Laser Original

Pulse Propagation in the Amplifier and in the Saturable Absorber of a High-Power Iodine Laser

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Pulse propagation in a photodissociation iodine laser amplifier and saturable absorber are investigated by the use of semi-classical treatments. Based upon the numerical integration of the semi-classical equations, the effects of the linear propagation loss and of the input pulse energy on nonlinear pulse amplification are discussed. From our calculations, it has been made clear that the pulse showing stable propagation through the amplifier is the one having a pulse area of 2.46π and which extracts energy efficiently from the amplifier. It is also shown that there is a close relation between the peak power of the propagated pulse and the rise time, and that the disadvantages of nonlinear amplification can be eliminated. In treating energy absorption, the results we obtained provide a good fit with those obtained experimentally. Our semi-classical equations are useful for analyzing pulse propagation in a complete iodine amplifier system with a saturable absorber.

1. Introduction

The iodine photodissociation laser, as well as several other lasers, such as CO₂, Nd-glass, and HF chemical lasers, are now of interest in connection with fusion experiments and laser-produced plasma. To be able to carry out laser fusion experiments, master oscillator and energy amplifier systems producing high-power, short-duration laser pulses are required.

The iodine laser system stores a large amount of energy in the amplifier Stage, and its wavelength of 1.315 μm is longer than one would like for laser fusion, but it is acceptable. Also, as in all gas laser systems, due to the optical homogeneity which exists in the amplifier stage, a large tube diameter amplifier must be used to obtain a large amount of energy from the amplifier. Many workers have been actively studying the iodine laser system which consists of an iodine master oscillator being able to generate short-duration laser pulses and of energy amplifier stages. A short-duration oscillator pulse on the order of 1 nsec fed into a chain of amplifiers has been obtained either by the mode-locking method or by the pulse cutting method. Amplified spontaneous emission in the whole amplifiers can be eliminated by control of the stimulated emission cross-section through pressure broadening using a suitable buffer gas. In 1976, E. Fill developed a saturable absorber for iodine laser systems using thermally dissociated iodine atoms to prevent the generation of amplified spontaneous emission in the amplifier stage. Based upon these methods, outputs of 300 J with 1 nsec have been obtained.

Now, there are two serious problems to be solved in order to develop these iodine laser systems into the desired one producing higher energy, shorter duration (100 psec or less) iodine laser pulses. One is the development of techniques by which the master oscillator can

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generate pulses of 100 psec duration or less. The other problem is the avoidance of the linear bandwidth limitation of the iodine amplifier. Regarding the iodine oscillator, studies utilizing the Free-Induction Decay phenomena have succeeded, as in the work done by E. Fill8'. The Free-Induction Decay phenomenon arises from nonlinearity laser active material due to coherent interaction between the field and the active medium. Although much is known about certain phenomena which are very important in iodine laser systems, considerably less work has been done on short-duration pulse propagation through the iodine amplifier and the saturable absorber involving the occurrence of coherent interaction between the propagated pulse field and the materials. It is important to understand short-pulse propagation in iodine laser systems in order to be able to estimate the output energy and to determine the pulse shape emerging from the iodine laser system.

What must be remembered in the theoretical analysis of short-pulse propagation in the amplifier or in the saturable absorber is to treat any nonlinearity of the laser medium. In particular, when one must treat a short-pulse having a width comparable to or shorter than the transverse relaxation time of the amplifying or the absorbing medium, the coherent interaction phenomena between the propagated pulse field and the medium are unable to be neglected. In the case of dealing with such short-pulse propagation in the amplifier or in the saturable absorber, since rate equation approximations do not describe short-pulse propagation characteristics, one must use a semi-classical treatment in their description.

We have reported on semi-classical treatment of short-pulse propagation in the amplifiers of high-power iodine laser systems9'. The semi-classical equations we obtained were characterized by certain terms stemming from considerations of all hyperfine sublevel populations, all allowed optical transitions between hyperfine sublevels, and Doppler detuning effects. From our numerical calculations, the effects of the population in the \( ^3P_{1/2}(F=2) \) level on pulse amplification and the feasibility of avoiding linear bandwidth limitations were made clear. However, our results showed that pulses which emerged from the amplifier on nonlinear amplification formed a multi-pulse train, which would be a disadvantage of nonlinear amplification from the viewpoint of the pulse temporal quality.

