SIMULATION OF NEW TYPE SOLAR POWERED LASER

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Abstract

The new type of high efficiency solar pumped laser based on the active element of Nd:Cr:GSGG in the form of a thin slab with side pumping by concentrated solar radiation at the focus of parabolic concentrator with a diameter of 1 m2 is studied by computer simulation method.

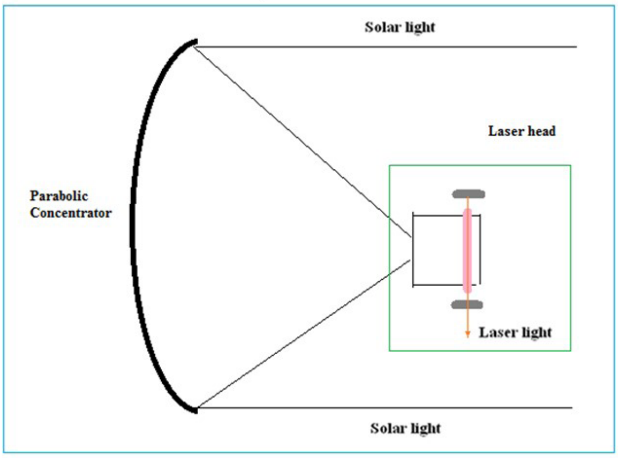
The solar pumped laser (SPL) is a device that converts the solar radiation energy into the laser light energy. The SPLs use different active mediums that absorb the solar light and transform it into the laser light. The main problem of SPLs today is low efficiency. The maximal efficiency achieved is 30W/m2 which is less than 5 % with the use of Nd: YAG (Neodymium doped Yttrium Aluminum Garnet, chemical formula - Nd:$Y_3Al_5O_{12}$). Therefore in this work we propose to use active element of Nd:Cr: GSGG (Neodymium and Chromium codoped Gallium Scandium Gadolinium Garnet) to increase the efficiency.

Keywords: computer simulation, Monte-Carlo method, modeling of absorption, solar powered laser.

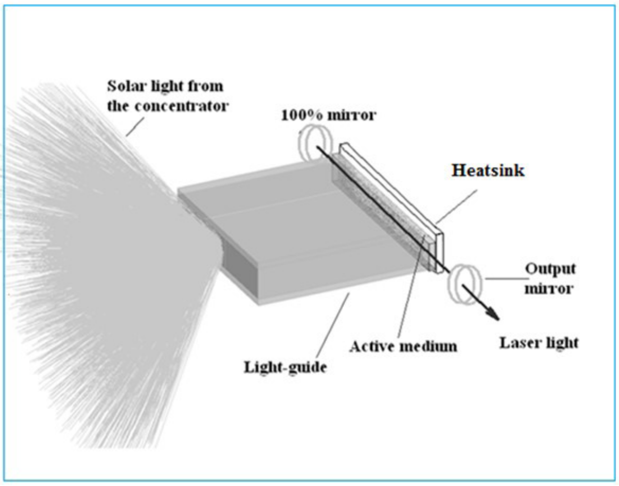
Introduction

It is known that in the cases when it is necessary to determine the optimal variant among numerous, and especially when it is difficult to find an analytical solution in the theoretical study, one of the powerful methods is the method of simulating [1-2] the operation of the laser system (modeling of elementary processes that are repeated many times, the laws of which are fairly well known), which allows to significantly reduce the time spent on research and other material and financial costs. To determine the optimal design of solar pumped Nd:Cr:GSGG laser, various schemes of the laser system were considered by conducting numerical experiments. One of the optimal design options that we find is shown in Figure 1. As it is shown in the figure, concentrated solar radiation in the focus of a solar concentrator with a diameter of 1 m is introduced through an input window 1x1 cm2 in a metal light guide-a pump chamber that provides uniform pumping by multiple reflections of the solar radiation inside the pumping chamber. The internal walls of the pump chamber were assumed to be coated with a silver coating, the reflection coefficient of which is about 97%. The working dimensions of the Nd:Cr:GSGG active element are 50x8x2mm^3. The rear surface was assumed to have silver reflective coating through which heat exchange takes place by a water-cooled heat sink. For thermal contact, special heat-conducting pastes can be used.

