Theoretical study on the laser gain of a multi-stage dye laser amplifier

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Theoretical studies on laser gain of a multi-stage dye laser amplifier are presented in this paper. The results show that the influences of amplified spontaneous emission (ASE) and nonlinear absorption of excited-state on the gain are different for different input laser energies and gains. A threshold input intensity exists for a specific system. If the input intensity is higher than the threshold, the nonlinear absorption of excited-state will be the main cause for gain decrease. Otherwise, the ASE is the main cause. A new scheme is proposed to calculate the gain of the amplifier by the comparison of the input intensity with the effective saturation intensity and the choice of the calculation gain method.

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Dye laser amplifiers are always pumped by high intense sources such as Nd-YAG and copper vapor lasers, and amplify the low power laser produced by a laser oscillator. So the output can get high power and keep fine spectral characteristics. In recent years, these systems, expecially the multi-stage dye laser amplifier due to its high gain[1,2], have attracted more and more attentions[1−9]. Ganiel *et al.* proposed a standard rate-equation model for single-pass transversely pumped dye lasers and amplifiers[3]. After that, various works about it were discussed[4−9]. Dasgupta *et al.* discussed the effect of nonlinear excited-state absorption in detail, and presented a laser gain expression[5]. Using this method, Wang *et al.* considered optimum gain length for single cell of dye laser amplifiers[7]. However, those models are mostly based on single dye cell[3−9]. If they are directly used in multi-stage dye laser amplifiers, there would be large inconsistency between theoretical values and experimental results. In fact, in the process of amplifying, energies of signal laser for front cells are small, but those for back cells are large, usually close to or over saturation intensity. So effects of amplified spontaneous emission (ASE) and excited-state absorption on laser gain are different. Therefore, laser gains of different cells even in one amplifier system must be considered separately.

In this paper, we suggest a gain calculation method of multi-stage dye laser amplifiers, and combine the methods of Ganiel and Dasgupta[3−5]. This method will choose proper gain equations for front and back cells according to the energy of input signal laser and the gain of front cells.

Energy-level diagram of dye molecules is shown in Fig. 1. K_{st}^{-1} is the singlet to triplet intersystem crossing time, and τ_{t} is the lifetime of phosphorescence. These processes are slow on the time scales of interest to us and can be neglected under the condition of laser pumped. τ_{s} is the spontaneous radiation lifetime of the first excited state, σ_{01}^{λ} and σ_{01}^{p} are the ground state absorption cross-sections for signal laser wavelength and pump laser wavelength, respectively. $\sigma_{\mathrm{e}}^{\lambda}$ and σ_{12} are the emission cross-section of the first excited state and excited state absorption cross-section for signal laser wavelength, respectively.

As shown in Fig. 2, the dye amplifier system is a transversely pumped, single-pass multi-stage dye laser amplifier. As to the dye amplifier cells, one-dimensional model is chosen[3−9]. Pump laser is focused on the direction of Y-axis, and signal laser enters the cell in the direction of Z-axis. Supposed the gain region is a cylinder with a length L and a diameter d, with $d \ll L$. The variation of pump energy in X and Y directions due to absorption is neglected, and an average pump energy is used.

We define E_{po} as the incident pump energy, and the effective pump energy E_{pe} averaged over the width of the dye cell is

$$E_{\mathrm{pe}} = P_{\mathrm{e}} E_{\mathrm{po}} (1 - T)/\ln(1/T), \tag{1}$$

where T is the dye cell transmission at the pump wavelength. Being different from other works[3−9], Eq. (1) uses the effective pump factor P_{e}, which is the ratio of pump energy to total pump energy in effective gain region and determined by the reflection and the shape of the dye cell.

Supposed reflection coefficients of two dye cell windows are equal to r. Through the analysis of the equations of laser transport and ASE transport, the transcendental equation for laser gain of single pass dye amplifier cell can be obtained[3,4,6],

$$\left(1 - \frac{B}{\sqrt{1 + \ln G_f}}\right) \ln G_f + \frac{B(1-r)(G_f - 1)}{(1 - rG_f)\sqrt{1 + \ln G_f}} = \alpha_0 L - \frac{I_{\mathrm{in}}}{I_{\mathrm{s}}}(G_f - 1), \tag{2}$$

where B is the coefficient which describes properties of the ASE flux in the direction of Z-axis, and can be calculated by

$$B = Q\left[1 + \frac{L}{d} - \sqrt{1 + \left(\frac{L}{d}\right)^2}\right] \frac{d}{L}, \tag{3}$$

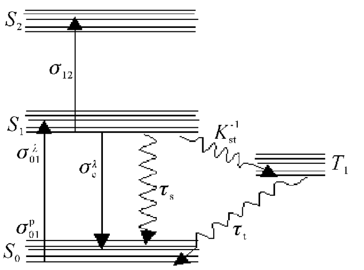

Fig. 1. Energy level structure of dye molecules.