In this report, further calculations are discussed. Our purpose here is to study the influence of a linear loss on nonlinear pulse amplification, on the pulse shape and on the population distributions in each of the hyperfine sublevels, and to make clear a feasibility of obtaining a single pulse emerging from the amplifier under nonlinear amplification. We also find that the semi-classical equations we obtained can describe pulse propagation characteristics in a saturable absorber using thermally dissociated iodine atoms for suitable values of some parameters and some initial population distributions in the hyperfine sublevel terms of our equations.

2. Semi-classical Equations for the Iodine Laser Model

We will now discuss and outline the features of photodissociation iodine lasers and the semi-classical equations for pulse propagation in the iodine amplifier or absorber.

The pumping mechanism of the iodine laser is as follows. The fluoro-alkyl-iodine molecules have an absorption band in the 2700 Å region and dissociate into alkyl radicals and excited iodine atoms when irradiated with U. V. light from a Xe flash lamp. The 1.315 \( \mu \)m laser radi-
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A detailed spectroscopic analysis shows hyperfine splitting of both the $^2P_{1/2}$ and $^2P_{3/2}$ levels, as the I$^{125}$ atom has a nuclear spin of $I=5/2$\(^{10}\).

Figure 1 shows the different hyperfine levels and the $F$ numbers. Each hyperfine level is degenerated and the degeneracy is listed on the right hand side shown in Fig. 1. Due to the selection rules of the optical transition $F=0$, $\pm 1$, six transitions (3-4, 3-3, 3-2, 2-3, 2-2, 2-1) are allowed between the $^2P_{1/2}$-$^2P_{3/2}$ levels. These six transitions are shown in Fig. 1 by six arrows.

The usual conditions in iodine laser systems are as follows:

1. The lifetime of the excited iodine atom and that of the ground state are quite long compared to the pulse width of interest.

2. Internal relaxation among the hyperfine sublevels between the $^2P_{1/2}$ and $^2P_{3/2}$ levels cannot be neglected because these internal relaxation times are comparable to or shorter than the propagated pulse width.

3. The relaxation time among the hyperfine levels of the $^2P_{1/2}$ level results from Van der Waals interaction in collisions with any particle in the laser medium\(^{10}\) which has a similar transverse relaxation time\(^{10}\).

4. Relaxation among the hyperfine levels of $^2P_{1/2}$ occurs efficiently only if the collision partner has a degenerate electrical angular momentum. The cross-section for the relaxation processes are of its same order as in the case of collisional relaxation of the ground state\(^{10}\).

5. The oscillating laser line is that generated by transitions between $F=3-F=4$\(^{10}\).

6. Hyperfine sublevels are degenerated into each degeneracy. We have obtained semiclassical equations for describing short-pulse propagation in the iodine amplifier. The detailed procedure for obtaining these equations and the notations used in these equations are given in eqs. (9) and (13).

7. The equation for the magnetic field envelope is:

$$\frac{\partial \epsilon}{\partial z} = -\kappa \epsilon + \frac{1}{2} \alpha \frac{1}{T_z} \sum_{i,j} <P_{ij}>_v$$  \(1\)

8. The equations for the polarizations are:

$$\frac{\partial P_{ij}}{\partial t} = -\left[\frac{1}{T_i} - \pi (\nu_j - \nu_j) + KV\right]$$

$$P_{ij} + \left(\frac{\mu_{ij}}{\mu_c}\right)^2 \varepsilon \left(\frac{R_i}{g_i} - \frac{R_j}{g_j}\right).$$  \(2\)
(9) The equations for the population densities of the hyperfine sublevels are:

\[
\frac{\partial R_i}{\partial \tau} = \frac{1}{T_i} \left[ R_i - \frac{g_i}{g_a} \sum \frac{R_n}{n} \right] - \frac{1}{4} \sum_j (\varepsilon P_{ij}^* + \varepsilon^* P_{ij}) \tag{3}
\]

\[
\frac{\partial R_j}{\partial \tau} = -\frac{1}{T_i} \left[ R_j - \frac{g_j}{g_b} \sum \frac{R_m}{m} \right] + \frac{1}{4} \sum_i (\varepsilon P_{ij}^* + \varepsilon^* P_{ij}) \tag{4}
\]

The subscripts \(i, j\) represent the hyperfine levels in the \( ^1P_{1/2} \) and \( ^3P_{3/2} \) levels; i.e., \( i \) equals 3 or 2, and \( j \) equals 4, 3, 2, or 1.

