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Kobry El-Kobbah,
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Computer aided design, optimization and performance enhancement of solid state laser cavities

By

Ahmed H. A. Badia. * Amro M. Youssef* Samy A. Ghoniemy* Mohy S. Mansour**

Abstract:

Design of laser cavities is a complicated process. It includes several optical, geometrical and material parameters. Computer Aided Design of laser cavities reduces the time and effort required to reach the optimum design.

In this paper an accurate and fast three dimensional CAD model for simulating solid-state laser systems is developed. Numerical estimations of the geometrical transfer efficiency of various cavities are presented. Analytical and iterative methods to achieve a feasible converged solution for designing optimum pumping champers which contains different geometrical dimensions of laser rods, flash lamps and walls reflectivity are discussed.

A simulation study of the pumping efficiency of the laser heads with respect to the cavity geometry, different geometries of laser rods and flashlamps, and reflecting coatings have been carried out. The goal is to achieve a maximum concentration of the light flux of the pumping source towards the active medium. Results are presented using Matlab and Microsoft office excel. Computer aided design is then used to create three dimensional parametric model of laser cavity assembly. The proposed model has been compared with published results and shown to be very accurate and efficient for modeling three-dimensional solid-state laser chambers.

Keywords:

Solid state lasers, laser efficiency, laser pump cavities and cad modeling

* Egyptian Armed Forces
** Faculty of Engineering, Cairo University

1. Introduction.

A major concern in laser development is to achieve the maximum transfer efficiency of the radiation from the pump source to the laser crystal with a uniform absorption distribution [1].
Solid state lasers assume different pumping arrangements depending on the active medium shape (cylindrical or slab), method of pumping and on the radiant source characteristics (lamp or diode) [2].
Energy flow in solid state laser system discussed from an efficiency perspective, where a product of efficiencies approach is developed and applied to describe overall laser systems' performance [3].
In the development of solid state lasers, different cavities have been designed [4]. Among them is the elliptic cavity, which has relative high efficiency [5], in which a lamp-pumped laser makes use of a hollow reflective pump cavity to couple the optical radiation from the radiant source with the laser rod. The elliptical cavity is based on the geometric theorem that rays originating from one focal line of an elliptical cylinder are reflected into the other focal line; therefore the energy can be transferred from a line source (lamp) to a line absorber (crystal). As a consequence of the preservation of angles, the portion of the elliptical reflector nearer the lamp forms a magnified image at the laser rod while that portion nearer the crystal forms a reduced image of the lamp. The transfer efficiency of the elliptical cavity and its dependence on the cross-section of the reflector, radiant source, laser crystal, the walls reflectivity and ellipse eccentricity were extensively discussed in [5-8].
Besides the optical coupling efficiency, the pump cavity also determines the pump light distribution at the laser rod surface with a polished surface. The focusing properties of the elliptical cylinder and the direct radiation from the pump source lead to approximately elliptically shaped concentration of the pump radiation on the central core region of the rod. To improve the pump uniformity, diffusive reflectors are often employed; however, an asymmetric gain distribution remains unchanged since the rod is pumped just from one side. On the other hand a relatively uniform gain distribution can be achieved only by using a multiple elliptical cavity [8].
Researching the area of high performance solid state laser cavities showed that the transfer efficiency is of high importance as uniform pumping. Transfer efficiency depending mainly on optimum reflections inside pump cavity with minimum losses which can be achieved by pumping cavity geometry design. This depends mainly on the shape of lasing material and the method of focusing the pumping energy onto the lasing material.
The transfer efficiency formula for diffusely reflecting laser pump cavities is intensively discussed in [9], while the calculation methodology of pump efficiency in reflecting close coupled cavities was discussed in [10].
A comparative study between different pump cavities for compact pulsed Nd:YAG lasers for specular and diffused reflections was presented in [11]. Analyzing these research efforts leaded us to conclude that solid-model-based mechanical design and analysis, three dimensional parametric solid modeling CAD systems are necessary to allow laser systems to be virtually built, assembled, and analyzed prior to manufacturing [1]. In this paper, analytical modeling and simulation of the laser heads pumping efficiency with respect to the cavity

geometry, different geometries of laser rods, flashlamps and reflecting coatings have been carried out to achieve a maximum concentration of the light flux of the pumping source. For this purpose, three dimensional solid model is developed based on parametric programming using Pro/Engineer CAD/CAM software. The proposed model provides the optimum transfer efficiency that fulfills the required output power and beam shape (or profile). The proposed model is dynamically adapted according to the requirements which in turn dynamically adjust the pump chamber geometric design parameters.

