Investigation of absorption pump light distribution in edged-pumped high power Yb:YAG\YAG disk laser

H. Aminpour[1],*, A.Hojabri[1], M. Esmaeili[2], and I. Mashaiekhy Asl[2]

[1]**Department of Physics, Karaj Branch, Islamic Azad University, Karaj, Iran**

[2]**Iranian National Center for Laser Science and Technology (INLC), Tehran, Iran**

***Corresponding Author:** Ph_matnava@yahoo.de

Abstract- In this article, we present a specific shape of disk laser which is side-pumped by four non-symmetric hollow- ducts. The use of non-symmetric hollow duct based on two goals of the uniformity of the pump light distribution profile and the homogeneity of pump light profile through the disk. First of all we simulated the pump light distribution in the disk by using Monte-Carlo ray tracing method. Then, by using finite element analysis (FEA) method, we calculated the absorbed pump light distribution through the disk for 12%, 14% and 20% concentration of Yb^{+3} ions. Finally, the results of calculation have been presented.

KEYWORDS: disk laser, hollow duct, Absorption efficiency, edged-pumped disk laser

I. INTRODUCTION

One of the important properties of YAG crystal as a mean of the active medium of solid state lasers is its excellent thermal conductivity comparing with the other crystalline [1]. The ion of Yb^{+3} has been a promising candidate for high-power laser–diode (LD)-pumped solid state lasers [2,3]. High output power lasers based on Yb:YAG have been achieved with high efficiency by using different laser cavity configurations, such as end-pumped microchip lasers, side–pumped and edge-pumped laser systems [4-6]. Yb:YAG as a quasi-three-level laser medium, has attracted a great amount of applications in micro-welding and laser industrial cutting preciously with high beam quality [7-8].The main disadvantage of ytterbium-doped material is their quasi- four level nature caused by the thermal population of terminated lasing level [9]. This effect becomes worse at high temperature induced from the heat generated by the absorbed pump power inside the Yb:YAG crystal. The thermal conductivity of Yb:YAG decreases and the thermal loading parameter increases with increasing ytterbium concentration. In addition, there is strong emission quenching, which is attributed to uncontrolled impurities during crystal growth. These concentration dependent thermal properties of Yb:YAG have great unwanted effects on the laser performance of side–pumped Yb:YAG disk laser. The thermal conductivity, thermal expansion coefficient, and thermal loading of Yb:YAG crystals related to the temperature, temperature rise induced by the pump power deposited on the gain medium are critical factor to be considered in the laser performance of side-pumped Yb:YAG high power disk laser. So, different value of Yb^{+3} ions concentration in the active medium have an effect directly on the final uniformity and the final homogeneity of the absorbed distribution profile through the gain medium. In this paper, we focus on the uniformity and the homogeneity of pump light distribution through the disk. In Section I, we simulated the pump light distribution in the disk by using Monte-Carlo ray tracing method. In Section II, we used finite element analysis (FEA) method to calculate the pump light absorbed distribution through the disk in 12%, 14% and 20% concentration of Yb^{+3} ion. In Section III, the consequence results of our piece of work have been presented and the paper is concluded in Section IV.

II. Modeling of Irradiance Distribution Profile

Improving of new geometric structure of devices used to increase the irradiance of diode laser radiation for pumping solid-state lasers have attracted especial attention recently. Requiring homogeneity pumping of the side-pumped gain medium with inclined sides that is improved in order to obtain better pumping by increasing the entrance area of the gain medium on the one hand and uniform distribution of it by homogenizing the pump light on the other hand, encourages us to achieve a good beam shaping of the pump profile and high output power corresponding to the specific geometry of the gain medium which is illustrated in Fig. 1.

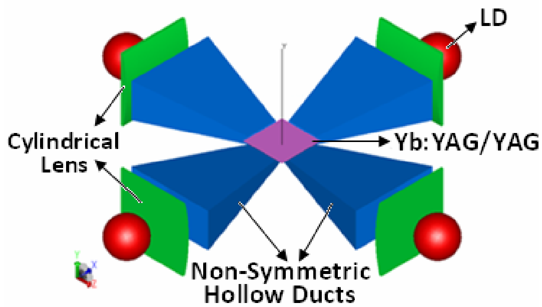


Fig. 1: Schematic view of Yb:YAG disk laser with four non-symmetric hollow ducts of side-pumped configuration.