(10) The initial conditions of population distributions are as follows:

In \( ^1P_{1/2} \): \( F=3, R_3=1; F=2, R_3=5/7 \).
In \( ^3P_{3/2} \): \( F=4, R_4=0; F=3, R_4=0; F=2, R_4=0; F=1, R_4=0 \).

(11) The amplifying length \( \alpha z \) used is as follows:

\[ \alpha z = g_s \sigma N_0 z \]

where \( g_s, \sigma, \) and \( N_0 \) are, respectively, degeneracy factor (\( g_s = 7 \)) of the \( ^1P_{1/2}(F=3) \) level, the stimulated emission cross-section of the \( ^1P_{1/2}(F=3) - ^3P_{3/2}(F=4) \) transition, and the initial population density of the \( ^1P_{1/2}(F=3) \) level. The absorbing length \( \alpha z \) is given by \( \alpha z = g_s \sigma N_0 z \) where \( g_s \) and \( N_0 \) represent the degeneracy (\( g_s = 9 \)) of the \( ^3P_{3/2}(F=4) \) level and the initial population density of the \( ^1P_{1/2}(F=4) \) level, respectively.

3. Results and Discussion

We have calculated the solutions of equations (1)–(4) by numerical integration for specific choices of parameters. The integration procedure and the initial conditions are given in Ref. 9, 13).
and the pulse energy $E_{az}$ (J/cm²) at $az$ is

$$E_{az}(J/cm²) = \frac{E_{total}}{S_{az}} = \frac{S_0 E_0}{S_{az}}$$

$$= E_0 \exp \left( -\frac{\kappa}{\alpha} az \right) \quad (J/cm²)$$

where $E_0$ and $E_{total}$ represent the energy density and the total energy at the entry plane ($az=0$) of the amplifier medium, respectively. When the beam cross-sectional area $S_{az}$ at $az=200$ is twice as large as that at $az=0$, the apparent linear loss coefficient $-\kappa/\alpha$ equals $3.64 \times 10^{-3}$, and when $S_{az}$ is seven times as large as that at $az=0$, $-\kappa/\alpha$ is $1 \times 10^{-2}$.

The evolution of the pulse shape propagated in an amplifier with apparent linear losses of $1 \times 10^{-2}$ and $1 \times 10^{-4}$ resulting from beam cross-sectional area enlargement are shown in Fig. 2 and Fig. 3, respectively. The initial conditions are the following: the transverse relaxation time of the medium $T_2$ equals $1/5$ GHz and the input pulse width and input pulse energy density are $\tau/T_2 = 0.2$ (40 psec) and $21.6$ mJ/cm², respectively. As for the cases of $-\kappa/\alpha = 10^{-2}$ and $10^{-4}$, below amplifying length of $az=50$, the initial pulse shape is almost destroyed by the strong dispersion of the amplifier medium. However, when the pulse propagates through an amplifier of with amplifying length of more than $az=50$, the propagated pulse shape is affected by coherent interactions between the propagated pulse field and the amplifying medium, and is then further propagated through an amplifier exhibiting nonlinear amplification and is split into a pulse train having several pulses.

Beyond $az=50$, the peak power of each

![Fig. 2](image2.png) Fig. 2 The evolution of pulse shape propagation in an amplifier with a linear loss of $1 \times 10^{-2}$. (Input pulse energy; 21.6 mJ/cm² in pulse width of 40 psec.)

![Fig. 3](image3.png) Fig. 3 The evolution of pulse shape propagation in an amplifier with a linear loss of $1 \times 10^{-4}$. (Input pulse energy; 21.6 mJ/cm² in pulse width of 40 psec.)
pulse in the pulse train has an exponential relationship to the peak power of the first pulse in the pulse train as shown in the following. In the case of an apparent linear loss of $-\kappa/\alpha = 1 \times 10^{-2}$, the peak power of the second pulse is represented by

$$P = P_{\text{first}} \exp\left(-0.18 \tau / T_2\right)$$

In the case of an apparent linear loss of $1 \times 10^{-4}$, the peak power of the second pulse is represented by

$$P = P_{\text{first}} \exp\left(-2 \tau / T_1\right)$$

where $P_{\text{first}}$ is peak power of the first pulse in the pulse train. With the above mentioned relationship, it is clear that in a case of a large apparent linear loss, the first pulse of the pulse train becomes the dominant portion of the pulse train in terms of the total pulse energy density.

