A key issue for next generation Diode Pumped Solid State Laser Drivers for IFE: Amplified Spontaneous Emission in large size, high gain Yb:YAG slabs

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Abstract. Amplified Spontaneous Emission (ASE) is one of the key issues to be addressed when designing a diode pumped laser with a large transverse size / high gain amplifier. A 3D model using the Monte-Carlo method computing the effect of ASE in the quasi-three-level system of Yb$^{3+}$:YAG is actually under development for the Lucia-project. This work is performed within the Lucia project [1].

1. Introduction
The unavoidable Spontaneous Emission (SE) of any medium with population inversion might get amplified by stimulated emission on its way through the gain medium. This process is called Amplified Spontaneous Emission (ASE). While ASE is sometimes negligible for small size applications or in the case of small gain, it can be very important for gain media with either large dimensions or a high gain. This gets even more important in the case of applications which demand large sizes and a high gain.

Most of the papers discussing ASE are restricting themselves to one-dimensional, often pencil-like, geometries. [2,3] Almost all of the publications use simple geometries or geometrical symmetries to estimate a solid angle, in which the photons have a major influence on the ASE. In more general geometries this process is complicated, thus numerical computations are necessary.

In this work we will show the actual development at the Lucia-project to numerically evaluate the influence of ASE in the quasi-three level laser case of Yb$^{3+}$:YAG. We will present first numerical results and an example for different scaling methods for laser materials.

2. Rate Equations
Recent papers evaluated the influence numerically in the case of four-level systems [4], this paper will concentrate on the quasi-three level system including reabsorption,[5]

The rate equation for the excited state (1), normalized to the total doping density, can be split up into three independent parts, containing the action of the pump, the spontaneous emission and the influence of the amplified spontaneous emission.

\[
\frac{d\beta}{dt} = \frac{d\beta_{\text{pump}}}{dt} + \frac{d\beta_{\text{rad}}}{dt} + \frac{d\beta_{\text{ASE}}}{dt}
\]  (1)
The action of the pump and the spontaneous emission are shown in equation (2). The absorption coefficient \( \alpha \) depends on the absorption and emission cross section, \( \sigma_A \) and \( \sigma_E \) respectively.

\[
\frac{d\beta_{\text{pump}}(r,t)}{dt} = \frac{\alpha(r,t,\lambda) \int I_{\text{pump}}(r,t,\lambda) \, d\lambda}{n_{\text{tot}}} ; \quad \frac{d\beta_{\text{rad}}(r,t)}{dt} = \frac{\beta(r,t)}{\tau_{\text{rad}}} \tag{2}
\]

\[
\alpha(r,t,\lambda) = \sigma_A(\lambda) \cdot [n_{\text{tot}}(r) - n(r,t)] - \sigma_E(\lambda) \cdot n(r,t) \tag{3}
\]

Equations (1) – (3) are well known and not discussed in detail at this point. The last term, which appears in (1), is the topic of the numerical modeling. Equation (4) has a form similar to the pump (2), describing the effect due to the incoming ASE-flux.

The flux at the position \( r \) has its origin in the spontaneous emission at the position \( r' \), its amplification \( G \) on its way through the gain medium from \( r' \) to \( r \), integrated over wavelength and averaged over the whole solid angle. The spectral distribution is taken into account by the line shape function \( g(\lambda) \). The information about the geometry and structure of the gain medium is included in (5).

\[
\frac{d\beta_{\text{ASE}}(r,t)}{dt} = \int \alpha(r,t,\lambda) \cdot \Phi_{\text{ASE}}(r,t,\lambda) \cdot n_{\text{tot}} \, d\lambda \tag{4}
\]

\[
\Phi_{\text{ASE}}(r,t,\lambda) = \int \frac{d\Omega}{4\pi} \frac{n(r',t)}{\tau_{\text{rad}}} g(\lambda) \cdot G_{r'\rightarrow r} \, dr' \tag{5}
\]

3. Monte-Carlo Model

We wrote a numerical model which is between the standard Monte-Carlo model, which uses random positions \( (x,y,z) \) and random directions \( (\theta,\phi) \) and a deterministic model which emits from every position a specified number of test rays. We emit from every position within the gain medium, but in random order. The spatial distribution of the emitted rays on every point is homogeneously distributed but in random order too. The spectral distribution of this emission is determined by the amplifier material.

