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Analytical and numerical solutions to the amplifier with incoherent pulse temporal overlap

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ABSTRACT

Serious pulse temporal overlap in amplifiers would result in the decrease of energy extraction efficiency and the increase of pulse-shape distortion (PSD). Precisely predicting pulse temporal overlap is of significance to an effective amplifier design. In this work, the analytical expressions with complete pulse overlap are derived and a numerical method is proposed to solve the case with partial temporal overlap for a double-pass Nd:YAG amplifier. Our studies, in which pulse temporal overlap is taken into account, can precisely predict the output energy and temporal shape, compared to the results from Hirano and other experiments. In addition, our numerical routes could provide the applicable range of analytical solutions to conventional Frantz–Nodvik equations in the case of pulse overlap, further extending the applicability and reducing computational costs. For given conditions, energy reduction and PSD are mainly determined by the overlap degree. For step-shaped pulse, we demonstrate that avoiding overlap in the peak pulse and allowing overlap in the foot pulse have small impacts on the energy extraction and PSD, which extends the range of duration of the pulse for a designed amplifier. Our investigations might provide an efficient way to carefully design a pulsed amplifier with controllable temporal overlap.

1. Introduction

Temporal overlap is a phenomenon that the forward and backward beams overlap in the gain medium of a laser. If the beams are coherent, this would result in the so called spatial hole burning (SHB) effect in a laser oscillator and also occurs quite often in a multipass continuous wave (CW) laser amplifier [1]. While in a compact pulsed laser amplifier SHB effects may be much less, since the beams are generally located at different frequencies and the interference fringes are moving in the gain media, the SHB tends to be washed out or averaged [2]. In some multipass pulsed amplifiers, the beams are orthogonally or circularly polarized and SHB will be eliminated [3–6]. However, consequent problems aside SHB due to temporal overlap can be arose in a pulsed amplifier, i.e., the degradation of energy extraction efficiency and pulse-shape distortion (PSD) etc. [7–9]. To simplify the model dealing with pulse temporal overlap, we assume that the two beams are incoherent. Since pulsed amplifiers are used quite often and widely in today's high energy laser systems [10–12], it is deserved to find an efficient way to guide the design of pulsed amplifier and reduce the effects of incoherent temporal overlap on the amplifier performance.

The Frantz–Nodvik equations [13] are usually employed to characterize the energy extraction and PSD of a pulsed amplifier without temporal overlap. However, the Frantz–Nodvik equations cannot precisely predict the output energy as well as the pulse temporal shape distortion [7,8] once there has temporal overlap. This is because that in the overlap case, the forward and backward beams simultaneously extract energy from the gain media, while the initial condition for the backward beam is unknown. Pierre firstly noticed the disagreement between the experiments and simulations obtained by Frantz–Nodvik equations in the overlap case, and explained the disagreement (energy decrease) as the backward beam robbed gain from the forward beam. After that, an iterative method was proposed by Hirano [8] to solve the rate equations. The method mainly has two steps, firstly using the Frantz–Nodvik equations to solve the double-pass amplifier without considering temporal overlap; secondly applying the

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obtained results of the backward beam as the input, and then iterating the initial forward beam and this input beam with considering the overlap degree to get a same output after single-pass amplification. Although a good agreement with the experiments was obtained, the computational costs of Hirano's method are higher due to iterations. In addition, the iterative method requires that the pulse duration is longer than the delay time, which is required for the pulse to travel from the gain media to the high reflection mirror (HR mirror) and back to the rear face of the gain media. However, this requirement may not be satisfied in some ultra-short pulsed amplifier, such as picosecond or femtosecond regenerative thin disk [14,15]. Without considering the optical losses, a simplified solution to the complete temporal overlap case was given by Pearce, which roughly predicts the energy reduction [9]. To obtain more precise predictions for amplifiers with considerable optical losses, derivation of an analytical solution is necessary.

Bearing these in minds, an analytical solution considering the optical losses to the complete temporal overlap case is then derived for a double-pass amplifier and an intuitive numerical method aiming at solving the case of partial temporal overlap is proposed for a multi-pass amplifier. By meshing the gain media and pulse into an equivalent optical path length (EOPL) [16], only three equations are adequate to characterize the amplifier with temporal overlap. Compared with the iterative method, the EOPL method just has its first step, thus greatly reducing the computational costs. Compared with the work from [8], our studies well take the pulse temporal shape into account and further extend its applicable range to a more general design of amplifier with pulse temporal overlap.

