Spatial light modulation characteristics of reverse saturable absorber

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Abstract. Construction of a spatial light modulator (SLM) using reverse saturable absorber molecules is suggested. The SLM characteristics are derived using a recently proposed steady-state kinetic analysis. Results are presented for the rhodamine 6G dye molecules.

1. Introduction

In principle optical-processing and computing systems based on Fourier-transform type operations offer processing speeds approaching the velocity of light. However, the speeds of these systems are severely limited by the response times of the input and output transducers. To fully utilize the potential of all optical processing and computing systems, real-time reusable two-dimensional input transducers or spatial light modulators are required for data presentation at both input and Fourier planes. The SLMs can also be used for image amplification, time/space transformation, scratch pad memory, programmable detector masking and page composition for hologarphic memories. Hence, in the past decade the list of SLMs under development or in production has expanded considerably. Recently it has been shown that the organic materials which have been playing very important role in the field of Q-switching and mode-locking of lasers (Shapiro 1977) and second-harmonic generation (Chemla and Zyss 1987) may provide the ideal medium needed for the optical hardware used in optical information processing and computing systems. Hence, the phenomena of optical modulation, (Kirkby and Bennion 1986) optical bistability (Orenstein et al 1987) and optical phase conjugation (Kramer 1986) in organic materials have also been studied. A detailed study of the possibility of constructing a molecular SLM using a nonlinear absorber has been reported recently (Speiser and Dantsker 1989). Using a steady-state kinetic analysis it has been shown that a probe light can be modulated by propagating through a medium excited by another light.

The nonlinear absorbers having excited state absorption cross sections larger than the ground state absorption cross section known as reverse saturable absorbers (RSA), have been receiving attention recently because of their usefulness in the process of mode locking of lasers (Harter et al 1985). Organic dye molecules such as Rhodamine 6G exhibit RSA characteristics over a certain range of wavelengths (Harter et al 1984).

A systematic study of the transmission characteristics of an RSA has been presented (Reddy 1987). In the present paper we explore the possibility of using an RSA for the construction of a molecular SLM. The kinetic analysis of Speiser and Dantsker (1989) is extended to study the SLM characteristics of an RSA molecule. Details of this analysis and the results obtained are presented here.

2. Analysis

We assume an SLM configuration similar to the one considered earlier (Speiser and Dantsker 1989) in which a writing light of intensity $I_W(x, t)$ excites the RSA medium, which in turn modulates a probing read light of intensity $I_R(x, t)$. In the present analysis we consider only the case of read and write light beams propagating in the same direction and $I_W \gg I_R$. A schematic diagram of the vibrational levels of an RSA is given in figure 1. We assume that the transitions from levels 3 to 2 and 4 to 2 are extremely fast. Thus the effective populations in the levels 3 and 4 are negligible and only levels 1 and 2 are appreciably populated. Thus the total population is $n = n_1 + n_2$ where n_1 and n_2 are the populations in levels 1 and 2 respectively. The dynamics of this system for a write beam propagating in the x direction is described by the following rate equations

$$\frac{\partial n_1}{\partial t} = -I_W(x, t)\sigma_{13}(W)n_1 + \frac{n_2}{\tau_r} \tag{1}$$

