

## Dye high power optical switch

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**ABSTRACT.** Experimental and numerical results are presented showing that a dye laser amplifier can be used as a very fast high power optical switch. The operation of the device is based on the fact that the absorption and transmission of the pump beam in the laser amplifier strongly depends on the intensity of the amplified signal beam [1]. In particular it is shown that with relatively small signal beams it is possible to control large transmitted pump beams. A comparison between the numerical and the experimental observations show them to be in good qualitative agreement.

**RESUMEN.** Se presentan resultados experimentales y numéricos que muestran que un amplificador láser de colorante puede ser usado como un interruptor óptico de respuesta rápida. La operación del dispositivo se basa en que la absorción y transmisión del haz de bombeo en el amplificador depende fuertemente de la intensidad de la señal láser amplificada [1]. En particular se muestra que con haces de señal de relativamente baja intensidad, es posible controlar la transmisión de intensos haces de bombeo. La comparación entre los resultados numéricos y las observaciones experimentales mostró estar en buen acuerdo cualitativo.

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### 1. INTRODUCTION

As it is well known, most amplifier devices (*e.g.* vacuum tubes and transistors) can also be used as switching elements if they are operated in appropriate configurations. In particular, laser pumped fluorescent dyes have been widely used as amplifier media for incident laser signal beams at several wavelengths [2, 3]. More recently it has been shown [1] that in the steady-state the transmission of the *pump* beam through a laser amplifier can be strongly controlled by the intensity of the signal beam. This steady-state result suggest that a laser amplifier can be used as an optical switch. In this communication the idea is studied numerically by solving the spatial and temporal system of equations which describe the atomic medium and the laser pump and signal beams. In order to obtain a clearer understanding of the dynamics of the switching process the temporal-varying shape of real laser pulses is taken into account. The results obtained show that an effective switching can be realized for the pump beam by a modulation in the signal beam incident in the amplifier and that the switching process occurring is very fast. These results were compared to experimental observations and were shown to be in good qualitative agreement. Nevertheless the overall efficiency of the process can be small due to excited-state absorption.

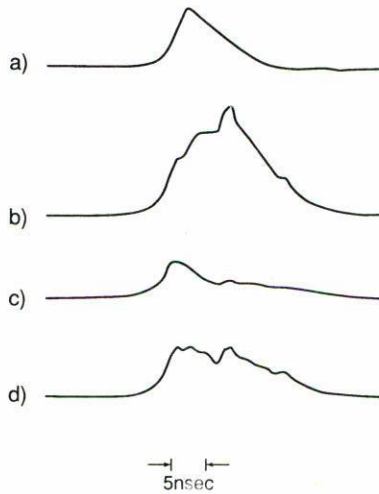


FIGURE 1. Experimental results obtained for an incident pump energy of  $20 \text{ mJ/cm}^2$ . (a) and (b) show the temporal shapes of the incident signal and pump beams and (c) and (d) show the transmitted pump beam after the signal-pump interaction when the signal energy pulse was 23 and  $2.3 \text{ mJ/cm}^2$  (the vertical axes are not comparable).

## 2. EXPERIMENT

The experimental set-up used was the same that the one described in Ref. [1]. There, counterpropagating pump and signal beams interacted in a 1 cm cell containing a solution of Rh<sub>6</sub>G at a concentration of  $N_t = 4 \times 10^{16} \text{ cm}^{-3}$ . The pump beam was a frequency doubled Q-switched Nd:YAG laser ( $\lambda_p = 532 \text{ nm}$ ), and the signal beam was produced by a laser-pumped Rh<sub>6</sub>G dye laser ( $\lambda_s = 565 \text{ nm}$ ). The experimental results of the pump-signal interaction were observed using ITL S-20 vacuum diode detectors and a four channel Le Croy 7200 Digital Oscilloscope with an effective bandwidth of 1 GHz. Figure 1 shows (directly from the oscilloscope) a laser-printed copy of the experimental results obtained for an incident pump pulse of energy density  $20 \text{ mJ/cm}^2$ . In this figure traces (a) and (b) correspond to the incident signal and pump beam (vertical axes are not comparable), and (c) and (d) correspond to the transmitted pump beam after the signal-pump interaction when the incident signal energy density was 23 and  $2.3 \text{ mJ/cm}^2$  respectively. By comparing (c) and (d) with the incident pump of (b), a switching process can clearly be seen taking place after an initial transient in the transmitted pump.