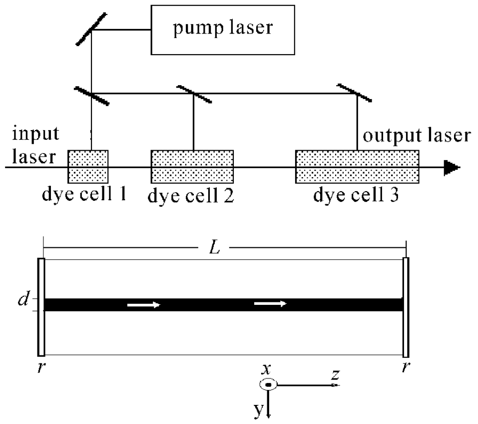

Fig. 2. Dye amplifier system and dye amplifier cell.

where Q is quantum efficiency of fluorescence. In Eq. (2), I_{in} is the intensity of signal laser (photons/(cm^{2}s)). α_0 (cm^{-1}) is the small-signal gain, I_s and I_p are the effective saturation intensity and the intensity of pump laser in the gain region, respectively. α_0 and I_s can be obtained as

$$\alpha_0 = \frac{n\sigma_e^{\text{eff}}(\sigma_{01}^{p} I_p \tau_s - \sigma_{01}^{\lambda}/\sigma_e^{\text{eff}})}{1+\sigma_{01}^{p}\tau_s I_p}, \qquad (4)$$

$$I_s = \frac{1+\sigma_{01}^{p}\tau_s I_p}{\sigma_e^{\lambda}\tau_s(1+\sigma_{01}^{\lambda}/\sigma_e^{\lambda})}. \qquad (5)$$

In those equations, σ_e^{eff} is the effective emission cross-section for signal laser, which is given by

$$\sigma_e^{\text{eff}} = \sigma_e^{\lambda} - \sigma_{12}. \qquad (6)$$

Dasgupta *et al.* presented a gain expression in which the influence of excited-state absorption was considered, but the influence of ASE was neglected. The amplifier equation for laser gain can be obtained using the corresponding rate equations[5],

$$G_p = \frac{\alpha_0}{SI_{\text{in}}} - \left[\frac{\alpha_0}{SI_{\text{in}}} - 1\right]\exp\left(\frac{\ln G_p - \alpha_0 L}{1+\alpha_0/SI_s}\right), \qquad (7)$$

where expressions for α_0 and I_s are the same as Eqs. (4) and (5), and the parameter S is given by

$$S = n\sigma_{12}\sigma_{01}^{\lambda}\tau/(1+\sigma_{01}^{p} I_p \tau). \qquad (8)$$

Now we consider a concrete two-stage dye amplifier. The total pump energy is distributed uniformly in an effective pumped region with a length of 4 cm and a diameter of 2 mm. The length of the first dye cell is 1.5 cm. The dye is R6G and the center wavelength is supposed to be 570 nm. The pump source is the second harmonic of an injection-seeded Q-switched Nd:YAG laser with output energy of 200 mJ/pulse at 532 nm. The duration of pulse is 10 ns, and the repetition rate is 20 Hz. The radio of pump energy in the first and the second dye cell is 1 : 9. Other parameters used in the numerical calculation are listed in Table 1.

Table 2 shows the results of calculation using different gain methods to two cells separately. The method 1 takes into consideration of the ASE effects in both cells, and calculates the gains in the cells using Eq. (2). The method 2 takes into consideration of the ASE effect in the first cell and the absorption of excited-state in the second cell, and calculates the gains in two cells using Eqs. (2) and (7). The method 3 calculates the gains in two cells using Eq. (7). G_1 and G_2 in Table 2 are the gains in the first and the second dye cell, respectively.

The calculation results of the laser gain in the first dye cell show that when the input signal laser energy is very small, the gain calculated with Eq. (7) is larger than the gain with Eq. (2). This means the effect of ASE to laser gain in this condition is larger than that of excited-state absorption. The laser gain calculated with Eq. (7) is larger than the true value. As the increase of the input laser energy, the effect of ASE on the laser gain is becoming smaller and smaller. For the example in the Table 2, when the energy of the signal laser is

Table 1. Parameters Used in the Calculations

Parameter	Value	Reference
σ_{01}^{p}	4.20×10^{-16} cm^2	10
σ_e^{λ}	2.60×10^{-16} cm^2	10
σ_{01}^{λ}	1.25×10^{-18} cm^2	5
σ_{12}	0.91×10^{-16} cm^2	5
τ_s	5.5 ns	3
Q	0.85	4
n	6.0×10^{-4} mol/L	
r	2.0×10^{-4}	
P_e	0.9	