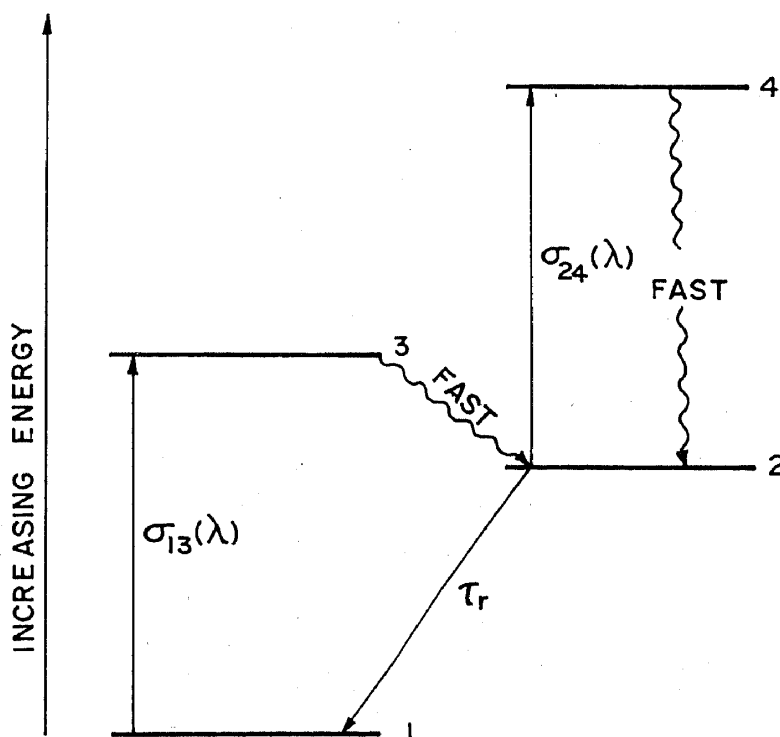$$\frac{\partial n_2}{\partial t} = -I_W(x, t)\sigma_{24}(W)n_2 - \frac{n_2}{\tau_r} \tag{2}$$

Figure 1.   Schematic energy level diagram of an RSA.

$$\frac{\partial I_W(x,t)}{\partial t} + c\frac{\partial I_W(x,t)}{\partial x} = -\alpha_W I_W(x,t) \tag{3}$$

where $\sigma_{13}(W)$ and $\sigma_{24}(W)$ are the ground state and the excited state absorption cross-sections respectively, τ_r is the lifetime of the excited level 2 and α_W is the absorption coefficient given by,

$$\alpha_W = n_1\sigma_{13}(W) + n_2\sigma_{24}(W). \tag{4}$$

Equations (1)–(4) yield at steady state,

$$\frac{dI_W(x)}{dx} = -\alpha_W^0\left(\frac{1+\beta(W)(I_W/I_S)}{1+(I_W/I_S)}\right)I_W(x) \tag{5}$$

where the small signal absorption coefficient $\alpha_W^0 = n\sigma_{13}(W)$, $\beta(W) = \sigma_{24}(W)/\sigma_{13}(W)$ and the saturation intensity $I_S = (\sigma_{13}(W)\tau_r)^{-1}$. Assuming the dye medium of length L, the intensity equation can be integrated to yield,

$$Y = \frac{I_W(L)}{I_W(0)} = \exp(-\alpha_W^0 L)\left[\frac{1+\gamma I_W(0)\,Y}{1+\gamma I_W(0)}\right]_\delta \tag{6}$$

where $I_W(0)$ is the intensity at $x = 0$, $I_W(L)$ is the intensity at $x = L$, $\gamma = \sigma_{24}(W)\tau_r$ and $\delta = (\beta(W)-1)/\beta(W)$.

Similarly for the read beam intensity we have

$$\frac{dI_R(x)}{dx} = -\alpha_R I_R(x) \tag{7}$$

where $\alpha_R = n_1\,\sigma_{13}(R) + n_2\,\sigma_{24}(R)$ is the absorption coefficient for the read beam. Substituting the values of n_1 and n_2 obtained from eqns (1) and (2) for steady state we get,

$$\alpha_R = \alpha_R^0\left[\frac{1+\beta(R)(I_W/I_S)}{1+(I_W/I_S)}\right], \tag{8}$$

where $\alpha_R^0 = n\,\sigma_{13}(R)$ and $\beta(R) = \sigma_{24}(R)/\sigma_{13}(R)$.

From eqns (5) and (7), we can write,

$$\frac{dI_R(x)}{I_R(x)} = \left(\frac{\alpha_R}{\alpha_w}\right)\frac{dI_W(x)}{I_W(x)}$$

$$= \left(\frac{\alpha_R^0}{\alpha_W^0}\right)\left[\frac{1+\beta(R)(I_W/I_S)}{1+\beta(W)(I_W/I_S)}\right]\frac{dI_W}{I_W}.$$