Table 1 The parametric of the gain medium used in our modeling.

Parameters		Units	Value
Crystal Thickness	Doped region	μm	200
	Undoped region	mm	1.3
Length of crystal		mm	8
Width of crystal		mm	8
Inclined side of crystal		degree	30
Pump wavelength		nm	941
Material of disk		#	Yb:YAG
Power of LD		W	500
Coolant Temperature		°K	300

As shown in Table 1, in this work, model parameters are obtained from our previous paper [10]. A thin disk with slanted edges is pumped with a maximum pump power P_p=2 kW by use of four stacked diode lasers set at 941 nm. Top view of thin-disk active media is a 8mm×8mm square and thickness of 0.2 mm. Its edges are cut at 30° with respect to the floor and Yb/YAG active medium is bonded on a 1.3 mm thick YAG top layer to act as a covering cap to reduce amplified spontaneous emission effect and deformation. Dopant concentrations of disk are used in different value of 12%-, 14%- and 20%-atom. The parameters of the gain medium which are coupled to the non-symmetric hollow-duct for side-pumped are described in Table 1.

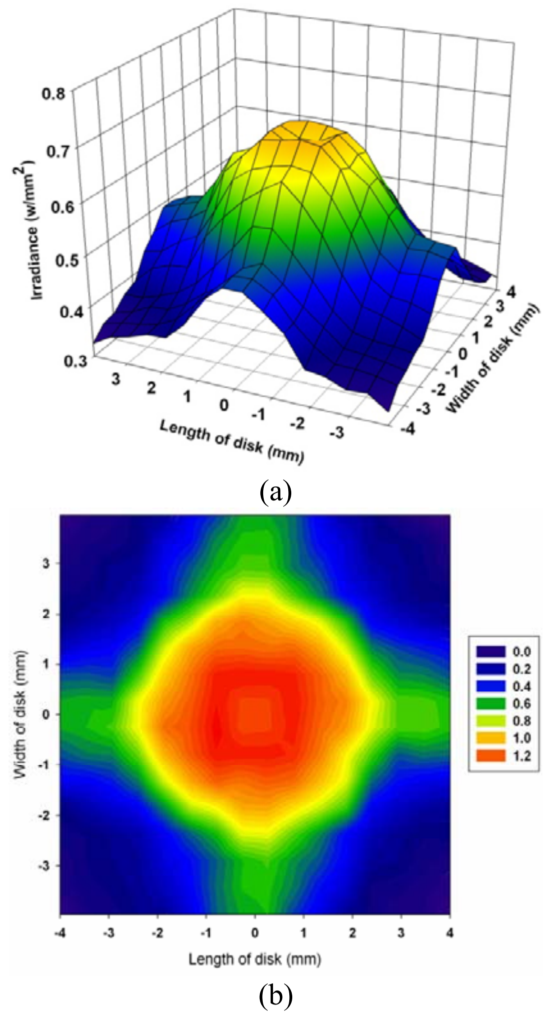


Fig 2. a) Irradiance distribution of the pump light profile through the disk, b) Contour profile of pump light irradiance which is indicated the homogeneity of pump light distribution in the center of the disk

Using of those types of non-symmetric hollow ducts in our work have an important role in order to obtaining uniform and homogeneity of pump light distribution of edged pumped high power disk laser. Regarding the optical configuration of our work which is illustrated in Fig. 1, we simulated the irradiance profile with the goals of uniformity and homogeneity of pumped light through the active medium by using simple ray tracing method. Final irradiance profiles in the thin disk medium by using four non-symmetric hollow ducts are shown in Figs. 2(a) and 2(b). Every incoming ray which is incident from the entrance slanted faces of non symmetric hollow ducts into the disk edges has a fraction of diode pump power at the pump wavelength (941 nm) with 3 nm spectral width. The modeling would be based on both random positions on the edge surfaces of thin disk and random moving direction consist of calculated angle of ray tracing through the active medium. In Fig. 2(b), we illustrated the intensity contour profile of side-pumped with its legend which is indicated the homogeneity of pump light distribution in the center of the active medium.