For paper organization, paper consists of seven sections, section one is an introduction contains literature survey, the important results and the work which will be done, section two discuss analytical modeling and numerical estimation of geometric transfer efficiency of elliptical cavity, section three discuss the mathematical modeling of elliptical cavity geometrical parameters, for section four and section five cavity optimization algorithm and CAD modeling of proposed optimized cavity will be discussed respectively, model verification and conclusion will be presented in section six and section seven.

2. Analytical modeling and numerical estimation of geometrical transfer efficiency of elliptical cavity.

In this paper, geometrical transfer efficiency has been estimated assuming cylindrical rod as lasing material and flashlamp as the optical pumping source. In case of single elliptical cavity, the main principle is to position the rod and the lamp in the foci of the ellipse where the rays transmitted from the lamp will be reflected to the other foci at the centerline of rod as shown in figure (1).

In this figure, the position "P" determines whether the reflected beam is focused or defocused on the rod, "2a" and "2b" are the major and minor diameters of the ellipse, "2c" is the geometrical distance between the rod and lamp centers, "$2r_R$" and "$2r_L$" are the rod and lamp diameters, respectively.

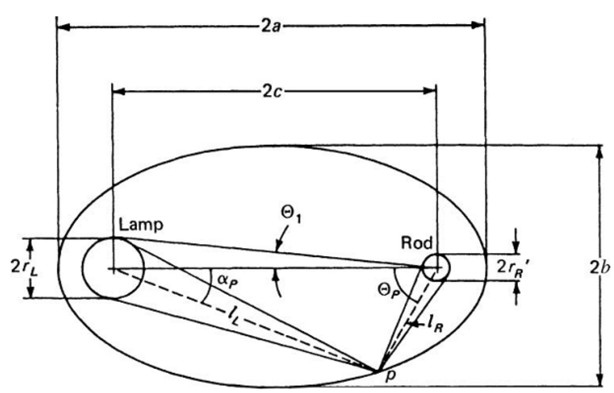


Figure (1): *cross section of elliptical pump cavity.*

The geometric transfer efficiency "η_{geo}" can be analytically estimated by calculating the ratio of the focused reflected energy on the rod to the emitted energy from the lamp and integrating over all possible positions of "P" [4] and given by;

$$\eta_{geo} = \frac{100}{\pi}\left(\alpha_p + \frac{r_R}{r_L}\theta_p\right) \tag{1}$$

in which

$$\alpha_p = \cos^{-1}\left(\frac{\left(1-0.5\left(1-e^2\right)\left(1+\frac{r_R}{r_L}\right)\right)}{e}\right) \tag{2}$$

$c = \sqrt{a^2 - b^2}$ and $e = \frac{c}{a}$ where "e" is the eccentricity,

$$\theta_p = \sin^{-1}\left(\frac{r_R}{rL}\sin\alpha_p\right) \tag{3}$$

Where "α_p" and "θ_p" are in radians. Using equations (1)-(3), the transfer efficiency "η_{geo}" is calculated and plotted as shown in figure (2). This figure shows that the transfer efficiency is a monotonically increasing function with increasing the ratio (b/a) and saturates approximately when (b/a) reaches 1. It also shows that for specific (b/a) ratio the transfer efficiency increases as increasing the rod to lamp radius ratio which means that in general "r_R" should be large than "r_L" where portion of elliptical reflector nearer the lamp forms a magnified image at the laser rod, while the portion near the crystal forms a reduced image of the lamp. Back to figure (1), a point "P" with corresponding angles "α_p" and "θ_p" measured from the lamp and rod axis, respectively, may be defined to divide these two regions, at which the ellipse generates an image of the lamp which exactly fills the crystal diameter.