2. Analytical and numerical methods with temporal overlap

Fig. 1 shows the model of a three-state pulse propagation in the laser amplifier. In the first state the seed pulse injects into the gain medium without temporal overlap (NTO). In the second state the pulse leading edge overlaps its latter part in the gain medium when it returns from the HR mirror, in which partial temporal overlap (PTO) and complete temporal overlap (CTO) can occur and this depends very much on the distance between the rear face of the gain medium and the HR mirror (L_1), as well as the length of the gain medium (L_0). In the third state the tailing edge leaves the gain medium without overlap. The delay times $\delta\tau_0$ and $\delta\tau_1$ for optical path length of L_0 and L_1 can be expressed as

$$\delta\tau_0 = n_0 L_0 / c_0 \ \text{and} \ \delta\tau_1 = L_1 / c_0 \tag{1}$$

where c_0 is the speed of light in vacuum and n_0 is the refractive index of the gain medium.

Suppose a square pulse with duration of τ_P traveling through the amplifier. When $2\delta\tau_1 \geq \tau_P$, the pulse leading edge will not overlap its latter part in the gain medium, we referred it as the "NTO case"; then the second state will not be considered and the multipass amplification can be modeled with the Frantz–Nodvik equations. If $2\delta\tau_1 < \tau_P$, PTO will occur in the gain medium and we define a parameter η to describe the overlap degree:

$$\eta = \frac{\tau_P - 2\delta\tau_1}{\tau_P + 2\delta\tau_0} \tag{2}$$

Typically, η is the ratio of the duration of pulse experiencing temporal overlap to the total duration of the pulse traveling within the gain medium. Thus, when $\eta \to 1$, the pulses will nearly have overlap in the gain medium, and we refer this as the CTO case. If $\eta \to 0$, the PTO occurs just near the rear face of the gain medium. In general case with $0 < \eta < 1$, the propagation of the two counter propagating beams can be described by the following coupled equations, since we assume the beams are incoherent and the coherent effect is neglected [8].

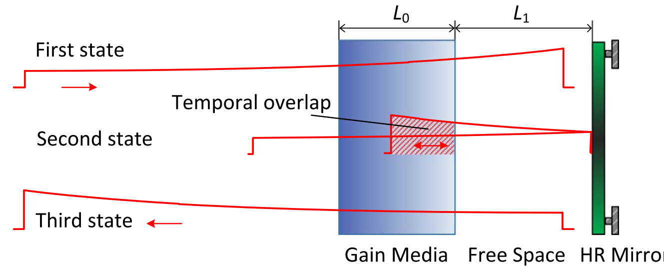

Fig. 1. Three states of the pulse propagation in the amplifier.

$$\frac{1}{c}\frac{\partial I_\pm}{\partial t'} = (\sigma_e \Delta n - \alpha) I_\pm \mp \frac{\partial I_\pm}{\partial z'} \tag{3}$$

Here, c is the velocity of the light in the gain medium; I_+ and I_- are the pulse intensities along the forward and backward directions, respectively; Δn is the population inversion density; σ_e is the stimulated emission cross section and α is the coefficient of the passive loss. Since the beams are assumed to be incoherent, the local laser intensity is the sum of the intensities of the two pulse intensities and thereby the population inversion density Δn can be written as

$$\frac{\partial \Delta n}{\partial t} = -\frac{\sigma_e \Delta n}{hv}(I_+ + I_-) \tag{4}$$

where hv is the photon energy.

2.1. CTO case

If an amplifier is without passive loss ($\alpha=0$), in CTO case ($\eta \to 1$), the input wave will immediately return into the gain media. Since the delay time is very short and the extracted energy is small, one can neglect the inversion population variation caused by the leading edge of the pulse. Then Eq. (3) can be transformed into moving pulse frame by using $z=z'$ and $t=t'-z'/c$ in CTO case [9],

$$\frac{\partial I^\pm}{\partial z} = \pm \sigma_e \Delta n I^\pm \tag{5}$$

$$\frac{\partial \Delta n}{\partial t} = -\frac{\sigma_e \Delta n}{hv}(I^+ + I^-) \tag{6}$$

where I^+ and I^- are the pulse intensities of the input and return beams in the moving pulse frame, respectively.

To ensure accurate predictions for a practical laser system, losses such as reflection, scattering, and absorption caused by various optical components are considered in the model. These losses can be simply characterized by the single pass transmission T through the resonator or amplifier [17]. Then the boundary conditions of Eqs. (5)–(6) are written as

$$I^+(0, t) = T I_{in}(t) \tag{7}$$

$$I^-(L_0, t) = T I^+(L_0, t) \tag{8}$$

where $I_{in}(t)$ is the seed pulse intensity, $I^+(0,t)$ is the initial intensity injecting into the gain medium for the input beam, $I^+(L_0,t)$ is the intensity at the rear face of the gain medium for the input beam, $I^-(L_0,t)$ is the initial intensity injecting into the gain medium for the return beam. To obtain the analytical expressions, we