## 3. NUMERICAL SIMULATION

Figure 2 shows the schematic model of the dye absorption and emission mechanism for a typical dye.  $\sigma_{p,s}^a$  and  $\sigma_{p,s}^s$  are the cross section for ground state absorption and stimulated emission for the pump and signal beam.  $\sigma_{p,s}^*$  are the cross sections for excited state absorption of pump (p) and signal (s) photons and  $\tau$  and  $\tau_{esa}$  are the life times of the laser and upper levels. Once a pump photon of frequency  $\omega_p$  is absorbed from state |1> to state |2>, a rapid ( $10^{-12} \text{ s}$ ) non radiative transition takes the dye molecule to state |3>.

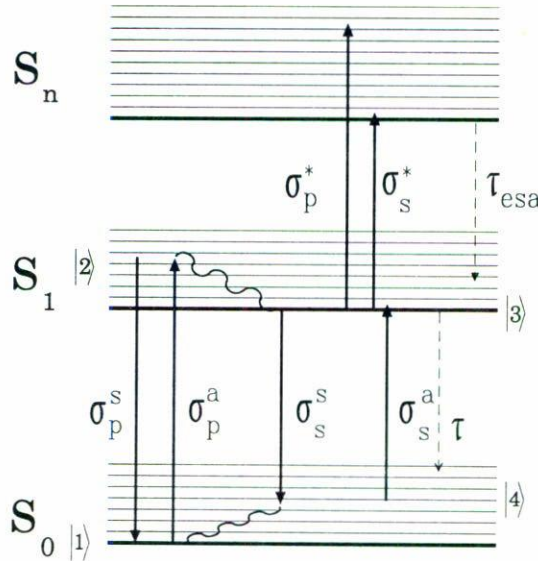


FIGURE 2. Model of the dye absorption and emission energy levels.

By stimulated emission between levels |3> and |4> a photon of frequency  $\omega_s$  is produced. A rapid non radiative transition takes the dye molecule from state |4> to state |1>.

The pump and signal intensities  $I_{p,s}[z, t]$  are described by the following equations:

$$\frac{\partial I_s}{\partial z} + \frac{n_s}{c} \frac{\partial I_s}{\partial t} = [-\sigma_s^a N_1 + (\sigma_s^s - \sigma_s^*) N_3] I_s \tag{1}$$

and

$$(\pm) \frac{\partial I_p}{\partial z} + \frac{n_p}{c} \frac{\partial I_p}{\partial t} = [-\sigma_p^a N_1 + (\sigma_p^s - \sigma_p^*) N_3] I_p, \tag{2}$$

where  $N_1[z, t]$  and  $N_3[z, t]$  are the population densities of level 1 and 3,  $n_{p,s}$  the refractive index of the dye at the pump and signal laser frequencies and  $c$  the speed of light. The (+, -) signs in Eq. (2) indicate that the beams are copropagating (+) or counterpropagating (-). The rate equation for  $N_3[z, t]$  is

$$\frac{\partial N_3}{\partial t} = -\frac{1}{\hbar\omega_s} (\sigma_s^a N_1 - \sigma_s^s N_3) I_s - \frac{1}{\hbar\omega_p} (\sigma_p^a N_1 - \sigma_p^s N_3) I_p - \frac{N_3}{\tau}, \tag{3}$$