We then considered the nature of the first pulse train obtained through nonlinear amplification in relation to coherent interactions between the propagated pulse field and the amplifier medium. The population distributions of all hyperfine levels and the propagated pulse shape at an amplifying length of $\alpha z = 150$ are shown in Fig. 4 and Fig. 5. Figure 4 shows them for an apparent linear loss $-\kappa/\alpha$ of $1 \times 10^{-2}$, and Fig. 5 for that of $1 \times 10^{-4}$. For the case of $-\kappa/\alpha = 1 \times 10^{-4}$, the population of the $^{2}P_{1/2}(F=3, 2)$ levels were restored to 80% of their initial populations at $\alpha z = 0$ by the time the first pulse in the pulse train passed the time point shown as “1” in Fig. 5. On the other hand, for the case of $-\kappa/\alpha = 1 \times 10^{-2}$, they were redistributed 0.5% or the populations of the initial conditions. The nature of the first pulses

![Fig. 4](image)

Fig. 4 The population distributions of all hyperfine levels, and the pulse shape at $\alpha z = 150$ with a linear loss of $1 \times 10^{-2}$.

![Fig. 5](image)

Fig. 5 The population distributions of all hyperfine levels, and the pulse shape at $\alpha z = 150$ with a linear loss of $1 \times 10^{-4}$. 
in the pulse train is similar to that of the "2π pulse" and the "π pulse" in a simple two-level systems, despite of the phenomenon occurring in a multi-level system. These population distributions suggest to us that the first pulse of a pulse train propagated through an amplifier with a linear loss is one which appears to have the nature of a pulse train with a large linear loss is capable of gaining energy from the amplifier efficiently, as is the case of the "π pulse" in a pure two-level system. Figure 6 shows the effect of the linear loss on the propagated process of the input pulse energy density through the amplifier. The energy density obtained at \( \alpha z = 150 \) with a linear loss of \( 1 \times 10^{-4} \) is 80 J/cm\(^2\). Of course, this is larger than in the case of \( 1 \times 10^{-2} \) linear loss where the energy density is 30 J/cm\(^2\). However, the beam cross-sectional area of a pulse propagated through \( \alpha z = 150 \) is different for linear losses of \( 1 \times 10^{-2} \) and \( 1 \times 10^{-4} \). The total pulse energy \( (E_{\text{total}}) \) at \( \alpha z = 150 \) in the case of a linear loss of \( 1 \times 10^{-2} \) is

\[
E_{\text{total}}(J) = 30 \left( \frac{1}{\text{cm}} \right) \times S_{\alpha z} \left( \text{cm}^2 \right) = 30 \times S_{\alpha}
\]

\[
\times \exp(k/z, \alpha z) = 130 S_{\alpha}(J)
\]

On the other hand, for the case of a loss of \( 1 \times 10^{-4} \), the total energy emerging from the amplifier is

\[
E_{\text{total}}(J) = 80 S_{\alpha}(J)
\]

Therefore, the total energy obtained from an amplifier with a large linear loss is larger than that from an amplifier with a small one.

Figure 7 shows the effect of the linear loss on the propagated process of the pulse field area, which is defined as \( A = 1/\hbar \int E \, dt \). For both the case of linear loss of \( 1 \times 10^{-2} \) and that of \( 1 \times 10^{-4} \), the pulse area reached a constant value of \( A = 2.46\pi \). Figure 8 shows the effect of the input pulse energy on the propagated
process of the pulse field area. The stationary value of the area is 2.46 $\pi$, which is independent of its input pulse energy. From this fact, we see that the stable propagated pulse field area in the iodine amplifier is 2.46 $\pi$.

When considering nonlinear amplification of the peak pulse power, coherent interaction between the propagated pulse field and the amplifier medium influences the relationship between the pulse field amplitude and the rise time of the leading edge of the propagated pulse in the amplifier. Figure 9 shows the relationship between the propagated pulse field amplitude and the rise time of the leading edge in the case where the transverse relaxation rate of the amplifier medium $1/T_2$ is 5 GHz and 10 GHz. The rise time of the propagated pulse field becomes shorter in proportion to the amplified pulse peak power. The pulse propagated through the amplifier is amplified maintaining this relationship between the rise time and the peak power as shown in Fig. 9. From this figure, we obtain the following relationship between the pulse field amplitude and the rise time of the leading edge of the pulse propagated in the amplifier.