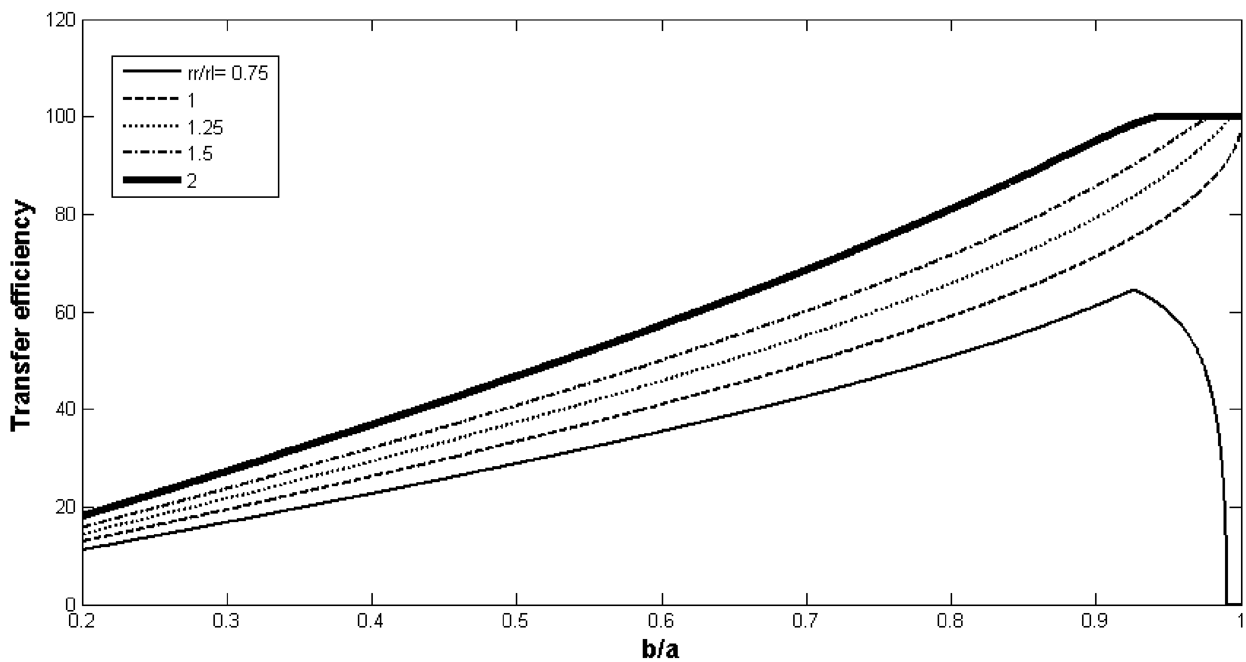


Figure (2): *Efficiency of single elliptical cavity vs. ellipse geometry for different rod/lamp radius ratios.*

The laser pump cavity with low eccentricity leads quickly to high transfer efficiency. Also, it can be observed that 100% theoretical transfer efficiency could be approached using almost circular cylinder when the rod diameter is twice that of the flashlamp.

3. Mathematical modeling of elliptical cavity geometrical parameters.

In this section, the geometrical design parameters of elliptical cavities can be estimated for specific transfer efficiency and output power under different rod/lamp radius ratios. For this purpose, a mathematical model is developed based on equation (1), and taking into consideration the lamp blocking effect, "η_{loss}", and given by;

$$\eta_{geo2} = \eta_{geo} - \eta_{loss} \tag{4}$$

In which "η_{geo2}" is the effective part of the transfer efficiency and "η_{loss}" is the reflected energy loss due to the lamp blocking and given by;

$$\eta_{loss} = \left(\frac{r_R}{r_L}\right)\left(\frac{\theta_1}{180}\right) \tag{5}$$

and

$$\theta_1 = \tan^{-1}\left(\frac{r_L}{2c}\right) \tag{6}$$

Where "2c" is the distance separation between two foci of single ellipse at which the lamp and rod are positioned. The value of "c" is assumed to be k*(r_R+r_L), where "k" is a ratio larger than unity and its value depending on the presence of flow tubes around rod and lamp or not.