III. MODELING OF ABSORPTION PUMP LIGHT DISTRIBUTION PROFILE

Thermal population has deleterious effects on the resonant reabsorption of laser emission by the thermally populated terminated laser level [9]. The effect becomes worse at high temperature induced from the heat generated by the absorbed pump power inside the Yb:YAG crystal. In addition, the thermal population still depends strongly on the concentration of Yb^{+3} lasants in YAG crystal. The thermal conductivity of YAG decreases and the thermal loading parameter increases with increasing ytterbium concentration. Furthermore, there is strong emission quenching, which is attributed to uncontrolled impurities during crystal growth. These concentration dependent thermal properties of Yb:YAG have great unwanted effects on the laser performance of Yb:YAG disk lasers at ambient temperature without sufficient active cooling system. The thermal conductivity, thermal expansion coefficient, and thermal loading of Yb:YAG crystals related to the temperature, temperature rise induced by pump power deposited on the gain medium are an important factors to be considered in the laser performance of Yb:YAG disk laser. Also, temperature has a great impact on the emission peak cross section of Yb:YAG crystals [11]. So, those mentioned effects would lead to the fraction of the gain medium due to the high temperature loading. In the following step, we calculated absorbed pump power density in the active medium by the means of Random Monte-Carlo ray tracing method. The first step in the modeling could be defined as the recognition of the simple optical ray tracing method as respect to the specific shape of the gain medium. The intensity of random rays would be exponentially damped through the disk as [12]:

$$I(v) = I_0(v)\exp\left[-\alpha(v)L\right] \tag{1}$$

Equation (1), indicates that the intensity depends on the path length of the ray through the gain medium. Therefore, some of pump power absorbed in the active medium, it can be called the absorption efficiency of the system, and the rest of the pump power is lost by thermal losses from the active medium. The next step would be meshing of the disk to the cubic elements with the same volumes for the upper and the bottom surfaces of the disk and the triangular elements with tiny dimensions for the slanted faces of the active medium. Each ray is specified by the random position on the slanted faces of the disk and hence, the ray path could be determined and the elements which have been passed would be distinguished from the others. We have used Monte- Carlo ray tracing approach with photon randomly emitted from the pump source to the disk faces. A passing photon is absorbed randomly in one of the element that passes in its way through the crystal. In our calculation we have used rays regarding that each element in the way of a passing ray obtains a fraction of the total energy. The absorption coefficient for pump radiation in active medium is given by [13]:

$$\alpha_0 = (f_{l1} + f_{u2})\sigma_{abs}(p)N_{Yb} \tag{2}$$

where f_{l1} and f_{u2} are pump $^2F_{\frac{7}{2}}$ and $^2F_{\frac{5}{2}}$ stark level Boltzmann occupation factor, respectively, σ_{abs} is the absorption cross section, N_{Yb} is the density of laser active ions. From the Eqs.2, one could easily realize that N_{Yb} refers to the Yb^{+3} ions concentration of the thin disk laser active medium. It is clearly indicate that the linear relationship between N_{Yb} and α. Although in Eqs. 1 we have also σ_{abs}, but the relationship of σ_{abs} with the Yb^{+3} ions concentration is ignored in our piece of work.

Then, the absorption efficiency in the active medium is derived by:

$$\eta = \frac{\text{The number of absorbed photons whithin the active medium}}{\text{The total number of injected photons}}$$

and in addition, the loss of the system is given by:

$$\gamma = \frac{\text{The number of absorbed photons whithin the active medium}}{\text{The total number of injected photons}} \\ \ldots.. + \frac{\text{The number of exited photons from the active medium}}{\text{The total number of injected photons}} \qquad (3)$$

or $\gamma = \gamma_{abs} + \gamma_{exi}$, where γ_{abs}, is absorbed pump power inside the active medium and γ_{exi} is the exited pump power.