In the case of $1/T_2$ being 5 GHz,

$$\tau = 100 \exp\left(-2.2 \times 10^{-2} x\right) \text{ psec}$$

$$x = HT_2 = \left(P(\text{W/cm}^2)/5.5 \times 10^4(\text{W/cm}^2)\right)^{1/2}$$

($10 \leq \tau \leq 50$, $x \leq 90$)

and in the case of $1/T_2$ being 10 GHz,

$$\tau = 60 \exp\left(-2.2 \times 10^{-2} x\right) \text{ psec}$$

$$x = |HT_2| = \left(P(\text{W/cm}^2)/5.5 \times 10^4(\text{W/cm}^2)\right)^{1/2}$$

($10 \leq \tau \leq 50$, $x \leq 90$)

The limits of coherent interaction which must be considered for short-pulse amplification in an iodine laser amplifier system are shown by these equations.

(B) Pulse propagation in the saturable absorber

We will now consider pulse propagation in a saturable absorber which uses thermally dissociated iodine atoms. Our semi-classical equations for pulse propagation in the amplifier can also describe pulse propagation in a saturable absorber for suitable initial conditions. The initial conditions and parameters used in the calculations are as follows.

1. The transverse relaxation time of the absorbing medium $T_2$ equals 1/1 GHz.
2. The Doppler width is 1 GHz.
3. The input pulse shape has a Gaussian profile with a pulse width of 1 nsec.
4. The initial population distributions of the hyperfine sublevels are

$^2\!P_{1/2}$: $N(F=3)=0$, $N(F=2)=0$

$^2\!P_{1/2}$: $N(F=4)=1$, $N(F=3)=7/9$,

$N(F=2)=5/9$, $N(F=1)=3/9$

5. The internal relaxation time among the hyperfine sublevels of the $^2\!P_{1/2}$ level is comparable to the transverse relaxation time of the absorbing medium because the collision partners of the excited iodine atoms are only $I_2$ molecules which have an electric angular momentum.

6. The absorbing line is the same as the lasing
Using above mentioned conditions, transmitting characteristics are as shown in Fig. 10. The circular points in Fig. 10 represent the experimental results obtained by E. Fill and the solid line represents the results of our numerical calculations. From our calculations, an input energy larger than 0.5 J/cm$^2$ saturates the energy absorption of the thermally dissociated iodine absorber, as seen in Fig. 10. In spite of the lack of detailed experimental data, especially that for the correct transverse relaxation time and for the correct pulse shape, our calculated results provide a good fit to experimental data on energy transmission.

The classical rate equation approximation is not suitable for analyzing pulse propagation in a saturable absorber because the propagated pulse width is comparable to or shorter than the transverse relaxation time of the absorbing medium, our semi-classical equations are particularly useful since they are applicable to such a case.

4. Conclusions

From our calculations, the nature of the pulse emerging from the amplifier during non-linear amplification was determined. With a small linear loss of $-\kappa/\alpha=1\times10^{-4}$, the first pulse of the pulse train coming out from the amplifier during nonlinear amplification is similar to the “$2\pi$ pulse” (the Self-Induced Transparency pulse) in a simple two-level system. With a large linear loss of $1\times10^{-2}$, the first pulse of the pulse train is the one which extracts energy from the amplifier stage efficiency and which is similar to the “$\pi$ pulse” in a simple two-level system. Due to the introduction of apparent linear loss in the amplifier stage which results from the beam cross-sectional area enlarging along the propagation axis in the amplifier reducing the pulse energy density in proportion to the amplifying length, the first pulse of the pulse train emerging from the amplifier becomes the dominant portion of the pulse train when considering the total pulse energy density. This fact suggests that a single pulse should be obtained from an amplifier with nonlinear amplification, which could eliminate the disadvantages of pulse breaking in the case without linear loss. When designing an ideal iodine amplifier system utilizing non-linear amplification, we suggest based on our calculations that the beam cross-
sectional area enlarging effect is an important factor in obtaining a good temporal pulse quality and in preventing damage of the optical materials in the final amplifier stage. Also, from our calculations, it was made clear that the stable pulse field area through the iodine amplifier is that of the 2.46 π pulse, the area of which is independent of the input pulse energy density and of the linear loss, and there is a close relationship between the pulse field amplitude and the rise time of the leading edge of the pulse propagated through the amplifier.

As for pulse propagation in the saturable absorber, the semi-classical equations used for describing pulse propagation in the amplifier are also useful for analyzing pulse propagation in a saturable absorber which uses thermally dissociated iodine atoms. Therefore, our semi-classical equations for pulse propagation in an amplifier and in a saturable absorber can describe the complete iodine laser amplifier system.

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References