where  $\hbar$  is Planck constant divided by  $2\pi$ , and the total population density is  $N_t = N_3 + N_1$ . For CW or pulses longer than the transit time of the dye cell, the temporal derivatives of Eqs. (1) and (2) can be neglected. With this assumption Eqs. (1), (2) and (3) were solved with initial conditions  $I_s(0, t) = I_{s0}(t)$  and  $I_p(0, t) = I_{p0}(t)$  for the copropagating case, and boundary conditions  $I_s(0, t) = I'_{s0}(t)$  and  $I_p(L, t) = I'_{pL}(t)$ , for the counterpropagating case ( $L$  being the dye cell amplifier length). The following first order algorithm used to

solve Eqs. (1), (2) and (3), proved to be good enough to accurately reproduce the steady state results given in Ref. [1] and the experimental results reported here:

$$I_s[\zeta + \Delta\zeta, \epsilon] = I_s[\zeta, \epsilon] + \phi[N_3(\zeta, \epsilon)]I_s[\zeta, \epsilon]\Delta\zeta, \quad (4)$$

$$I_p[\zeta + \Delta\zeta, \epsilon] = I_p[\zeta, \epsilon] + \gamma[N_3(\zeta, \epsilon)]I_p[\zeta, \epsilon]\Delta\zeta, \quad (5)$$

$$N_3[\zeta, \epsilon + \Delta\epsilon] = N_3[\zeta, \epsilon] + \eta[N_3(\zeta, \epsilon)]I_s[\zeta, \epsilon]\Delta\epsilon \\ + \varphi[N_3(\zeta, \epsilon)]I_p[\zeta, \epsilon]\Delta\epsilon - N_3[\zeta, \epsilon]\Delta\epsilon, \quad (6)$$

where  $\zeta$ ,  $\epsilon$ ,  $\Delta\zeta$  and  $\Delta\epsilon$  are the discrete spatial and temporal variables and its increments respectively, and the functions  $\phi$ ,  $\gamma$ ,  $\eta$  and  $\varphi$  are

$$\phi[\zeta, \epsilon] = \sigma'_s N_3[\zeta, \epsilon] - \sigma_s^a N_t, \quad (7)$$

$$\gamma[\zeta, \epsilon] = \sigma'_p N_3[\zeta, \epsilon] - \sigma_p^a N_t, \quad (8)$$

$$\eta[\zeta, \epsilon] = \frac{1}{\hbar\omega_s}(\sigma_s^a N_t - (\sigma_s^s + \sigma_s^a)N_3[\zeta, \epsilon]), \quad (9)$$

$$\varphi[\zeta, \epsilon] = \frac{1}{\hbar\omega_p}(\sigma_p^a - (\sigma_p^s + \sigma_p^a)N_3[\zeta, \epsilon]), \quad (10)$$

where

$$\sigma'_s = \sigma_s^s - \sigma_s^* + \sigma_s^a \quad (11)$$

and

$$\sigma'_p = \sigma_p^s - \sigma_p^* + \sigma_p^a. \quad (12)$$

Considering Rh<sub>6</sub>G, the following parameters [1,4,5] were used in the simulation:  $\sigma_s^s = 2.2 \times 10^{-16}$  cm<sup>2</sup>,  $\sigma_s^* = 0.5 \times 10^{-16}$  cm<sup>2</sup>,  $\sigma_p^a = 3.85 \times 10^{-16}$  cm<sup>2</sup>,  $\sigma_s^a \rightarrow 0$ ,  $\sigma_p^* = 0.38 \times 10^{-16}$  cm<sup>2</sup>,  $\sigma_p^s = 0.6 \times 10^{-16}$  cm<sup>2</sup> and  $\tau = 3.5$  nsec,  $L = 1$  cm,  $N_t = 4 \times 10^{16}$  cm<sup>-3</sup>. Figure 3 shows a numerical simulation using the same experimental parameters as those described above for Fig. 1. In this Fig. 3, (a) and (b) show the incident signal and pump beams and (c) and (d) show the transmitted pump beam when the signal energy was 23 and 2.3 mJ/cm<sup>2</sup>. As we can see, there is a good qualitative agreement between the experimental observations of Fig. 1 and the simulation results shown in Fig. 3.

