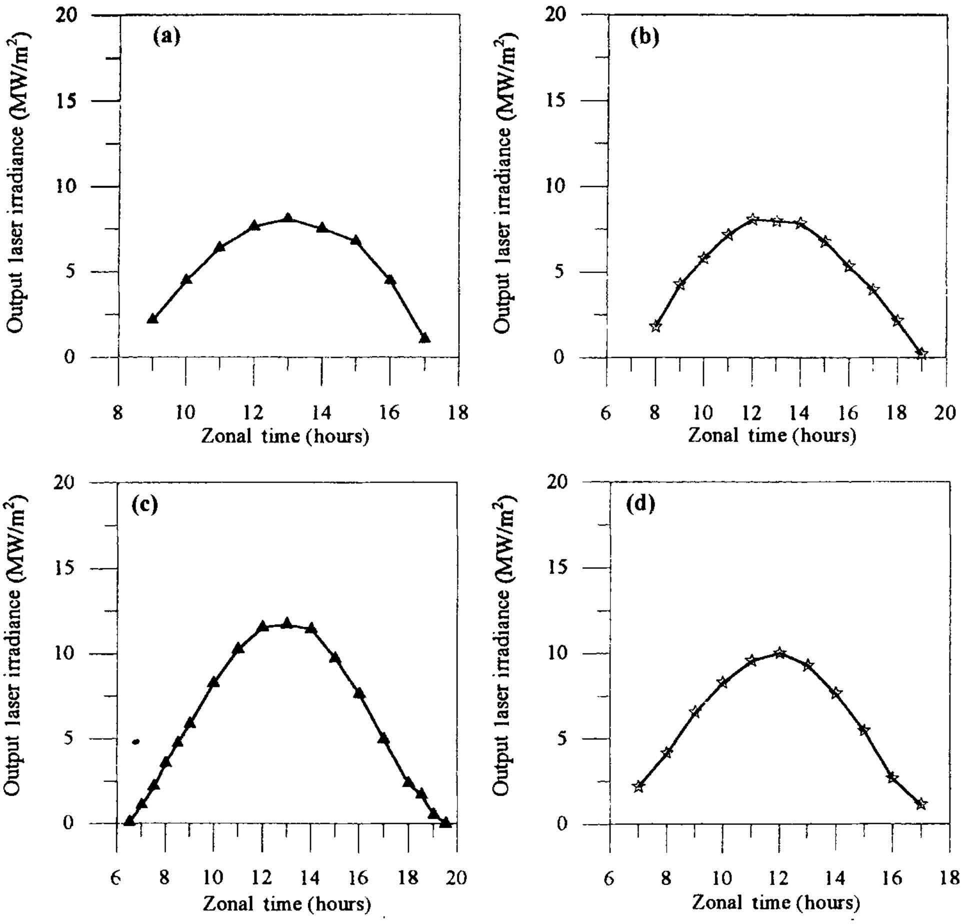

Figure 14. Hourly variations of the output laser irradiance during the day in the case of a CPC filled with sapphire concentrator in (**a**) Winter, (**b**) Spring, (**c**) Summer, and (**d**) Autumn seasons.

2·5 MW/m^2 of incident solar radiation. Also, after filling the secondary concentrator with a material of a refractive index more than unity like sapphire which has a refractive index of 1·76, the performance of the system will increase and we can easily reach higher input power and irradiance which will in turn give higher output ones.

By filling the secondary concentrator with sapphire which has a refractive index of 1·76, we can find that the yearly average maximum output power and irradiance obtained by this system will increase by a factor of 1·81, while the average daily output power and irradiance during the year obtained by this system will increase by a factor of 1·76.

The total efficiency of the side pumping technique solar laser system is nearly 0·3% in the case of air-filled secondary concentrator and 0·5% in the case of the sapphire-filled one. Thus, we can say that by filling the secondary concentrator with sapphire, the total efficiency of the side pumping system will increase by a factor of 1·76.

It is clear that 60 kW of incident power on the primary concentrator can give about 171·62 W of laser power as an output in the case of air-filled CPC and 309·32 W in the case of the sapphire-filled one, in the side pumping technique. This can be translated

Table 4. The seasonal behaviour of the maximum output of the solar laser system.

Refractive index	n = 1		n = 1·76	
Seasons	Power (W)	Irradiance (MW/m^2)	Power (W)	Irradiance (MW/m^2)
Winter	136·763	4·459	247·99	8·083
Spring	137·001	4·466	248·407	8·097
Summer	199·858	6·514	359·036	11·7
Autumn	169·971	5·54	306·435	9·988
Mean	160·8925	5·2448	280·467	9·467

Table 5. Variations of the average output of the solar laser system during the year.

Refractive index	n = 1		n = 1·76	
Seasons	Power (W)	Irradiance (MW/m^2)	Power (W)	Irradiance (MW/m^2)
Winter	89·8078	2·9268	148·5957	4·8431
Spring	92·9464	3·0298	157·1199	5·1214
Summer	141·651	4·6171	256·585	8·3637
Autumn	101·6264	3·3127	186·1627	6·0681
Mean	106·5079	3·4716	187·1158	6·0991

into 764 W/m^2 of incident irradiance which can give 5·59 MW/m^2 in the first case and 10·08 MW/m^2 in the second one which are highest values obtained by this technique and conditions.

In future using solar concentrators for laser generation in the desert can be cheaper than that for space because funds to push the system into space is very high from the economical point of view. It is recommended to use sapphire-filled concentrator in Egypt in the winter season in order to get a higher power and more intense output according to the data of the previous tables. Egypt has good conditions for using the solar laser systems which gives high outputs during the seasons. The season which gives higher ones is obviously the summer season while that which gives lower ones is winter with spring and autumn seasons registering outputs, in between.

The resulting data and its study are according to the measurements recorded at Helwan, an industrial and polluted area. We expect better results can be obtained if the system was set up in a less polluted and cleaner area.

References

1. Winston R and Welford W T 1980 *Design of nonimaging concentrators as a second stage in tandem with image-forming first-stage concentrators Appl. Opt.* **19** 347
2. Weksler M and Schwartz J 1988 *Solar-pumped solid-state lasers IEEE J. of Quantum Electronics* **24** 1222
3. Brauch U, Muckenschnabel J, Thompson G A, Hane Bernstein, Amnon Yogev, Reich A and Moshe Oron 1992 *Influence operating temperature on the power, divergence in solar-pumped solid state lasers Opt. Eng.* **31** 1072

4. Moalam Shaltout M A, Medhat M and Hadi Y A 1997 *End pumping technique model for laser pumped by solar energy, Proc. 4th IEEE Intl. Conf. Electronics, Circuits and Systems (ICE-CS'97)* vol. 2, pp. 766
5. Hadi Y A 1996 *Numerical simulation model for the optical behaviour of the compound parabolic and conical solar energy concentrators for laser beam generation* M Sc thesis, Ain Shams University, Cairo, Egypt
6. Winston R, Cooke D, Gleckman P and O'Gallagher J J 1992 *Ultra-high solar flux and applications to laser pumping, Proc. of Renewable Technology and the Environment* (ed.) A A M Sayigh ed. (Reading UK: Pergamon Press) pp. 83