This equation yields, after integration over the medium length L

$$\frac{I_R(L)}{I_R(0)} = \left(\frac{\alpha_R^0}{\alpha_W^0}\right)\left\{\ln\left(\frac{I_W(L)}{I_W(0)}\right) + \ln\left[\frac{1+\beta(W)[I_W(L)/I_S]}{1+\beta(W)[I_W(0)/I_S]}\right]\left(\frac{\beta(R)}{\beta(W)}-1\right)\right\}.$$

Defining $\Gamma \equiv \beta(R)/\beta(W) - 1$ and $\xi \equiv \alpha_R^0/\alpha_W^0 = \sigma_{13}(R)/\sigma_{13}(W)$ and using (6), the above equation can be rewritten as,

$$Z = \frac{I_R(L)}{I_R(0)} = \left\{ Y \left[\frac{1 + \gamma I_W(0)\, Y}{1 + \gamma I_W(0)} \right]^{\Gamma} \right\}^{\xi}. \tag{9}$$

3. Results and discussion

Equation (9) is the basic equation for the discussion of the molecular SLM performance of an RSA. We will consider an example of the dye rhodamine 6G. This molecule is found to have $\sigma_{24} > \sigma_{13}$ over the wavelength range from 400 to 465 nm (Hammond 1980). For the present analysis we consider the write light beam at wavelength 435 nm for which rhodamine 6G has $\sigma_{13}(W) = 0.33 \times 10^{-16}\,\text{cm}^2$ and $\sigma_{24}(W) = 4.29 \times 10^{-16}\,\text{cm}^2$. Considering the read light beam at wavelength 500 nm the corresponding absorption cross-sections are $\sigma_{13}(R) = 1.5 \times 10^{-16}\,\text{cm}^2$ and $\sigma_{24}(R) = 0.37 \times 10^{-16}\,\text{cm}^2$. Hence the dye molecule behaves as a RSA at write beam wavelength and as a saturable absorber at read beam wavelength. The relaxation time $\tau_r = 3.9 \times 10^{-9}\,\text{s}$. Assuming the concentration of the dye molecules $n = 3 \times 10^{17}\,\text{cm}^{-3}$, eq. (6) is solved for Y values using graphical solutions method and the corresponding Z values are computed from (9). The variations of Y and Z values for different input write beam intensity values $I_W(0)$ are shown in figure 2. These curves show a case of a normally closed SLM. By interchanging the wavelengths of write and read light beams the dye acts as a normally open SLM medium, as shown in figure 3. Characteristic curves for different values of L are shown in figure 4 for the normally open case of SLM. Finally the maximum contrast ratio is computed using the expression $R = \exp[\sigma_{24}(R)nL]$. The exponential dependence of R on the nL values is shown in figure 5 for rhodamine 6G dye.
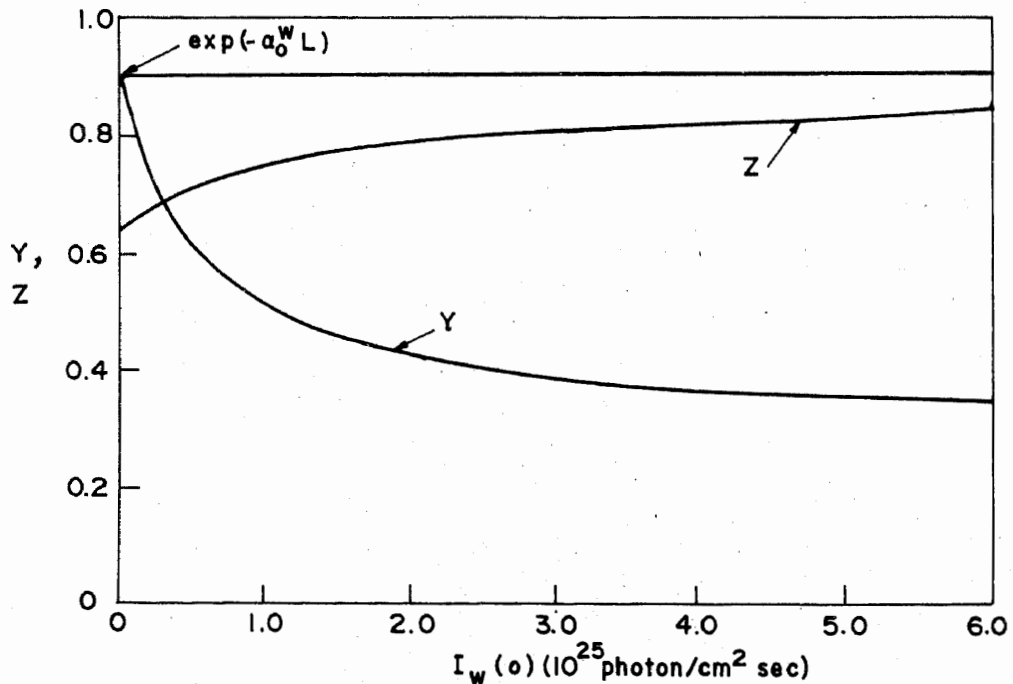