Rearrange equations (1)-(3) to find the value of "α_p", "θ_p" and eccentricity "e" by solving the following equations:

$$(-\eta_{geo} * \pi) + \left(\alpha_p + \frac{r_R}{r_L}\theta_p\right) = 0 \tag{7}$$

$$\sin^{-1}\left(\frac{r_R}{r_L}\sin\alpha_p\right) - \theta_p = 0 \tag{8}$$

$$-0.5\left(1+\frac{r_R}{r_L}\right) * e^2 + (\cos\alpha_p) * e - \left(1 - 0.5\left(1+\frac{r_R}{r_L}\right)\right) = 0 \tag{9}$$

The ellipse is defined by semi-major axis "a", semi-minor axis "b" and foci separation "c". Values of "a" , "b" can be obtained as function of eccentricity "e" and focal separation "c" from the following relations:

$$a = \frac{c}{e} \tag{10}$$

$$b = a\left(1-e^2\right)^{\frac{1}{2}} \tag{11}$$

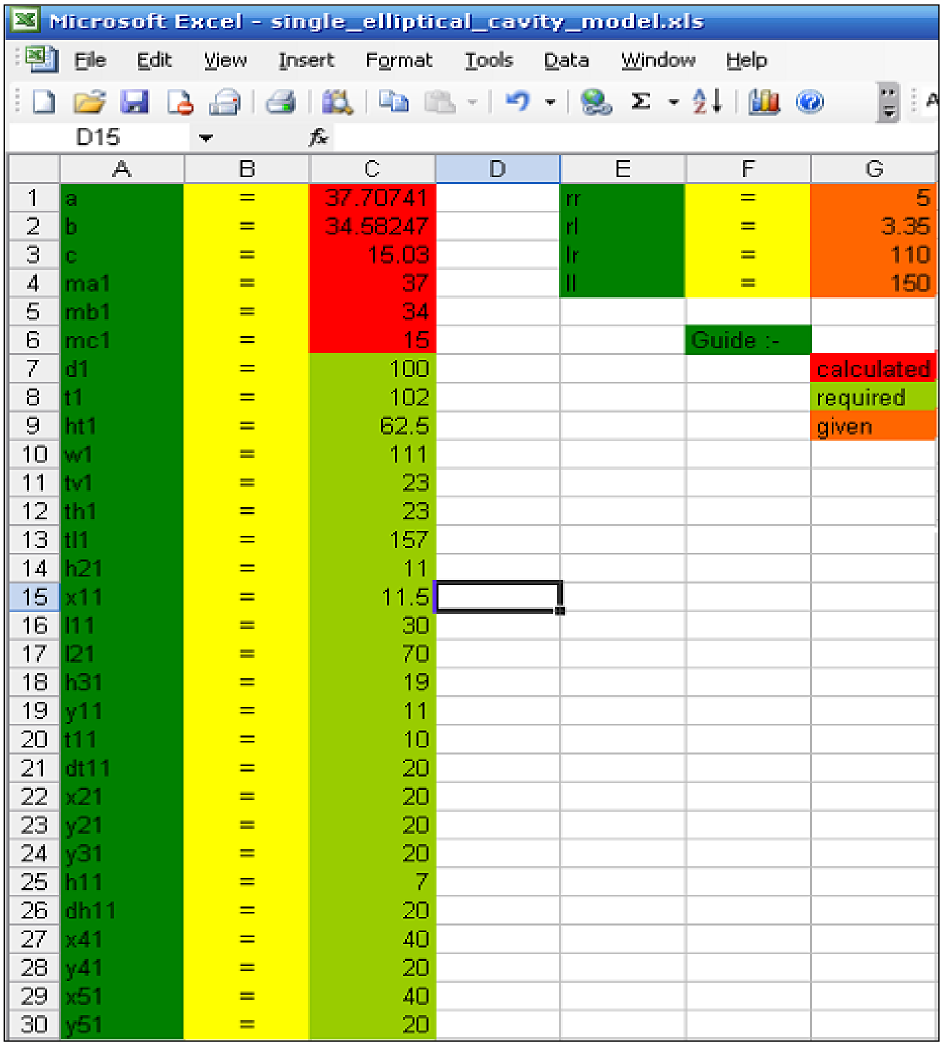
4. Cavity optimization algorithm.