A computer simulation was carried out within the framework of the model proposed in [1, 2] to determine the efficiency of absorption of solar radiation by the active element, for the configuration shown in Fig. 1.



General scheme of the solar laser system



Laser head on an enlarged scale

Figure 1 Schematic of solar laser system

Model description

The core part of the model consists in determining the sequence of intersection points by using geometrical optics and modeling the elementary processes such as reflection, refraction, absorption, and emission by Monte-Carlo method. In the following, we will describe the basics of the used model.

Launching a photon

In the first step the model sets the initial position of the photon on the surface of parabolic concentrator as well as the initial direction from the sun. The model uses three Cartesian coordinates to determine the position, along with three direction cosines to determine the direction of propagation inside the solid angle suspended by solar disk randomly. The initial start conditions will vary depending on application. However, for the considered case, the initial position and direction cosines can be set as follows (isotropic sources can easily be modeled by randomizing the initial direction of each photon):

Position:

$$x = r\cos\varphi$$

$$y = r\sin\varphi$$

$z = (x^2+y^2)/k$, (according to the equation of parabola with a parameter k, see below)

Direction cosines:

$$\mu_x = \sin\phi\cos\theta$$

$$\mu_y = \sin\phi\sin\theta$$

$$\mu_z = \cos\phi$$

where r is random number uniformly distributed between 0 and R (radius of parabolic concentrator), φ -random number uniformly distributed over the interval [0, 2π], ϕ - random number limited by the semi-angular diameter of the Sun which is equal to 0.0046 radians, θ -randomized azimuth angle limited by [0, 2π]

Wavelength and absorption coefficient selection

The wavelength is determined from the solar spectral intensity by solving following integral equation:

$$\xi = \int_0^{\lambda_0} I_{AM1.5}(\lambda)\frac{\lambda}{hc}d\lambda$$

where $I_{AM1.5}(\lambda)$ is the normalized spectral intensity [W/m²/nm] of the AM1.5 solar radiation at a given wavelength λ_0 [nm], ξ is the random number uniformly distributed over [0,1] and

$$S = \int_0^{\infty} I_{AM1.5}(\lambda)\frac{\lambda}{hc}d\lambda = 1$$

Absorption coefficient μ at a given wavelength is determined by using absorption spectrum of the active medium.

Absorption lengths selection

The absorption lengths l is the distance the photon travels until it is absorbed by the active medium. The following is the basic form (derived using the inverse distribution method and the Beer-Lambert law) of the photon absorption length selection we used in the model:

$$l = -\frac{\ln\xi}{\mu}$$

where ξ is random number and μ is absorption coefficient for the given wavelength.

Step size selection and photon movement

The step size r is the distance the photon travels between two intersection points. In order to determine the nearest intersection point at some part of the surface of the system, the following procedures were considered: Given the ray $p(r) = a + rb$ and the implicit surface $f(p) = 0$, we would like to know where they intersect. The intersection points occur when the points on the ray satisfy the implicit equation

$$f(p(r)) = f(a + rb) = 0$$

where a is the 3D vector with the components (x,y,z), b is the vector of direction cosines, r is the step size. Thus, intersection points were determined by substituting (x,y,z) in the above equations with the components of the ray (p_x,p_y,p_z) and solving for the values of r.

Modeling of Absorption

Given the absorption length and the step size, we would like to know where absorption occurs. The absorption occurs when photon travels the distance equal to the absorption length in the absorptive medium. In the model, the step size and the absorption length are compared each time before the movement to determine the point where absorption occurs. If absorption length is less than the step size, the latter will be replaced by the absorption length and the last movement will be executed. After that, the coordinates are stored or marked (by putting there a pixel) and the tracing of a photon is terminated. Alternatively, if absorption length is not less than the step size, the value of absorption length will be lessened by the step size and the tracing of a photon will be continued. The tracing process will be terminated when a photon is either absorbed or left the system.