Figure 2. Characteristic curves for write beam transmission Y and read beam transmission Z for rhodamine 6G $(\sigma_{24}(W) > \sigma_{13}(W);\ \sigma_{24}(R) < \sigma_{13}(R))$.
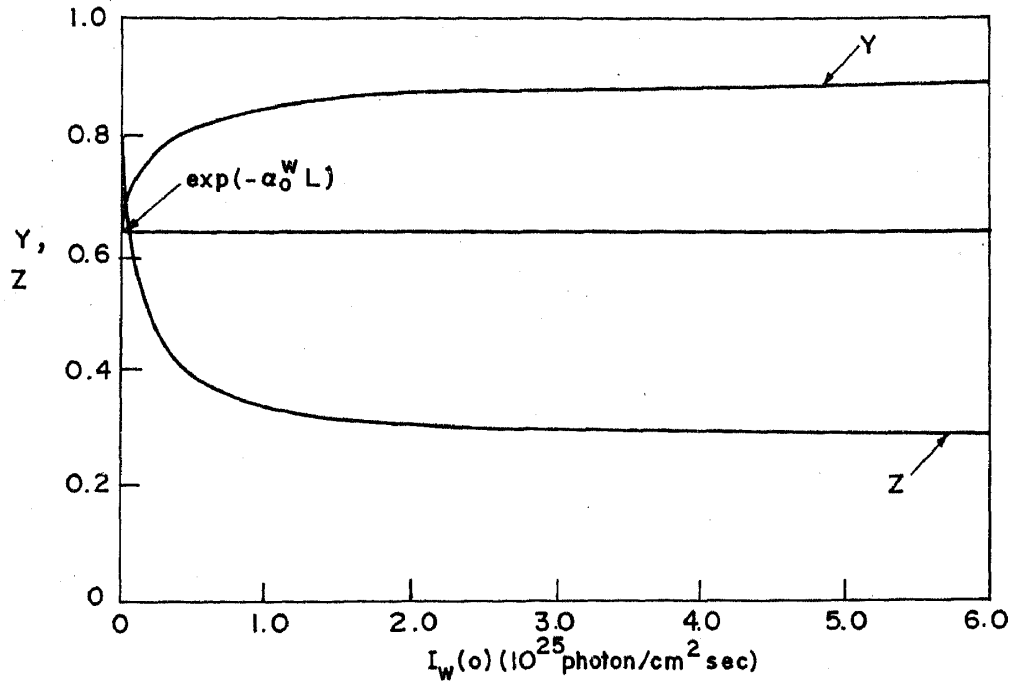
Figure 3. Characteristic curves for write beam transmission Y and read beam transmission Z for rhodamine 6G $(\sigma_{24}(W) < \sigma_{13}(W); \sigma_{24}(R) > \sigma_{13}(R))$.
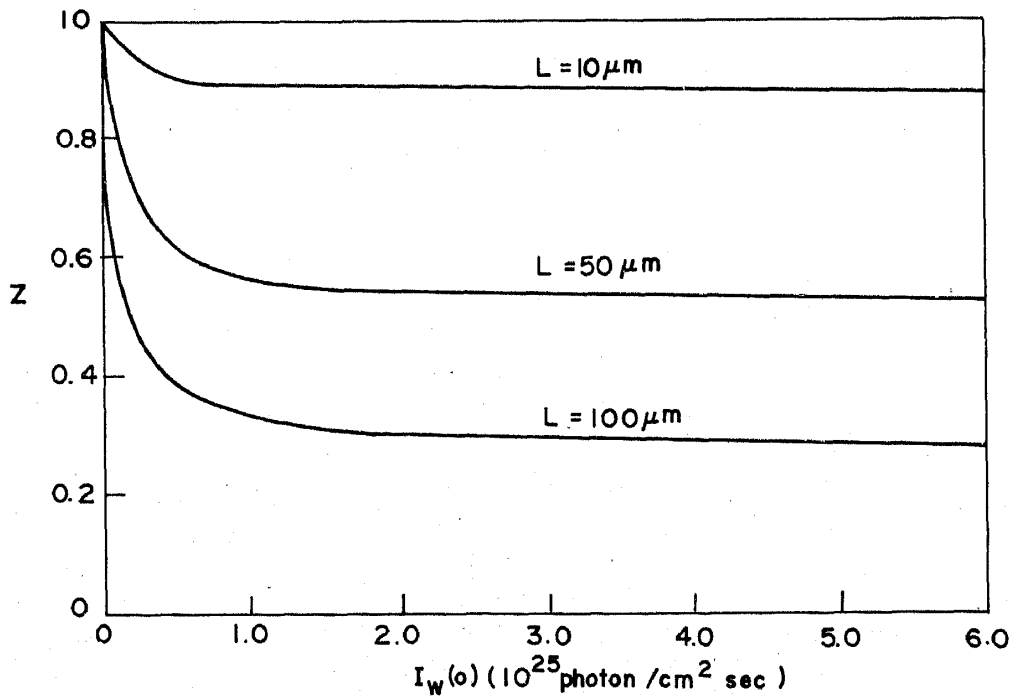