A final example which demonstrates clearly the fast switching properties of the device is shown in Fig. 4; this shows a 0.1 MW/cm<sup>2</sup> square wave modulated input signal beam in Fig. 4-(a) interacting with a 10 MW/cm<sup>2</sup> CW input pump wave. This produces a switched output pump beam with a "quasi square wave" shape that varies from  $\sim 0$  to 1 MW/cm<sup>2</sup> as is shown in Fig. 4-(b).

The time required to reach steady state depends on the magnitudes of  $I_s$  and  $I_p$ . The larger  $I_s$  and  $I_p$  are the smaller the time required. In fact, for typical experimental values

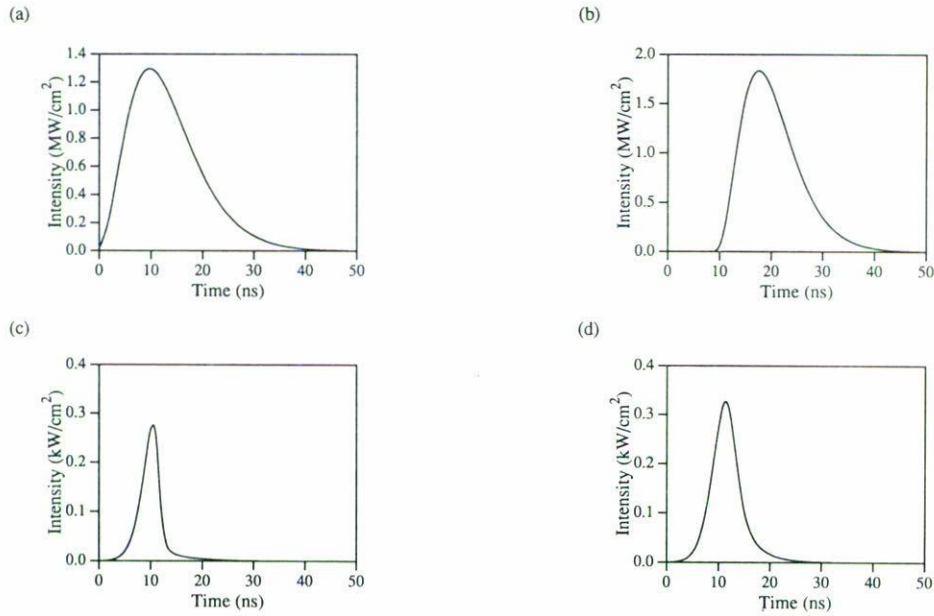


FIGURE 3. Numerical simulation of the experimental results shown in Fig. 1. (a) and (b) show the incident signal and pump beams and (c) and (d) show the transmitted pump beam after the signal-pump interaction.

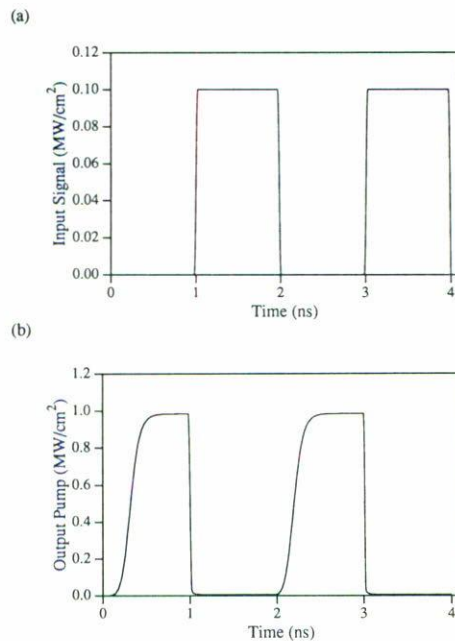


FIGURE 4. Numerical simulation of a  $0.1 \text{ MW}/\text{cm}^2$  square wave modulated input signal beam (shown in (a)), interacting with a  $10 \text{ MW}/\text{cm}^2$  CW input pump beam producing a switched output pump beam with a quasi square wave shape (shown in (b)).