The mathematical relation discussed in the previous section is used to create the model to solve the cavity geometry optimization problem. Matlab code was developed to carry out this task. The inputs are the required power and pumping efficiency then the optimization problem

is solved for different rod/lamp radius ratios under several constraints such as rod/lamp radius ratio ranges from 1 to 2 and the maximum output power is limited to 100 watts.
The optimization algorithm starts by assuming the separation distance “c” between two foci of ellipse, then calculate "θ_1" to evaluate the efficiency losses "η_{loss}" due to lamp blocking effect. Then the nonlinear equations (7-9) are solved to get the value of "α_p" and "θ_p" using a callback function with number of trials based on using trust region dogleg algorithm. The key feature of this algorithm is the use of the Powell dogleg procedure for computing a minimum error of the solution. The dogleg algorithm is efficient since it requires only one linear solve per iteration. Finally the eccentricity is evaluated to get different geometries of single elliptical laser cavity which satisfies the desired transfer efficiency and output power.

5. CAD modeling of the proposed optimized cavity.

From the previous section, output data "a", "b" and "c" are sufficient to describe the elliptical shape of the pump cavity. This data is used as main parameters of CAD parametric model where all parameters of the model are dependent on it. Parameters of CAD model and the parametric model developed for this pump cavity are shown in figure (4). This figure shows all the parameters required to update the parametric CAD model, where the required transfer efficiency is assumed to be 83.2% for rod radius 5mm and lamp radius 3.35mm.


Microsoft Excel - single_elliptical_cavity_model.xls

	A	B	C	D	E	F	G
1	a	=	37.70741		rr	=	5
2	b	=	34.58247		rl	=	3.35
3	c	=	15.03		lr	=	110
4	ma1	=	37		ll	=	150
5	mb1	=	34				
6	mc1	=	15			Guide :-	
7	d1	=	100				calculated
8	t1	=	102				required
9	ht1	=	62.5				given
10	w1	=	111				
11	tv1	=	23				
12	th1	=	23				
13	tl1	=	157				
14	h21	=	11				
15	x11	=	11.5				
16	l11	=	30				
17	l21	=	70				
18	h31	=	19				
19	y11	=	11				
20	t11	=	10				
21	dt11	=	20				
22	x21	=	20				
23	y21	=	20				
24	y31	=	20				
25	h11	=	7				
26	dh11	=	20				
27	x41	=	40				
28	y41	=	20				
29	x51	=	40				
30	y51	=	20				

Figure (4): *Simulation output for cavity parameters.*

Three dimensional solid models of single elliptical laser cavity are created using Pro/Engineer. The parametric design could be updated according to the resulting data from Matlab simulation code and the final parametric CAD model can be estimated using Pro/Engineer as shown in figure (5).