Figure 4. Characteristic read beam curves for normally open rhodamine 6G SLM for different L values.
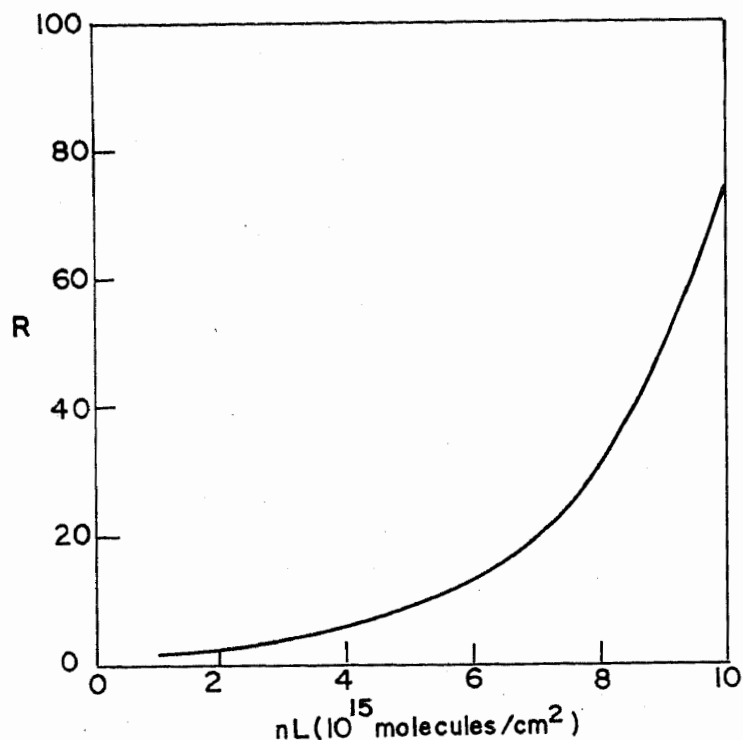
Figure 5. Variation of contrast ratio with *nL* for rhodamine 6G.

4. Conclusion

In conclusion, we have extended the study of SLM by nonlinear absorbers presented recently (Speiser and Dantsker 1989) to RSAs. The characteristic curves and the contrast ratio for the case of the dye rhodamine 6G are computed using the expressions derived in this paper. These curves are presented here for different combination of dye parameters. The results presented in this paper indicate that a molecular SLM can be constructed using rhodamine 6G dye which acts as an RSA over a certain wavelength range.

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