Every emitted ray is traced through the modeled gain medium, until one of the faces is hit. The properties of the face determines, if a ray stops or travels on under changed conditions. Different options are possible like Fresnel reflection, AR and HR coatings or a perfect absorbing cladding. Each ray affects the gain distribution.

After estimating (4) for every observed point, (1) is computed. This procedure is done for every time step.

4. Model and Numerical Simulation

The development of this model is related to the design of the amplifiers for the Lucia-project. To extract energy in the order of 100 J in a few passes and a compact design, an architecture based on thin slabs was chosen. The volume of the gain media used in the amplifiers is in the order of \((4 \times 4 \times 0.2) \text{ cm}^3\). The doping level is set to be 10 %. The amplifiers are pumped by diode laser arrays capable of delivering up to 264 Joules concentrated over a \(~10 \text{ cm}^2\) area with a \(~90 \%\) efficiency. Consequently, the small signal gain (ssg) reaches considerably high values in the order of \( g_0 = 3 \text{ cm}^{-1} \) at 1030 nm. The combination of a high ssg and large transverse dimensions of the crystal will bring up the problem of ASE. This gets even more important with a radiative lifetime (\(~1 \text{ ms}\)) which is in the same order as the duration of the pump pulses (1 ms) emitted by the laser diode stacks.
All surfaces are considered to be perfectly transmitting, except the backside which is perfectly reflective for the pump and the emission of the gain medium. The pump is reaching the gain medium (homogeneously doped with 10 at % Yb\(^{3+}\)) at normal incidence. The pump profile has a homogeneous super-Gaussian shape of the order 8 over a rectangular area of 3x3 cm\(^2\). The peak intensity is 20 kW/cm\(^2\) and taken to be constant in intensity over time. The pump spectrum is Gaussian shaped with a central wavelength of 941 nm and a spectral width of 2 nm (HWHM).

Figure 1 shows the calculated temporal behavior of the stored energy comparing it with the cases without any emission and spontaneous emission. While overall energy of 180 J was injected, just 50 J were stored in the gain medium. Losses due to spontaneous emission would result in about 100 J possibly stored energy. Figure 2 shows the evolution of the emission spectra (averaged over all surfaces and normalized for each time step). While within the first 250 µs, other spectral components are visible (thus indicating a SE regime), the 1030 nm line gets important after 250 µs. This shows the change from SE to ASE as the important mechanism for the losses.

5. Scaling Example

Scaling high gain laser materials can result in a decrease in energy storage efficiency. As an example, figure 3 shows two different possibilities scaling gain media. The first possibility is to keep the concentration and thickness of the sample constant. The second method would be to keep the [concentration \times length] product constant. Figure 3 shows, that the first option rapidly losses in effectiveness, while the second option shows a nearly constant energy storing capability. On the other hand with increasing thickness, thermal problems may occur on the application. Keeping in touch with the thin disk solution, the geometry of the gain medium has to be changed. Reducing the product length \times gain might be achieved by splitting the active area into hand able sizes and acceptable efficiency. Dividing the gain medium can be done in the longitudinal or transversal direction, depending on the geometry.

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![Figure 1](image.png)

**Figure 1.** Comparison of the stored energy for different physical properties used in the simulation.
Figure 2. The emitted normalized spectrum temporal evolution during the 1 ms pumping duration.

Figure 3. Comparison of two different scaling methods. A constant concentration (boxes) and a constant product length × concentration (triangles) are shown.

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