Amplifying Modeling for Broad Bandwidth Pulse in Nd:glass Based on Hybrid-broaden Mechanism

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Abstract. In this paper, the cross relaxation time is proposed to combine the homogeneous and inhomogeneous broaden mechanism for broad bandwidth pulse amplification model. The corresponding velocity equation, which can describe the response of inverse population on upper and low energy level of gain media to different frequency of pulse, is also put forward. The gain saturation and energy relaxation effect are also included in the velocity equation. Code named CPAP has been developed to simulate the amplifying process of broad bandwidth pulse in multi-pass laser system. The amplifying capability of multi-pass laser system is evaluated and gain narrowing and temporal shape distortion are also investigated when bandwidth of pulse and cross relaxation time of gain media are different. Results can benefit the design of high-energy PW laser system in LFRC, CAEP.

1. Introduction
Chirped pulse amplification (CPA) technology allows the production of high-power ultrashort pulses in solid-state lasing media [1,2]. The gain narrowing and temporal shape distortion occurred when broad bandwidth pulse is amplified in gain media are the main effects to exacerbate the output capability and beam quality of a high energy laser system. Traditionally amplifying model for investigating those effects is based on homogeneous broaden mechanism which means inverse population have the same response to different frequency in linewidth of gain media [3-7]. The model is valid only when the bandwidth of pulse is greatly less than linewidth of gain media such as Ti:sapphire. When pulse with bandwidth of several nanometers is amplified in Nd:glass (gain linewidth is about 16nm), the response of inverse population in gain media to the frequency of injected pulse is different. Amplifying model should include homogeneous and inhomogeneous broaden mechanism simultaneously to ensure the amplifying process of broad bandwidth pulse in Nd:glass can be described correctly.

In this paper, the cross relaxation time is proposed to combine the homogeneous and inhomogeneous broaden mechanism for broad bandwidth pulse amplification model. The corresponding velocity equation, which can describe the response of inverse population on upper and low energy level of gain media to different frequency of pulse, is also put forward. The gain saturation and energy relaxation
The amplifying capability of multi-pass laser system is evaluated and gain narrowing and temporal shape distortion are also investigated when bandwidth of pulse and cross relaxation time of gain media are different. Results can benefit the design of high-energy PW laser system in LFRC, CAEP.

2. Broadband pulse amplifying physical model

For broadband pulse laser, it is important to consider the response of the gain medium itself to laser frequency, where it can be think of whole nonhomogeneous and part homogeneous. The cross relaxation time \( \tau_{cr} \) is introduced to describe the process of the population densities varying after the acting of laser, see Fig.1. Thus

\[
\frac{\partial n_1(v)}{\partial t} = \int \Delta n(v) \sigma(v,v') \frac{I(v')}{h\nu'} dv' - \frac{n_1(v)}{\tau_1} - \frac{n_2(v) + n_1(v)}{1 + k_2} \frac{I(v)}{\tau_{cr}}
\]

\[
\frac{\partial n_2(v)}{\partial t} = \int \Delta n(v) \sigma(v,v') \frac{I(v')}{h\nu'} dv' - \frac{n_2(v)}{\tau_2} - \frac{n_1(v) + n_2(v)}{1 + k_1} \frac{I(v)}{\tau_{cr}}
\]

\[
\frac{\partial n_1}{\partial t} = \frac{n_1}{\tau_1} - \frac{n_1 + n_2}{1 + k_2}
\]

\[
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\]

\[
\frac{\partial}{\partial \nu} + \frac{1}{\nu} \frac{\partial}{\partial \nu} I(v) = \left[ \int \Delta n(v) \sigma(v,v') dv - \alpha \right] I(v)
\]

\[
g_{\nu} (v,v') = \frac{1}{1 + \left( \frac{v - v'}{\Delta v_{\nu}} \right)^2}
\]

\[
g_{\nu} (v,v) = \int_{-\infty}^{\infty} g_{\nu}(v,v') dv'
\]

\[
n_i = \int n_i(v) dv
\]

| \( \Delta n(v) \) | inverse population densities distribution of the apparent central frequency |
| \( I(v) \) | the pulse intensity distribution of the apparent central frequency |

The physical meanings of parameter in Eqs.(1-10) are show in Table 1.
summation for upper and ground state energy level population of the apparent central frequency

the sum population densities of sub energy level that degenerate with the up and down energy level of laser acting

the scale coefficient of upper and ground state degeneracy energy level population at thermal balance

upper and ground state energy level life time of laser

sub energy level life time that degenerated with the upper and ground state energy level at laser working

thermalization times of upper and ground state energy level

cross relaxation time

the function of homogeneous broaden linetype, homogeneous linewidth

the normalized function of nonhomogeneous broaden linetype, nonhomogeneous linewidth

the center frequency of nonhomogeneous broadening

stimulated emission cross section, absorption coefficient

3. Code CPAP development and verification

Based on the broadband pulse amplifying physical model, computer simulation design software of propagation and amplification named CPAP (Chirp Pulse Amplification and Propagation) has been developed. At present, this software has the function of energy amplification, gain-narrowing, gain absorption etc. it would be accomplished at the middle of this year. Interface of CPAP is shown in Figure 2.

Because cross relaxation time can not be determined and it can influence the calculation results of amplification, we cannot compare it with other amplification directly. A reasonable way to verify the amplifying model is to simple the broadband model to narrow model and compare it with well known traditional amplifying model.

Because narrowband amplifying model adopting homogeneous-broaden linewidth while broadband model adopting nonhomogeneous-broaden linewidth, so only when the cross relaxation is progressing to 0, hybrid-broaden linewidth transit to homogeneous linewidth, and broadband pulse amplifying physical model transit to narrowband physical model. The simulation results with CPAP compared with SG99, seen Fig.3. SG99 is a mature narrowband amplifying software developed by The Laser Fusion Research Center, CAEP, which was demonstrated theoretically and experimentally to simulate the amplification and propagation in the high power solid state laser facility. There are also given the results compared with one-dimension Schoderge Eqs. It is shown that the results from CPAP are consistent with that by SG99 and one-dimension model.
4. The influence of cross relaxation time on output energy of TIL

To study the influences of cross relaxation time on output energy output capability of TIL (the prototype of SG-III laser facility, Technical Integration Line, shown in Fig.4) when a chirp pulse with bandwidth of 2nm is passed through. Output energy capability is calculated by CPAP with different cross relaxation time shown in Fig.5. It shows that different cross relaxation time affect greatly on the output energy of amplification, narrowband laser has highest output energy, homogeneous linewidth laser take second place, and nonhomogeneous linewidth has lowest. In general, calculation result shows that the range of cross relaxation time is about 0ns–10ns roughly. The calculation parameters includes: beam size is 29cm, small gain coefficient of Nd glass is 0.05cm⁻¹.

5. Conclusion

In this article broadband amplifying physical model and the corresponding code CPAP are presented to describe the broadband pulse amplification processes. This physical modeling and CPAP can be applied to design broadband laser facility. Hybrid-broaden linewidth, homogeneous and nonhomogeneous, was emphatically concerned. The key parameters, cross relaxation time of Nd glass is discussed and its range sound to be in from 0ns to 10ns.

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