Modeling of Reflection and Refraction processes

As we consider a single photon, it can be either reflected or refracted. Therefore, to model these processes we use following approaches:

In principle, the reflection coefficient depends on the incident angle as well as on the polarization of the light. Since solar light is not polarized, we used average value of reflection coefficients for two polarization states (s and p) of solar light:

$$R_{ref} = \frac{1}{2}\left[\frac{\sin^2(\alpha-\beta)}{\sin^2(\alpha+\beta)} + \frac{tg^2(\alpha-\beta)}{tg^2(\alpha+\beta)}\right]$$

where α and β are the angles of incidence and refraction, respectively.

To determine which of the two processes is occurred, the random number ξ is generated and compared with the above reflection coefficient. If $\xi<R_{ref}$, the reflection otherwise the refraction is selected. Note that the reflection from the parabolic concentrator is independent of the incident angle as well as of the polarization of light, it is constant. For the reflected photon the new direction cosines are determined as:

$$\mathbf{b} = \mathbf{a} - 2(\mathbf{a}\cdot\mathbf{n})\mathbf{n}\,,$$

where we use vector notation for simplicity, **a** is incident vector, **n** is unit normal vector to the considered surface and **b** is reflected vector. Note that normal vector is distinct for different parts (end sides, lateral surface of an active medium, the surface of parabolic concentrator and different surfaces of frequency converter) of the laser system considered.

Expressions used for refracted photon are as follows: When a ray travels from a medium with refractive index n1into another medium with a refractive index n_2, some of the light is transmitted and bended. Snell's law tells us that

$$n_1 \sin\alpha = n_2 \sin\beta$$

$$\cos^2\beta = 1 - \frac{n_1^2(1-\cos^2\alpha)}{n_2^2}$$

The bended photon direction cosines can be determined as:

$$\mathbf{c} = \frac{n_1(\mathbf{a}+\mathbf{n}\cos\alpha)}{n_2} - \mathbf{n}\cos\beta$$

$$= \frac{n_1(\mathbf{a}+\mathbf{n}(\mathbf{a}\cdot\mathbf{n}))}{n_2} - \mathbf{n}\sqrt{1-\frac{n_1^2(1-(\mathbf{a}\cdot\mathbf{n})^2)}{n_2^2}}$$

where we use the vector notation again for simplicity, **a** is incident vector, **n** is unit normal vector to the considered surface and **c** is refracted vector.

It is important to mention that the equation above works regardless of which one of $n_1$and n_2 is larger. But if the number under the square root is negative, then there is no refracted ray and all of the energy is reflected. This is known as total internal reflection.

Thus, the obtained result for the absorption efficiency was 31%. At the next stage, based on the simulation result for the absorption efficiency and considering the efficiency of energy transfer, which is considered close to 90%, the dependence of the output laser power on the solar power was calculated using the well-known expression for a four-level laser (Fig. 2).

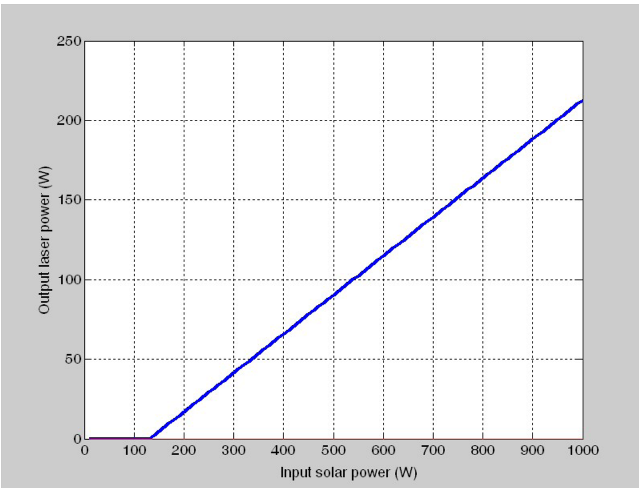


Figure 2 Output laser power vs. input solar power

As the results show, the proposed configuration could significantly increase the laser power by 3-4 times compared to a record power of about 30 W/m2 [3], obtained up to the present time. Moreover, the proposed configuration could also allow the use of other laser materials having relatively low thermal conductivities and which were considered unsuitable for pumping by concentrated solar radiation to date.

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