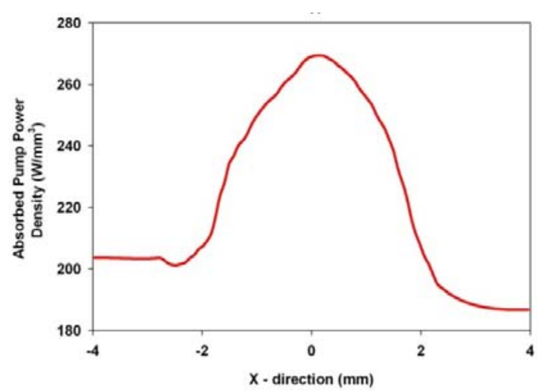
The absorbed pump power distribution is carried out through in three steps as follows:

1) Calculation of pump light distribution through the disk by using Random Monte-Carlo ray tracing method by using Math-lab numerical software, 2) Solution of the 3D differential equations of heat conduction, and 3) Solution of the differential equation of structural deformation through the active medium.

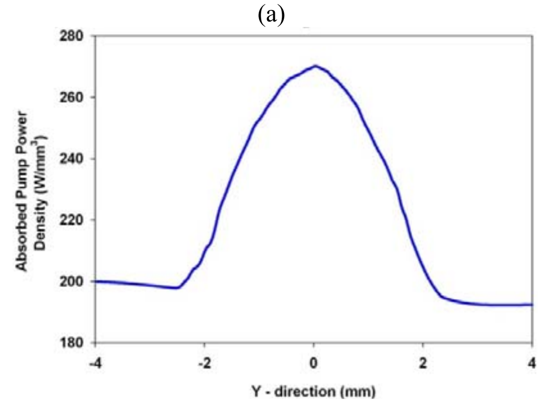
As shown in Fig. 3, the absorbed pump power distribution in two sides of the disk. It is clear that the absorbed pump power density profiles in X-direction and Y-direction are approximately similar to each other and have a uniform profile. Absorbed pump power density has a peak around the center of the disk and has its value in X-direction and Y-direction is $279\,W/mm^3$ and $287\,W/mm^3$, respectively.

Then, we calculated the absorbed energy of each photon by using finite element analysis (FEA) method by using LASer Cavity Analysis and Design (LAS-CAD) software [14].

In the following step, due to the random propagation of the rays through the active medium in different meshes in the thin–disk, we assume that each meshes absorbed a part of total energy of photons during the propagation of rays through the disk. We have done this calculation of absorbed energy for different Yb^{+3} ions concentrations which are shown in Figs. 4(a, b, c).

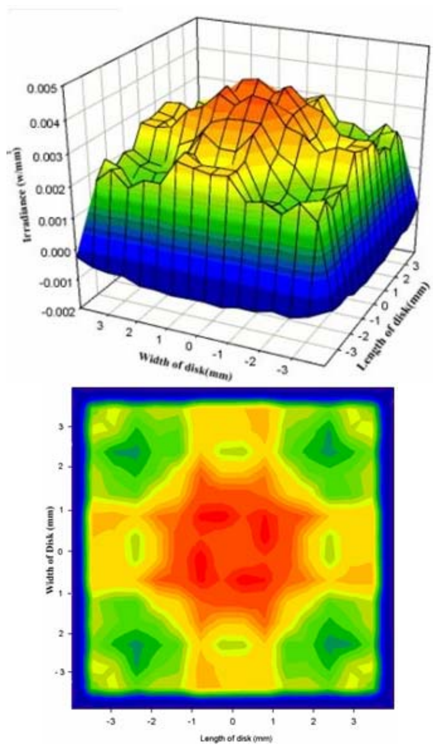


(a)

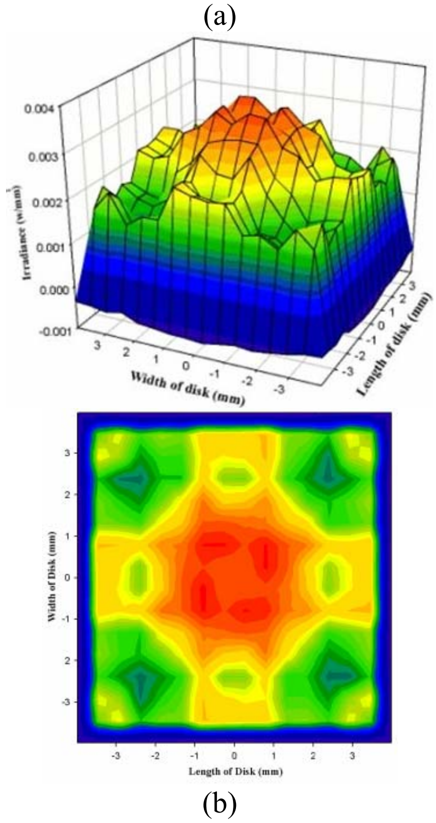


(b)

