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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:Y₃Al₅O₁₂). 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.
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:

\[
\begin{align*}
x &= r \cos \varphi \\
y &= r \sin \varphi \\
z &= (x^2 + y^2)/k,
\end{align*}
\]

(according to the equation of parabola with a parameter \(k\), see below)

Direction cosines:

\[
\begin{align*}
\mu_x &= \sin \varphi \cos \theta \\
\mu_y &= \sin \varphi \sin \theta \\
\mu_z &= \cos \varphi
\end{align*}
\]

Wavelength and absorption coefficient selection

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

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

where \(I_{\text{AM1.5}}(\lambda)\) is the normalized spectral intensity [W/m²/nm] of the AM1.5 solar radiation at a given wavelength \(\lambda_0\) [nm], \(\xi\) is the random number uniformly distributed over [0,1] and

\[
S = \int_0^{\pi} I_{\text{AM1.5}}(\lambda) \frac{\lambda}{hc} d\lambda = 1
\]

Absorption coefficient \(\mu\) at a given wavelength is determined by using absorption spectrum of the active medium.

Absorption lengths selection

The absorption length \(l\) 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 \(\xi\) is random number and \(\mu\) 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:

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

where \(\alpha\) and \(\beta\) are the angles of incidence and refraction, respectively.

To determine which of the two processes is occurred, the random number \(\xi\) is generated and compared with the above reflection coefficient. If \(\xi < R_{rof}\), 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:

\[
b = a - 2(a \cdot n)n,
\]

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 \(n_1\) into another medium with a refractive index \(n_2\), some of the light is transmitted and bended. Snell’s law tells us that

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

The bended photon direction cosines can be determined as:

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

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

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](image-url)
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.

References