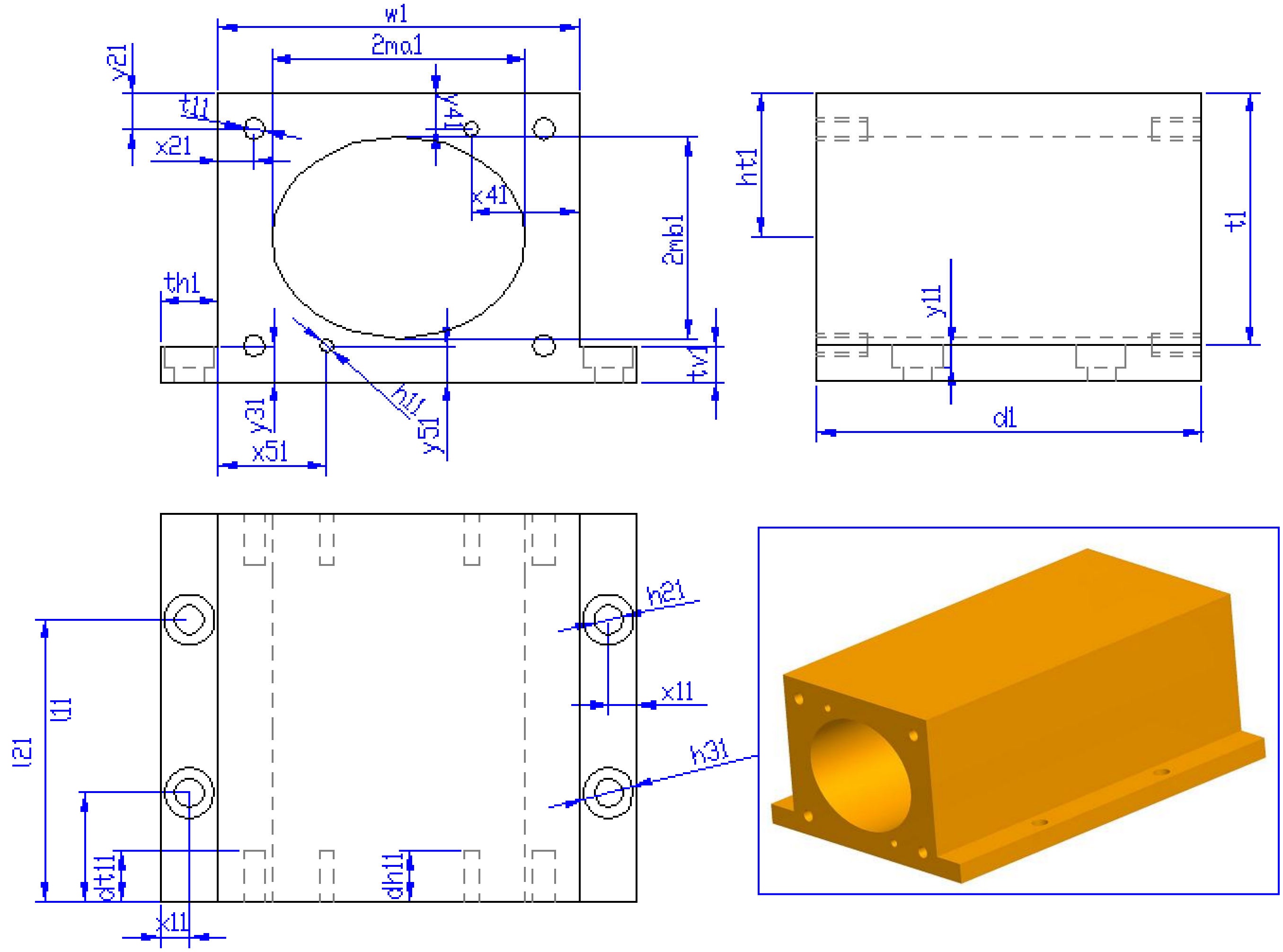


Figure (5): *Parametric CAD model of single elliptical laser cavity.*

6. Model comparison.

The results of the optimization algorithm were verified against the results presented in [4]. The results from the current work are designated in Table (1) by "M1" and are compared with the results found in literature and designated by "H1". From table (1), it can be observed that the results are in agreement with the published results.

Table (1): *Optimization results and Hachfeld [4]*

ηgeo2 %		ηgeo %		e		2a (mm)		2b (mm)		2c (mm)	
M1	H1	M1	H1	M1	H1	M1	H1	M1	H1	M1	H1
90.2		95.4	95.48	0.3	0.298	100	100.9	95	96.4	30	
83.2		88.5	88.48	0.4	0.399	75	75.4	69	69.1	30	
75.2		80.5	80.48	0.5	0.499	60	60.2	52	52.2	30	
66.4		71.6	71.68	0.6	0.598	50	50.2	40	40.3	30	

56.4	61.6	61.68	0.7	0.699	43	43	31	30.8	30
44.7	50	50	0.8	0.8	37	37.6	22	22.6	30

7. Conclusions.

This paper presents an optimum geometric design of single elliptical cavity model that can be reached, and optimization of the geometric parameters using computer aided design. The developed model fulfills the desired geometric transfer efficiency and output power for different laser rods and flashlamps. This could save cost and time for the design and manufacturing processes of the optimized solid state laser cavities.

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