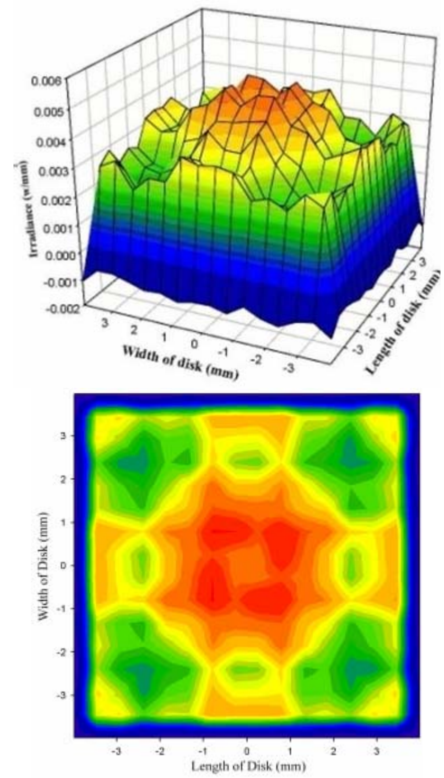
Fig. 3. Absorbed pump power distribution in two sides of the disk. a) Absorbed pump power density profile in X-direction. b) Absorbed pump power density profile in Y-direction. These are approximately similar to each other and have a Gaussian profile.



(a)



(b)



(c)

Fig 4. Absorbed pump light distribution profiles with their contour profiles of different Yb^{+3} ions concentration, a) 12% Yb^{+3} atom, b) 14% Yb^{+3} atom and c) 20% Yb^{+3} atom, respectively.

As shown in Fig. 4(a), according to the absorption distribution profile in 12% Yb^{+3} ions concentration with total pump power $\left(P_p\right)$ of 2KW, we obtained total absorption efficiency of 72%. By increasing Yb^{+3} concentrations from 12% to 14%, we obtained 76% of absorption efficiency at the similar conditions of cooling and other parameter of our configuration which is illustrated in Fig. 4(b).

In addition, we extended our calculation to high Yb^{+3} ions concentration to 20% which is in fact under the damage threshold of Yb crystal due to the thermo-mechanical properties of Yb:YAG crystal. For the last construction we obtained 84% of absorption efficiency which is depicted in Fig. 4(c). By comparison of the 3D diagrams and their contours profiles in Figs. 4(a, b, c), one would realized an increasing of absorption efficiency about 12% due to increase of Yb^{+3} ions concentration from 12% to 20%. We have done also 2D comparison of absorbed pump light distribution in different Yb^{+3} concentrations which the result is pictured in Fig. 5.

Finally, as shown in Fig. 5, we obtained an increase of absorption efficiency by neither increasing Yb^{+3} ions concentration in our work, but we should neither ignore the uniformity nor the homogeneity of the absorbed pump light distribution within the disk.

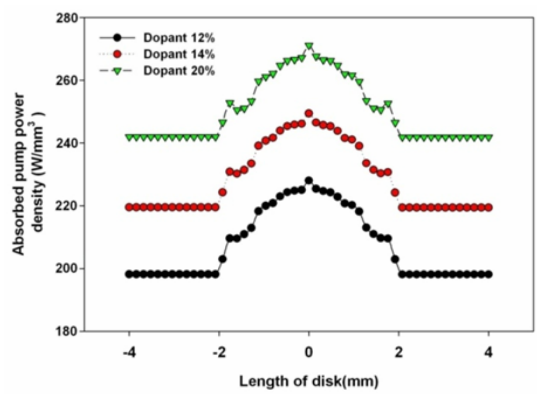


Fig 5. 2D comparison of absorbed pump light distribution through the disk for 12, 14 and 20 % of Yb^{3+} ions concentration , respectively.