Table 2. Computed Results of Gain with Different Methods

Input	Method 1		Method 2		Method 3	
Energy (μJ)	G_1	G_2	G_1	G_2	G_1	G_2
0.01	1108	1854	1108	5374	219920	28
0.08	1100	691	1100	685	75699	11
0.5	1052	141	1052	116	12578	10
1	1000	76	1000	62	6377	10
5	702	23	702	18	1317	10
30	231	12	231	9	227	10
100	80	11	80	8	70	9

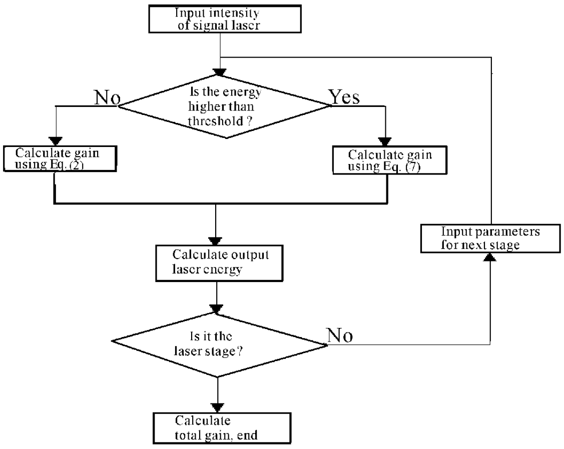

Fig. 3. Flow chart of the calculation of total gain.

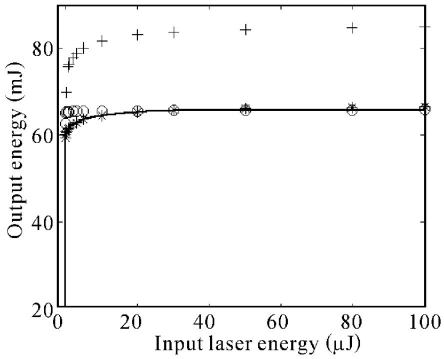

Fig. 4. The calculated results. (The curve is the results of the method of Fig. 3. The symbols + are for the results of method 1, * for the results of method 2, and o for the results of method 3.)

30 μJ, the ratio of the signal laser intensity to the effective saturation intensity is about 0.17, and the effects of ASE and excited-state absorption to the laser gain are very close. As an approximate method, the laser gain in the first dye cell can be calculated by different ways according to the input laser energy. If the signal energy is smaller than 30 μJ, the effect of ASE should be taken into accounts and the gain should be calculated by Eq. (2). Otherwise, the effect of excited-state absorption should be considered and the gain should be calculated by Eq. (7).

The same idea can be used in the second dye cell. In Table 2, we find if the energy of input laser is extremely small, the effect of ASE is still the main cause of the gain decrease for the laser in the second dye cell. So the laser gain should still be calculated by Eq. (2). For the above numerical example, if the input laser energy of the first cell is 0.08 μJ, then the effects of ASE and excited-state absorption to laser gain in the second dye cell are very close. We should pay more attention to that the ratio of the signal laser intensity to the effective saturation intensity in the second dye cell is about 0.17. In other words, if the ratio is larger than 0.17, the gain of the cell should be calculated by Eq. (7). Otherwise, the gain of the second cell should be calculated by Eq. (2).

So when laser gain of every dye cell in multi-stage dye laser amplifiers is calculated, the intensity of input signal laser for this cell should be compared with the corresponding threshold first, and then the proper equation for gain calculation can be chosen. The flow chart of this calculation method is shown in Fig. 3. Using this method to calculate the total gain of the amplifier system of Table 1, a curve of the relationship between the input and the output laser intensity is shown in Fig. 4, together with the results using other methods.

The main shortcoming of this method is that when the intensity of input laser is close to the threshold, the influences of ASE and absorption of exited-state are also close. The gain calculated with Eq. (2) or (7) will be greater than the true value. So a better method should be set up in order to consider those two factors at the same time, and this is the next step we will try to do.

In summary, numerical calculation and theoretical study on the laser gain of multi-stage dye amplifiers are described in detail in this paper. The results show that because the energy of input signal laser and the gain of dye cell are different, the influences of ASE and absorption of excited-state on the gain of dye amplifier are different. There is a threshold input intensity for a specific dye amplifier. When the input intensity is higher than the threshold intensity, the absorption of exited-state is the main factor causing the gain decrease. Otherwise, when the input intensity is lower than the threshold value, the ASE is the main factor to influence the gain. Therefore, we proposed a new scheme to calculate the total gain of multi-stage dye amplifier gain by the comparison of input intensity with the effective saturation intensity and the choice of calculation method. Using this method, a better agreement between theoretical calculation and experimental values can be achieved.

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