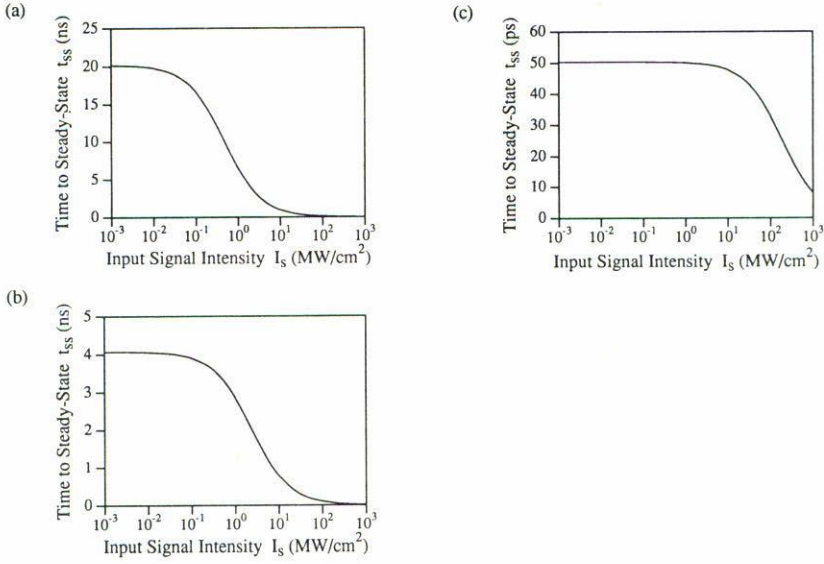


FIGURE 5. (a), (b) and (c) show a plot of Eq. (17) when  $I_p = 0.01, 1$  and  $100 \text{ MW/cm}^2$  respectively and  $I_s$  is varied from  $0.001$  to  $1000 \text{ MW/cm}^2$ .

of  $I_s$ , and  $I_p$  (tens or hundreds of  $\text{MW/cm}^2$ ) it is found that the required time is only a few picoseconds. A rough qualitative estimate of the time constant of the system may be obtained by rewriting Eq. (3) (with  $\sigma_s^a = 0$ ) as

$$\frac{\partial N_3}{\partial t} + \frac{N_3}{\tau} \left\{ 1 + \frac{I_p}{I'_p} + \frac{I_s}{I_s^{\text{sat}}} \right\} = \frac{N_t I_p}{\tau I_p^{\text{sat}}}, \tag{13}$$

where the saturation intensities for the pump and signal beam are

$$I_p^{\text{sat}} = \frac{\hbar\omega_p}{\tau\sigma_p^a}, \tag{14}$$

$$I_s^{\text{sat}} = \frac{\hbar\omega_s}{\tau\sigma_s^s}, \tag{15}$$

and

$$I'_p = I_p^{\text{sat}} \left[ 1 + \frac{\sigma_p^s}{\sigma_p^a} \right]^{-1}. \tag{16}$$

From Eq. (13) we can define an “effective time constant”  $\tau'$  as

$$\tau' = \tau \left[ 1 + \frac{I_p}{I'_p} + \frac{I_s}{I_s^{\text{sat}}} \right]^{-1} \tag{17}$$

Figures 5-(a), 5-(b) and 5-(c) show a plot of the time required to reach steady state ( $= 6\tau'$ ) for  $I_p = 0.01, 1$  and  $100 \text{ MW/cm}^2$  respectively, according to Eq. (17) when  $I_s$  is varied from  $0.001$  to  $1000 \text{ MW/cm}^2$ . As we can see, for typical experimental values very short response times are expected.

#### 4. CONCLUSIONS

Experimental and numerical results are presented showing that a dye amplifier can be used as a fast high power optical switch. The main limitation to the efficiency of the device is due to the presence of excited-state absorption. Therefore if excited-state absorption can be reduced the efficiency of the device will improve. We believe that one of the most important features of the process described here is the ability to control high intensity pump beam with relatively small signal beams.

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