From Fig. 5, we could realize that in one hand high absorption efficiency in edged-pumped Yb:YAG/YAG disk laser is critical fact and on the other hand the uniformity and homogeneity of absorbed pump light distribution have also important influence on the consequence calculation of the thin disk efficiency. As we shown in this article, by choosing the best Yb^{3+} ions concentration, we could obtain the goals of the uniformity and homogeneity of absorbed pump light distribution with high absorption efficiency through the disk. Those two last critical goals are important factors to designing an optimum laser resonators cavity to obtaining high output power with high beam quality (M^2) output at the same time. In our investigation, we obtained high absorption efficiency with appropriate absorbed distribution profile by choosing 14% Yb^{+3} ions concentration.

IV. CONCLUSION

We have done the calculation of absorbed pump light distribution for the specific construction of edged-pumped Yb:YAG/YAG high power disk laser in different value of Yb^{+3} ions concentration. First, we simulated irradiance pump light distribution through the disk by using Monte-Carlo ray tracing method. Second, Absorption pump light distribution have been calculated via FEA method for 12%, 14% and 20% of Yb^{+3} ions concentrations. The results show that by increasing of Yb^{+3} ions concentration over 14%, will influence of non-uniformity of absorbed pump light distribution in one hand and in addition absorption length through the disk also will decrease. However by choosing a suitable dimension of the active medium and appropriate cooling system, those loss effects will be eliminated and will improve the efficiency of the delivery laser system.

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Hamed Aminpour was born in Karaj, Iran in 1982. He received the B.Sc. degree in physics from the Teacher Training University (TMU), Iran, in 2008 and the M.Sc. degree in Condensed Matter of Physics from Azad University in 2011.

He has worked on diode-laser-pumped solid state lasers toward his M.Sc. thesis in Iranian National Center for Laser Science and Technology (INLC). He is currently joining to his supervisor's laboratory group as a part time researcher at Azad University, Karaj, Iran. His present research interests are focused on numerical calculation of Optical Path Difference (OPD) and calculation of Amplified Spontaneous Emission (ASE) effects in solid state lasers. Aminpour is a member of Optical Society of America (OSA), SPIE, European Optical Society (EOP) and Optics and Photonics Society of Iran (OPSI).

Alireza Hojabri was born in Tehran, Iran on January 30, 1968. He received the B.Sc. degree in Solid state Physics from the I. Azad University of Karaj, Iran, in 1990 and M.Sc. degree in Solid state Physics from I. Azad University of Tehran, Iran in 1992. He was doing his researches toward Ph.D. degree in Science and Research Campus of I. Azad University, Tehran Iran. His Ph.D. thesis was entitled “On the Investigation of Major Disruption and Mode locking in Iran - Tokamak1 (IR - T1)”. He received his Ph.D. degree in September 2000. From May 1993 he has been working in Physics department of I. Azad University in Karaj, Iran as a staff member and from November 2002 to 2005 he was deputy of the Faculty of Science, and from 2005 he is the dean of the Faculty of Science there. He has published over 30 technical articles and letters in scientific journals. His research has been concentrated on plasma physics, thin films and solid state physics.

Masoud Esmaeili received the B.Sc. degree in mechanical engineering from K. N. Toosi University of Technology, Tehran, Iran in 2004. He is teaching CAD/CAM/CAE software in Tehran Information College (TIC) since 2003. His interest's researches are stress analysis due to thermal effect, Structure design with suitable degrees of freedom. He is the author of several books in CAD/CAM/CAE software. Some of his books are references in universities and industries for students and engineers. He is the head of engineering authors in KELID publications.

Iraj Mashaiekhy Asl received the B.Sc. in Applied Physics Solid State from the University of Esfahan, Iran, in 1998 and M.Sc. in Solid State Physics from the University of Tehran, Iran, in 2003. His M.Sc. thesis is entitled "Design & construction of Dye Laser system with high accuracy in Litro & Littman array". He has worked on design and construction of high power diode pumped solid state lasers in different shapes of laser material (rod, slab and disc), industrial lasers such as: marking, engraving, cutting and welding and medical lasers. He is now working in Iranian National Center for Laser Science and Technology.